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CUTTING FORCES BY OAK AND DOUGLAS FIR MACHINING

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In memoriam of Dr. Manfred SCHWANNINGER

ABSTRACT

In this work the multi-factor, non-linear dependencies between main (tangential) F_C and normal (radial) F_N cutting forces upon two machining parameters by up-routing and down-routing wood of Douglas fir (Pseudotsuga *menziesii*) and Oak (*Quercus petraea*) were evaluated. The relationships are graphically illustrated and discussed. The obtained data were compared with cutting forces evolution models according to grain orientation from the literature in order to verify if literature statements or models comply with measured data. Evidence of several contradictions was found relative to results from available literature.

Keywords: Grain orientation, multi-factor non-linear statistical dependencies, cutting force, routing.

INTRODUCTION

Studies to understand and model wood cutting have been performed by several authors over the years. Low speed studies of cutting forces with different grain orientations were performed by Kivimaa (1950, 1952), Franz (1958) and McKenzie (1961). Because wood is usually machined along and across the grain researchers, have concentrated their efforts in the analysis and description of these two cutting situations and fewer studies concentrate on processing with different grain orientations. Studies when processing with different grain orientations, have been conducted also by Stewart (1971, 1983) for wood orthogonal cutting at low speed, Cyra and Tanaka (2000), Costes *et al.* (2004) during turning of a wood sample, whereby cutting occurred over all the grain orientations.

Prediction of reliable wood cutting tangential F_C and radial F_N forces for specific cutting conditions is a goal of many works (Naylor *et al.* 2012, Orłowski *et al.* 2013). However this problem seems to be not yet adequately solved due to large number of wood species, wood variability, different cutting set-up used in literature works that makes the work not very comparable and because of the large number of interactions involved between these variables. Even within the same tree, the properties of wood are depended from the sample position crosscut, the sample position along the log etc.

By another hand, incomplete sets of independent variables have been used in the published works, and there has been inadequate attention paid to have homogeneous data sets in order to be compared with statistical significance.

In several works results were presented in form of rough diagrams without statistical approach. In many cases any information about residuals was not reported.

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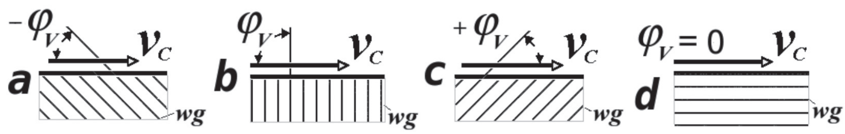


Figure 1. Wood cutting: *a:* against the grain; *b:* perpendicular the grain; *c:* along the grain; *d:* parallel to grain; wg = wood grain orientation.

Wood grain orientation is a very important parameter in machining of wood that can result in very different final surface quality, cutting forces and cutting mechanics. The main cutting conditions as regards grain orientation are shown in figure 1. One very important parameter is to be considered the wood grain orientation angle φ_V as shown for different situations in figure from a to d that is the angle between the grain orientation and the cutting velocity. In the case φ_V is 0° (Figure 1d) the machining is called parallel to the grain and this condition typically results in low cutting forces and high quality surface if compared to other values of φ_V (Figure 2d). In the case of φ_V lying in the range between -90° to 0°, known as cutting against the grain (Figure 1a), the fractures can propagate below the cutting plane (Figure 2a), resulting in severe surface damage. The process is completely different when cutting with the grain (Figure 1c) where φ_V lay in the range between 0° and 90° (Figure 2c, Figure 3).

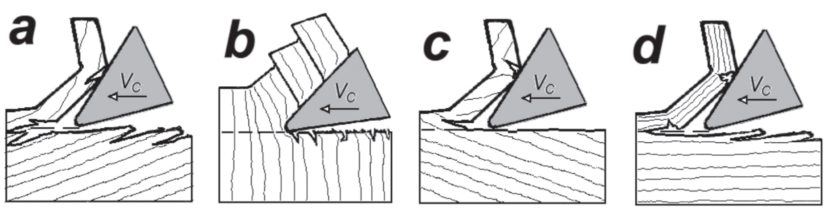


Figure 2. Chip and fractures formation during cutting: a: against grains grain (φ_K=90°, φ_V=-20°, φ_S=-20°); b: perpendicular (φ_K=90°, φ_V=90°, φ_S=90°) ; c: with the grain (φ_K=90°, φ_V=20°, φ_S=20°); d: parallel (φ_K=90°, φ_V=0°, φ_S=0°).

