# Determination and optimization of delimbing forces on hardwood harvesting heads

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Summary: Current harvesting heads are particularly efficient during delimbing process in coniferous trees. But they are definitely less efficient in broadleaved trees in terms of productivity, strength and quality, because of the shape, diameter and hardness of branches. One of the objectives of the so-called ECOMEF project (Eco-design of mechanized equipment for hardwood harvesting) was to develop new more efficient delimbing knives and to compare their performance with current knives, in terms of force, energy and time necessary to cut hardwood branches.

These parameters were assessed with FEM models and experiments on hardwood, with delimbing test benches developed for the project as well as field tests on a harvesting head, both for existing commercial knives and our innovative ribbed knives.

By assessing the energy and the forces necessary for branch-cutting, the knife shape was improved and optimized. This study has finally led to new patented delimbing knives for forest harvester heads, that are currently tested by professionals in logging conditions.

Keywords: Delimbing test bench, Harvester head, Cutting force, Ribbed knives, Blade shape, Hardwood tree, ECOMEF project.

## 1. Introduction

By the year 2020, the French wood harvesting is expected to increase by 21 million m³, among which 65% is hardwood [4]. However, most existing harvesting heads are dedicated to coniferous trees and lose their efficiency on hardwood, even leading to machine failure. Harvesting heads achieving the same productivity on hardwood trees as on coniferous trees have still to be developed. The ECOMEF research project (Eco-design of mechanized equipment for hardwood harvesting) has the ambition to develop such heads.

The harvesting process with this kind of machines can be divided into four steps:

- First, the operator chooses a tree and places the head on the trunk base.
- Then, the machine cuts the tree, that falls down.
- When the tree is down, the machine delimbs the tree, until the length of the first piece of wood is achieved (Fig. 1a).
- Finally, the head cuts a log of the trunk at the desired length. Those two last steps are repeated until the end of the tree.

The typical harvesting head considered in this paper is the Kesla 25 RH [11]. It uses two propelling rollers and two pairs of delimbing knives that brace tightly the trunk (Fig. 1b). All the actuators are hydraulic.

One strong limitation of this type of heads is that they cannot move smoothly on hardwood trunks. Some experimental results [3] showed that the same machine could produce 1.4m³/min for coniferous trees (fir) and only 0,5m³/min for hardwood (beech). Typical problems are: 1- the head cannot delimb big branches; 2- the head passes trunk curves with difficulty.


*Figure 1: Example of harvesting head Kesla 25RH [11].*
*a) Harvesting head and its carrier during delimbing; b) Description of head components.*

After a previous work on innovative grippers [5], we focus this paper only on the first problem of big branches, while passing the crooked trees is considered in a separate paper [1]. Some experimental results collected by FCBA during log cutting show that difficulties may occur during up to three quarters of the delimbing time (Table 1). Providing a head with better delimbing abilities for big branches will contribute to increase productivity up to 40%, one of the main objectives of the ECOMEF research project.

| Wood Type | Trunk Diameter | Total Duration | Duration of motion with Loaded arms | Duration of Delimbing | Duration of Logging | Description of difficulties | % of time with difficulties during delimbing |
|---|---|---|---|---|---|---|---|
| Oak | 25cm | 1 min 56 sec | 28 sec | 1 min 19 sec | 9 sec | Bayonet + crooked trunk : 14sec<br>Branches + crooked trunk : 46 sec | 77% |
| Oak | 40cm | 4 min 31 sec | 32 sec | 2min 04 sec | 31 sec | Fork + big branches : 1 min 07 sec<br>Top branches + crooked trunk : 48 sec | 71% |

*Table 1: Two representative results of log cutting with timings (FCBA report).*

## 2. Existing delimbing knives

The knives currently available on the market have the shape of curved blades made of hardened steel and soldered to a curved pivoting arm (Fig. 2a). The delimbing process consists in translating the knife along the trunk surface with a given speed (typically 1-7m/s). Then, branches are cut after shocks with the cutting edge of the blade, located close to the trunk surface.

A first preliminary work was performed to evaluate the delimbing performance of straight blades, assuming the blade curvature does not significantly modify the delimbing phenomenon. A test bench was built for comparing many types of delimbing blades on various types of branches (Fig. 3). It includes a blade support gliding on guiding rails and actuated by a hydraulic cylinder. The branch is maintained by two supports and the blade parameters (cutting force and displacement) are measured by two sensors.

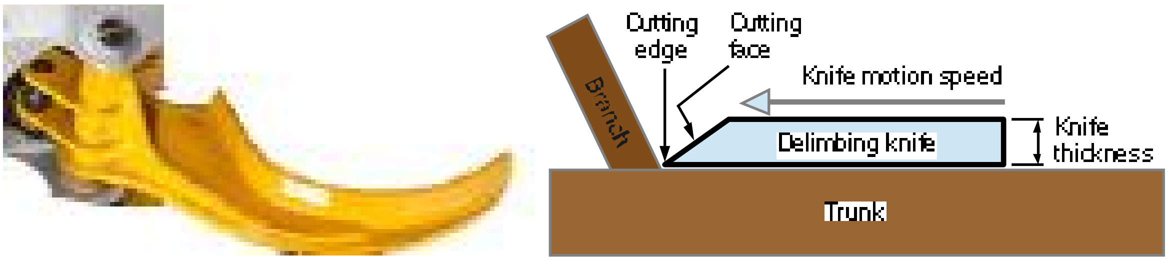


*Figure 2: Delimbing with a classical knife: a) Knife of Kesla 25RH; b) Delimbing process.*