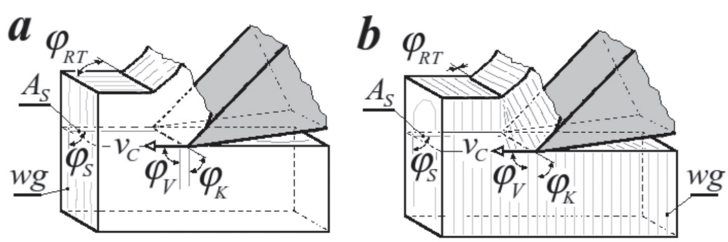


Figure 3. Orientation angles between wood grain (*wg*) and: v_C - vector of cutting velocity; *k* - cutting edge; A_S- cutting plane; for perpendicular cutting case (φ_K=90°, φ_V=90°, φ_S=90°); by growth rings orientation angle φ_{RT}: a - φ_{RT}=90° (radial); b - φ_{RT}=0° (tangential); A_S- cutting plane.

Another very severe condition in wood cutting is the "cutting across the grain" as shown in figure 1b and figure 2b. A review of the works performed on the subject of machining with different grain orientations can be found in (Wyeth *et al.* 2009). The notation of φ_V is not a standard and can be different in different works (Porankiewicz *et al.* 2011, Goli *et al.* 2007, Goli *et al.* 2009a). As regards the use of a turning rotational tool for cutting, φ_V evolves during the whole cutting path then it is essential to define what moment we take into consideration. For this paper φ_V was defined as the grain orientation as respect to the cutting velocity at the maximal chip thickness.

Maderas. Ciencia y tecnología 16(2): 199-216, 2014

As regards cutting forces, a very controversial issue in literature is related to the symmetry or asymmetry of cutting forces for φ_V in the range going from -90º to 0º, and from 0º to 90º. In several works a general symmetry of the forces was reported (Afanasev 1961, Amalitskij and Lûbčenko 1977, Beršadskij 1967, Orlicz 1982) while in other works, especially for blunt tools, a lack of such symmetry was reported (Axelsson *et al.* 1993, Porankiewicz *et al.* 2007, Porankiewicz *et al.* 2011, Goli *et al.* 2009b, Wyeth *et al.* 2009). The present work attempts to evaluate statistical, non-linear, and multi-variable dependencies of cutting forces $F_C=f(\varphi_V, a_{Px})$ and $FN=f(\varphi_V, a_{Px})$ for Douglas fir wood, as well as $FC=f(\varphi_V)$, and $FN=f(\varphi_V)$ (Figure 4) for Oak by up-routing and down-routing cases.

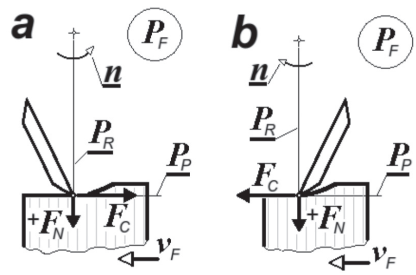


Figure 4. Main F_C and the normal F_N cutting forces, and stereo-metrical parameters for: a = up-routing; b = down-routing; P_F = Working plain; P_R = Tool reference plain; P_P = Back plain; n = rotational speed.

EXPERIMENTAL

Experiments were performed on a CNC routing machine and the forces acquired by a Kistler dynamometric platform. The test set-up is described in table 1, for deeper information please refer to Goli *et al.* (2009a) and Goli *et al.* (2009b).

Table 1. Mechanical and physical properties of wood specimens and machining parameters.