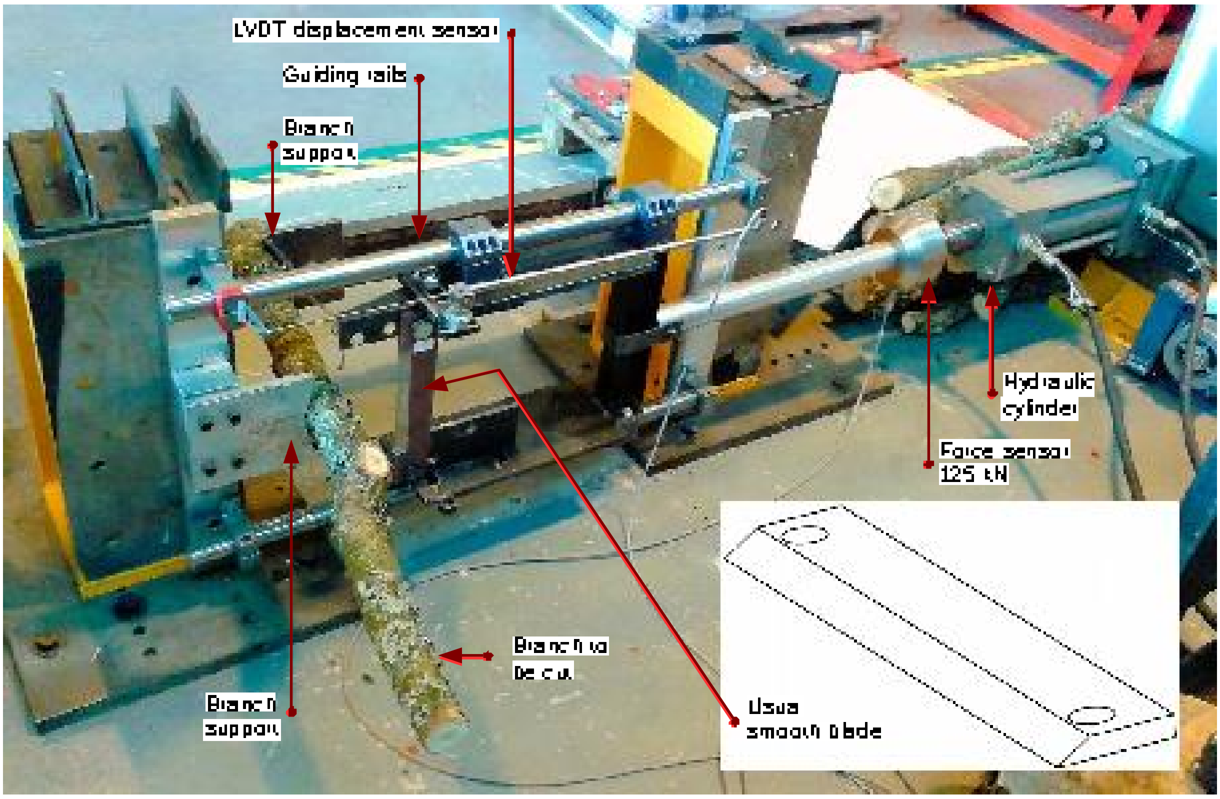


*Figure 3: Delimbing test bench testing an existing smooth blade.*
*a) Geometry of a classical smooth blade ; b) Delimbing testbench.*

| Blade type | Test # | Diameter (mm) | | | Area (cm²) | Max force (kN) | Energie (J) | Values for an equivalent diameter 80 mm | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Along cutting Direction | At 90° with Cutting dir. | Average | | | | Force (kN) | Energy (J) | Average Force (kN) | Average Energy (J) |
| Smooth 8mm | 6 | 78,17 | 75,80 | 76,98 | 46,51 | 37,07 | 1780 | 30,97 | 1410 | 33,0 | 1489 |
| | 47 | 98,47 | 99,63 | 99,05 | 77,05 | 48,78 | 2743 | 34,70 | 1527 | | |
| | 43 | 105,90 | 96,56 | 101,73 | 80,31 | 45,61 | 2787 | 30,37 | 1464 | | |
| Smooth 10mm | 17 | 84,63 | 74,54 | 79,59 | 49,55 | 36,06 | 1587 | 36,47 | 1617 | 36,5 | 1643 |
| | 14 | 88,10 | 79,97 | 84,01 | 55,30 | 37,10 | 1855 | 34,55 | 1467 | | |
| | 44 | 100,76 | 106,73 | 100,75 | 80,65 | 55,46 | 2407 | 38,53 | 1850 | | |

*Table 2: Average force and energy required to cut a branch of 80mm of diameter.*

A wide delimbing test-campaign containing more than sixty tests was performed [6]. Table 2 presents some results for two smooth blades of thickness 8mm and 10mm. In average on three different branches, the required force and energy to cut a 80mm-diameter branch are respectively of 36,5 kN and 1643 J. With a blade of only 8mm, the cutting force decreases to 33 kN and the energy to 1489 J. This confirms the intuitive result according to which the thinner the blade, the lower the delimbing force of the branch.

## 3. Innovation for delimbing knives

Harvesting heads generally brace the trunk with one or several delimbing units. The top delimbing unit generally comprises three knives: one knife fixed to the body and two mobile knives shaped as arms. However, many innovations were proposed to this archetype during the last forty years.

Many patents concern the kinematics of knives: specific cam stops for end-positions [13]; articulated fixed knife in three parts, with movable side blades [14] that fit better around the trunk; poly-articulated delimbing knives, comparable to a chain where each limb would bear a cutting edge, fixed at both ends to a rigid arm [8].

Other patents focus on the control of the mobile knifes so they firmly hold the trunk

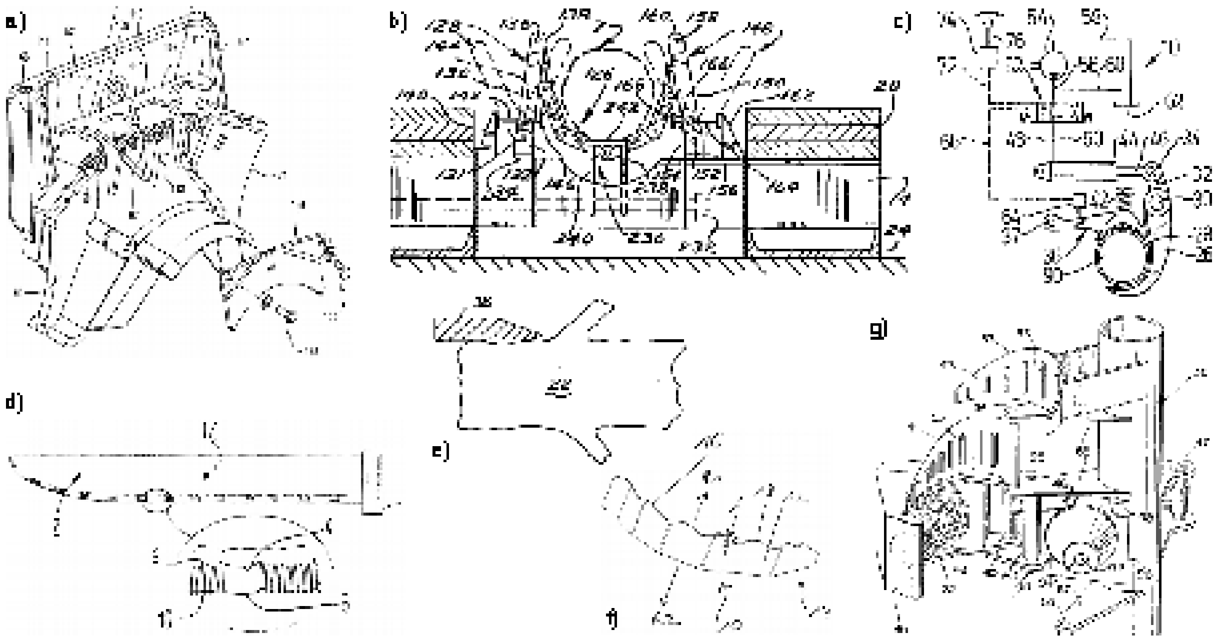

*Figure 4: Some patents about delimbing knives. a) Fixed knife with movable side blades [14]; b) Poly-articulated knife [8]; c) Motion and force control of knives [10]; d) Micro-teeth blade profile [15]; e) Bevels on the blade cross-section [16]; f) Specific wavy blade edge [12]; g) Knives with internal spacers [9].*

during diameter changes but are controlled to decrease friction during feeding motion with a suitable fluttering [7][10].

Although many special blades exist for general applications, such as micro-teeth blades [15], special profiles for forestry applications were not so much studied. One could mention a special wavy profile of the cutting edge [12], bevels on the cross section of the blades for easier delimbing [16] and spacers on the inner surface of knives to prevent biting into the bark and allow irregularities on the trunk to pass under the cutting edge [9].

## 4. Designing innovative knives

Improving the delimbing operation could be obtained with innovative knives, and the patent study of Section 3 tends to prove that innovative blade shapes could be provided. Moreover, the testing of existing blades (Section 2) showed that blade thickness had to be reduced for better cutting.

Using this idea, it was decided to try to decrease the cutting force needed to cut a branch by using a blade as thin as possible. By doing that, the contact surface between the knife and the branch is minimized during the cut. It helps to decrease the friction and also increases the stress on the wood fibres, that get torn by the blade cutting edge.

Obviously, a very thin blade has also to be strong enough to resist to the cutting loads and more generally to all the shocks that occur during forestry operations. In order to avoid any bending of the cutting edge, additional ribs, used as stiffeners, were positioned regularly along the cutting face. Figure 5 shows the new blade design and the associated dimensional parameters:

- $\beta$, the sharpness angle
- *th_b*, the blade thickness
- *l_r*, the rib depth
- *th_k*, the knife thickness
- *d_r*, the distance between ribs
- *th_r*, the rib thickness