Mechanical and physical properties of wood specimens:	
Douglas fir (*Pseudotsuga menziesii*), *Oak* (*Quercus petraea)*	Oak density $D_{12} = 660$ kg·m^{-3}
Douglas fir density, for $m_C = 12\%$, $D = 430$ kg·m^{-3}	Oak moisture content $m_C = 13$ %
Douglas fir moisture content $m_C = 13$ %,	Temperature of wood $T = 24$°C
Wood specimen dimensions: 80 mm, 30 mm, length, width and respectively	
Machining parameters:	
Cutting edge round up $\rho = 4$ µm	Average chip thickness $a_p = 0.039$; 0.068 mm
Contour wedge angle $\beta_F = 55°$	Maximum chip thickness $a_{px} = 0.077$; 0.134 mm
Contour rake angle $\gamma_F = 20°$	Feed per tooth $f_Z = 0.36$ mm
Contour clearance angle $\alpha_F = 15°$	Depth of cut $c_D = 0.5$; 1.5 mm
Cutting edge inclination angle $\lambda_P = 0°$	Width of cutting $w_C = 20$ mm
Cutting tool diameter $d_N = 40$ mm	Number of cutting edges z = 1
Spindle rotational speed $n = 13867$ min^{-1}	Angle between cutting edge and wood grain (Figure 3) $\varphi_K = 90°$
Cutting velocity $v_C = 29$ m·s^{-1}	Growth rings orientation angle towards cutting edge (Figure 3) $\varphi_{RT} = 90°$
Feed speed $v_F = 5$ m·min^{-1}	Initial, for up-routing case, and, final for down-mill case, wood grain orientation angle φ_V (Figure 1 and 3), equal the cutting plane A_S angle φ_S (Figure 3), (-90, -80, -70, -60, -50, -40, -30, -20, -10, 0, 10, 20, 30, 40, 50, 60, 70, 80, 90)°, where: $\varphi_V = -90°$, is equal to $\varphi_V = 90°$
Material of the cutting edge: a cemented tungsten carbide K05	Two edges, turn-over insert 50x12x1.5 mm

The cutting edge was made of tungsten carbide and the blade was new and checked to be perfectly sharpened by a microscope before use. The cutting angles (γ_F, β_F, α_F) are defined in working plane (P_F) as shown in figure 4. The cutting blade was subjected to a short run-in before the experiment start. The whole experiment was performed with the same cutting blade assuming that the small amount of chip meters machined did not result in significant changes of the round-up of the cutting edge after run-in was performed.

It was used one sample extracted from the same board The samples were 1 for every grain orientation in order to minimize wood variability. Specimens were cut from the same well-seasoned board and equilibrated in the workshop. The moisture content was determined immediately before the execution of the tests. The specimens were processed with the cutting speed vector parallel to the tangential direction of the rings. This allowed to avoid an alternation of different density zones during the cut and consequently the blade was engaged on early and late wood during the whole cut. This helped very much to reduce undesired cutting forces variation as well as to reach the steady state cutting condition. By the other side For every cut, the cutting forces were determined as the average of hundreds of cut. The experimental data of the cutting forces were acquired at a sampling rate of 10 kHz per channel. The signal resulted to be very noisy because of the system vibrations (dynamometric platform + machine) and in previous works performed (Goli *et al.* 2009b) these data were presented after filtering operations. Filtering resulted in much clearer signal for peak extraction if compared to unfiltered data but at the same time in a permanent signal alteration and reduction. In this paper the unfiltered data were analyzed and the cutting forces were computed by an automatic peak extraction performed by IDL software programming utility. The IDL algorithm performed an automatic extraction of a given series of peaks corresponding to the cutting frequency of the tool on the whole cutting path and the extracted peaks were averaged for every machining set-up and grain orientation in order to calculate the average F_C and F_N. Because the cutting path of the tool was about 150 mm and the initial part of the cut was not considered (because of the incomplete chip formation until one half of the tool is reached) as well as the final part (for the same reason) a 100 mm of clean tool travel was averaged corresponding to about 250 peaks. For every machining set-up, the grain orientation angle (φ_V) was adjusted at the grain orientation given by the angle between the cutting velocity and the grain at the maximal chip thickness (a_{Px}). The need to correct φ_V according to the maximal chip thickness and to a_{Px} was largely explained in Goli *et al.* (2009a) and Goli *et al.* (2009b). Once the good φ_V was computed, the average F_C and F_N at different grain orientations were fit as a function of φ_V and a_{Px} (only for Douglas fir), by the highest correlation coefficient R, by the lowest standard deviation S_D, and by the lowest summation of residuals square S_K. Thus one should get an adequate statistical model, of the F_C and F_N=f (φ_V, a_{Px}), and by the best fit of the experimental data of values of F_C and F_N were then corrected according to their orientation a a_{Px} intended to be the maximal chip thickness point. The choice of using a simpler mathematical equation usually results in decreasing approximation quality (lower R, larger S_D and S_K) but also in a lower reverse impact of independent variables.