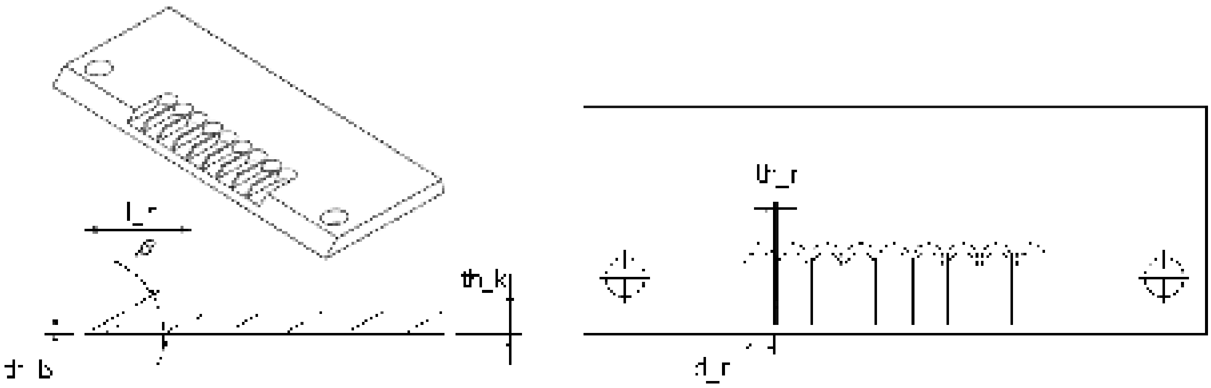


Figure 5: *Geometry of the innovative ribbed knife with its geometric parameters.*

The effects of the geometric parameters of the knife on the cutting force during the cut of the branch have been tested on the experimental test bench (Fig. 6). These tests highlighted a positive effect of the new ribbed blades on cutting force, compared to smooth blades.

The influence of the geometric parameters on the cutting forces was experimented during a design of experiment (Table 3). A low sharpness angle (close to 15°) decreased the cutting force but the blades were damaged due to a lack of mechanical strength. 30° seemed to be a good compromise. In a same way, low thickness blade (*th_b* < 1mm) was not enough resistant and judged not adapted to operating conditions. The effect of the depth of ribs was not clearly established and complementary tests should be performed. A low distance

Figure 6: *Delimbing with an innovative ribbed knife. The branch bends a lot before cutting.*

| Tested parameter | β Sharpness angle | | | *th_b* Blade thickness | | *l_r* Rib depth | | *th_k* Knife thickness | | *d_r* distance between ribs | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Parameter values | 15° | 30° | 45° | 1mm | 3mm | 20mm | 80mm | 8mm | 15mm | 8mm | 16mm |

*Table 3: Test variables for design of experiment on the ribbed knife*

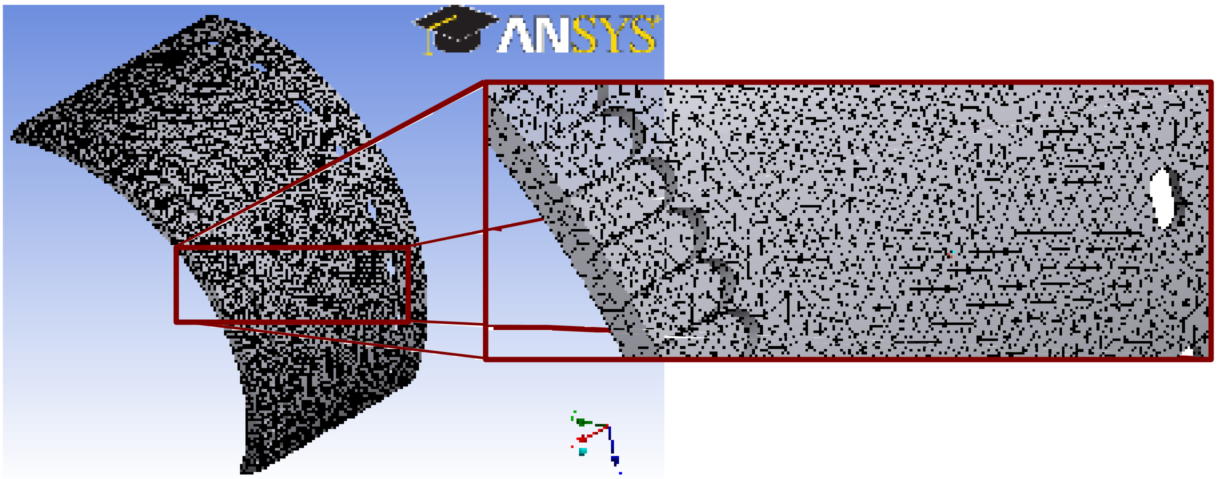


Figure 7: *Finite Element Model of a curved ribbed knife with Ansys software.*

between ribs (8 mm) significantly increased the cutting forces, and a good compromise between mechanical strength and cutting forces was established at 16 mm.

Complementary finite element simulations were performed on a curved knife model to optimize its geometry and find the maximal load admissible for different knife configurations (Fig. 7). The aim was to compare these loads to forces at the impact of the branch and during the branch-cutting.

The simulations permitted to extract nine configurations to test on the test bench (Table 4). For all these configurations, the sharpness angle $\beta$ was set to 30°, the ribs depth $l_r$ to 40 mm and the distance between ribs $d_r$ to 16 mm.

| Knife name th_k - th_b - th_r | Knife thickness th_k (mm) | Blade thickness th_b (mm) | Rib thickness th_r (mm) | Maximal cutting force (kN) |
|---|---|---|---|---|
| 1. Smooth 8 mm | 8 | / | / | 30 |
| 2. Ribbed 8-3-2 | 8 | 3 | 2 | 26.9 |
| 3. Smooth 10 | 10 | / | / | 32.9 |
| 4. Ribbed 10-3-1 | 10 | 3 | 1 | 26.3 |
| 5. Ribbed 10-3-2 | 10 | 3 | 2 | 25.6 |
| 6. Ribbed 10-5-2 | 10 | 5 | 2 | 27.4 |
| 7. Smooth 12 | 12 | / | / | 32.4 |
| 8. Ribbed 12-5-2 | 12 | 5 | 2 | 25.9 |
| 9. Ribbed 12-7-2 | 12 | 7 | 2 | 30.2 |

*Table 4: List of the nine tested configurations on the bench and maximal cutting force (branch diameter 80mm, $\beta$ = 30°, $l_r$ = 40 mm, $d_r$ = 16 mm).*

The curves of the experimental tests (Fig. 8) allow to draw the following conclusions:

- The blades of thickness *th_b* = 3 mm were not sufficiently rigid and plastic deformations occurred during delimbing:
  - A bending of ribbed knife 8-3-2 occurred for a 75 mm branch diameter (which corresponded to an axial load of 30 kN).
  - A bending of ribbed knife 10-3-2 occurred for a 100 mm branch diameter (which corresponded to an axial load of 48 kN).
- The thickening of the ribs from 1 mm to 2 mm increased slightly the cutting forces, that was 26.3 kN for Ribbed 10-3-1 and 25.6 kN for Ribbed 10-3-2.
- For a given knife thickness, the thinner the blade, the lower the max. cutting forces.