In order to evaluate relations $F_C=f(\varphi_V)$ and $F_N=f(\varphi_V)$ for Oak and $F_C=f(\varphi_V, a_{Px})$ and $Fn=f(\varphi_V, a_Px)$ for Douglas fir, linear equations and second order multinomial equations, as well as power and exponential type functions with and without interactions were analyzed in preliminary calculations. The most adequate appeared to be the non-linear, multi-variable equations (1) and (2) for Douglas fir (3) and (4) for Oak.

$$F_C = c_1 + c_2 \sin^2(\varphi_V + c_3) + c_4 a_{Px} + c_5 \varphi_v a_{Px} \text{ (N)} \tag{1}$$

$$F_N = d_1 + d_2 \sin^2(\varphi_V + d_3) + d_4 a_{Px} + d_5 \varphi_v a_{Px} \text{ (N)} \tag{2}$$

$$F_C = e_1 + e_2 \sin^2(\varphi_V + e_3) + e_4 \varphi_V^2 \text{ (N)} \tag{3}$$

$$F_N = f_1 + f_2 \sin^2(\varphi_V + f_3) + f_4 \varphi_V^2 \text{ (N)} \tag{4}$$

where: φ_V (rad).
Estimators for equations (1) through (4) were evaluated from a complete experimental matrix for variables: φ_V.

Coefficient of relative importance was calculated from equation (5).

$$C_{RI} = (S_K - S_{KCk0}) S_K^{-1} 100 \text{ (\%)} \tag{5}$$

In equation (5) the new terms are:
S_{KCk0} - Summation of square of residuals, by ck=0.
c_k - Estimator with number k index in statistical equation evaluated.

The summation of residuals square S_K, the standard deviation S_D, the square of correlation coefficient of the predicted, and observed values R^2 were used for characterization of the approximation quality. Calculations were performed at Poznań Networking & Supercomputing Center PCSS on a SGI Origin 3800 computer, using a special optimization program, based on a least squares method combined with gradient and Monte Carlo methods, mentioned in the work Porankiewicz (1988), (modified in order to improve calculation efficiency). For checking every statistical equation mentioned earlier, as well as for evaluation of the final equations (1) through (4), the necessary maximum iteration number was as large as 1.3×10^8.

The measured values of the main cutting force F_C after filtering were compared with values computed using Wood Cutting (W_C) program for the same cutting parameters for up-routing. The W_C program was developed on the basis of a literature data only for up-routing case. Because the Douglas fir has no representation in the W_C program, the Scotch pine (*Pinus sylvestris* L.) was chosen for comparison instead.

RESULTS AND DISCUSSION

Uncertainty of the measures

In order to determine the uncertainty of the measures the coefficient of variation (C_V) was determined for every machining set-up and the dispersion from the average resulted quiet limited for most of the cases. In fact the 68 % of the measures presented a C_V under the 5%, the 93 % of the measures under 10 %, 97 % under 15 % and the rest is higher up to a maximum of 20.8 %. The C_V for the different machining set up are shown reported in figure 5 and figure 6.