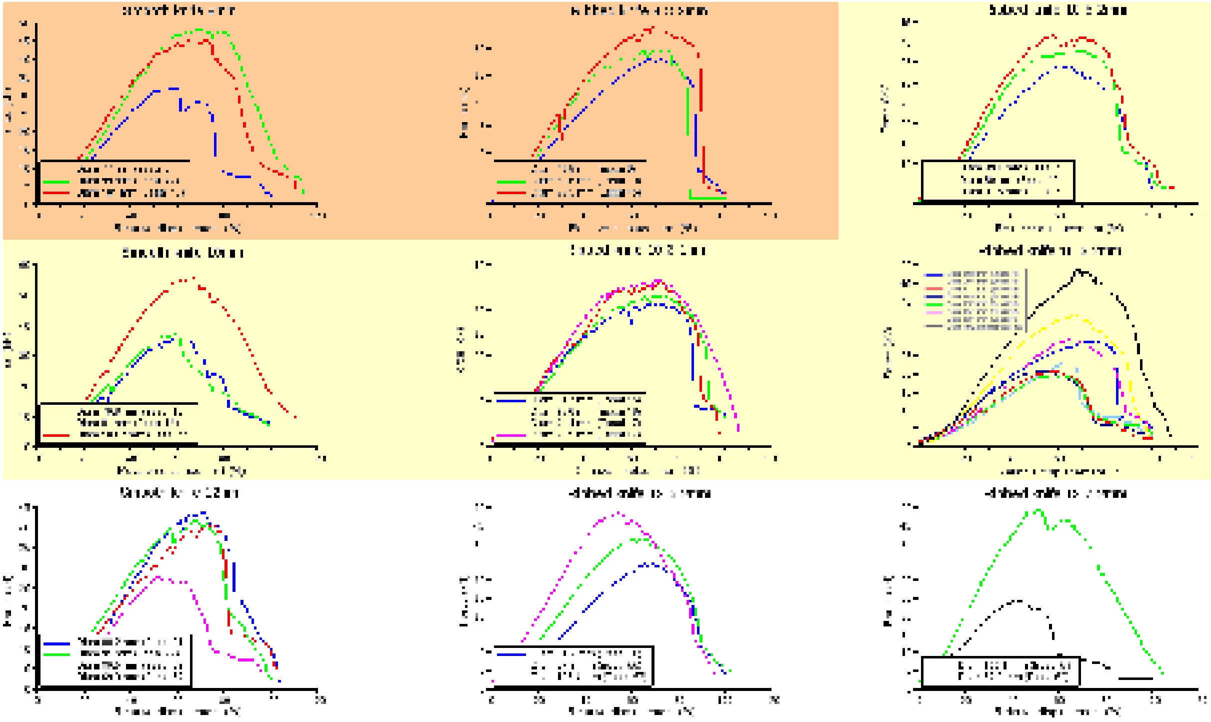

Figure 8: *Experimental test-bench curves of force against displacement for the nine knives.*

– For a given thickness of the cutting blade, the thickness of the knife and thus the height of the ribs had a little effect on the maximal cutting forces.

## 5. Field tests in real conditions

After the promising FEM models and experimental results on the test bench, a prototype ribbed top-knife was produced for tests on a Kesla 25RH harvesting head. The tests allowed to evaluate the material strength in real conditions, the values of delimbing forces and the gains of productivity. The experiments were organized in a woodlot with clumps of chestnut trees. Five prototype knives were tested, defined by their *th_k-th_b-th_r-l_r* parameters, each one on fifty trees, and the results are summarized in Table 5. All the innovative ribbed knives brought productivity gains from 8% to 40%. Long ribs were also tested with success. These results must be confirmed by additional experiments with a head equipped with three ribbed knives and extended statistical results. The innovative ribbed knife was patented [2].

| | | | | | |
|---|---|---|---|---|---|
| Knife type th_k-th_b-th_r-l_r | 12-5-2-43 | 10-3-2-43 | 12-7-2-43 | 12-5-2-94 | 12-7-2-94 |
| Productivity gain | 8% | 23% | 40% | 32% | 32% |

*Table 5: Productivity gains for the five tested ribbed knives with respect to a classical knife.*

## 6. Conclusion

This work was focused on the evaluation and minimization of the delimbing forces generated in harvesting heads equipped with knives. An overview of recent advances in delimbing devices showed that the delimbing knives could benefit from shape optimization, not so commonly in the domain.

Preliminary tests of straight smooth blades on a delimbing test-bench, created for the project, showed that thinner blades generated lower cutting forces, but at the price of a lack of robustness. In order to improve bending strength, an original knife profile with a thin blade stiffened by regularly spaced ribs was proposed.


Figure 9: *A prototype ribbed knife replacing the top classical knife on a Kesla 25RH head.*

Additional finite element models helped to find a compromise between cutting efficiency and material strength. Nine dimensional configuration were tested on the bench and the curves of force against displacement were provided for varied diameters of branches. The new ribbed knives consistently proved to generate lower cutting forces than the existing smooth blades. For this reason, the ribbed knives were patented [2]. Additional field tests on a Kesla 25RH harvesting head also showed that smaller delimbing forces could improve efficiency up to 40% with respect to classical smooth knives. This very encouraging result will be soon confirmed by extended experiments.


## Acknowledgements

This research work is part of FUI ECOMEF national project funded by the Fond Unique Interministeriel (FUI) of the French Government, Conseil Régional Auvergne, FEDER – "Europe en Auvergne", Clermont Communauté, Conseil Général 63 Puy-de-Dôme, Conseil Général 03 Allier, Région Limousin, Agglomération de Brive, Région Aquitaine, FEDER Limousin. These organisms are acknowledged for their financial support to this pre-competitive project. The authors also wish to thank all the ECOMEF partners: ISI, FCBA, FMA, Institut Pascal, IRSTEA, France Bois Forêt, Comptoir des Bois de Brive, Lycée forestier Claude Mercier, ViaMeca and Xylofutur.

**References**


[1] Z. Chebab, N. Perriguey, J.C. Fauroux, B. Hatton, D. Goubet, C. Devemy, G. Dargnat, V. Gagnol, B.C. Bouzgarrou and G. Gogu. *Harvesting Machines for crooked trees.* 5th Int. Forest Engineering Conference FEC-FORMEC 2014, 23-26 Septembre 2014, Gerardmer, France.

[2] G. Dargnat, C. Devemy, H.P. Pellet and J.C. Fauroux. *Lame courbe pour tête d'ébranchage, son utilisation et tête d'ébranchage correspondante.* French patent, to be published in 2014.

[3] J.C. Fauroux, D. Goubet, B. Hatton and E. Cacot. *Projet FUI ECOMEF - Eco-conception d'une tête d'abattage pour feuillus.* Invited conference, Journée Recherche et Innovation - Une opportunité pour la filière bois, Vendredi 13 décembre 2013, IFMA, Clermont-Ferrand, France, 20p.

[4] C. Ginisty, P. Vallet, S. Chabe-Ferret, C. Levesque and C. Chauvin. *Disponibilités en biomasse forestière pour des usages énergétiques et industriels en France.* Convention DGFAR/Cemagref E 19 / 06 du 20 octobre 2006. Cemagref.

[5] D. Goubet, J.C. Fauroux and G. Gogu. Gripping mechanisms in current wood harvesting machines. *Frontiers of Mechanical Engineering*, 8(1), 42-61 (March 2013), Springer, ISSN: 2095-0233.

[6] B. Hatton, G. Pot, B.C. Bouzgarrou, V. Gagnol and G. Gogu. Experimental determination of delimbing forces and deformations in hardwood harvesting. *Croatian Journal of Forest Engineering.* To be published in 2014.

[7] A. Johansson. *Method of controlling press power in a limbing knife assembly in a single-grip harvesting head.* World patent WO0223973. Applicant: SP-Maskiner. 16p. 13 September 2011.

[8] E.J. Jouppi. *Separable blade cradle device for delimbing trees.* US patent US3881532. 12p. 22 August 1973.

[9] J.L. Levesque. *Tree harvester.* US patent US3981336. 10p. 28 May 1974.

[10] S. Linderholm. *Delimbing device for a tree.* European patent EP0346308. Applicant: Grangärde Maskin AB. 5 p. 13 Decembre 1989.

[11] Kesla Inc. homepage. *25 RH harvesting head technical specifications.* http://www.kesla.fi, retrieved online 18th June 2014.

[12] G. Miggitsch and A. Zaglacher. *Cutting blade for delimbing with a wave-shaped sawtooth structure.* International patent WO96/25845. Applicant: Koller Gesmbh, 5 p., 29 July 2011.

[13] J.P. Smythe. *Delimb arm cam stop.* New-Zealand patent NZ20100585838. Applicant: Waratah NZ Ltd. 50p. 2 June 2010.

[14] D.C. Swinyard. *Delimb Knife With Integrated Side Blades.* US patent US2013/0327441, Applicant: Deere & Company. 21p. 5 March 2013.

[15] A. Verdier and R. Verdier. *Microdenture d'outil tranchant, couteau notamment.* French patent FR 2732920. 13p. 13 April 1995.

[16] P. Whitcomb. *Apparatus for delimbing trees.* US patent US4050486. 5p. 6 December 1976.