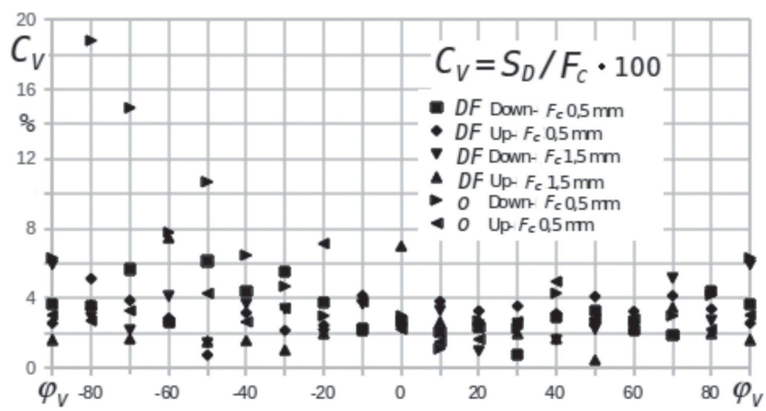


Figure 5. Coefficient of variation C_V (%) of the single, average main cutting force F_C, for every experimental set-up; D_F - Douglas fir (*Pseudotsuga menziesii*), *O* - Oak (*Quercus petraea*).

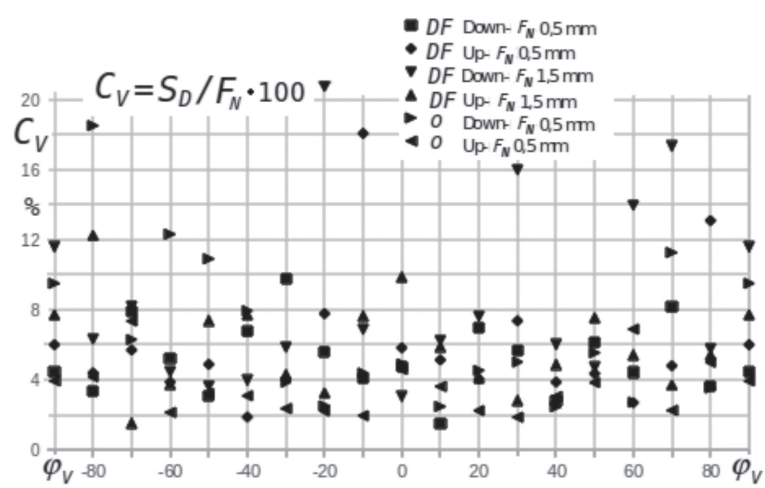


Figure 6. Coefficient of variation C_V (%) of the single, average normal cutting force F_N, for every experimental set-up; *DF* - Douglas fir (*Pseudotsuga menziesii*), *O* - Oak (*Quercus petraea*).

Up and down routing of the Oak wood

For ***up-routing of Oak wood***, the relation between the main force and the wood grain orientation angle $F_C=f(\varphi_V)$, according to equation (3), following estimators were evaluated: e_1=1.76115, e_2=1.16336, e_3=27.03116, e_4=0.2224. The quality of the fit was characterized by the quantifiers: S_K=2.1, R=0.9, R^2=0.81, S_D=0.35 N/mm. The coefficients of relative importance took values as follows: C_{RI1}=2904.8, C_{RI2}=508.1, C_{RI3}=245.3, C_{RI4}=144. Measured and fit data are shown in figure 7a.

For up-routing of oak wood, the relation between normal cutting force and the wood grain orientation angle $F_N=f(\varphi_V)$, according to equation (4), following estimators were evaluated: f_1=1.23808, f_2=1.67683, f_3=27.26714, f_4=-0.19122. The quality of the fit of this equation was characterized by the quantifiers: S_K=2.3, R=0.76, R^2=0.58, S_D=0.37 N/mm. The coefficients of relative importance took values as follows: C_{RI1}=1242.2, C_{RI2}=913, C_{RI3}=165, C_{RI4}=92.9. Measured and fit data are shown in figure 7b.

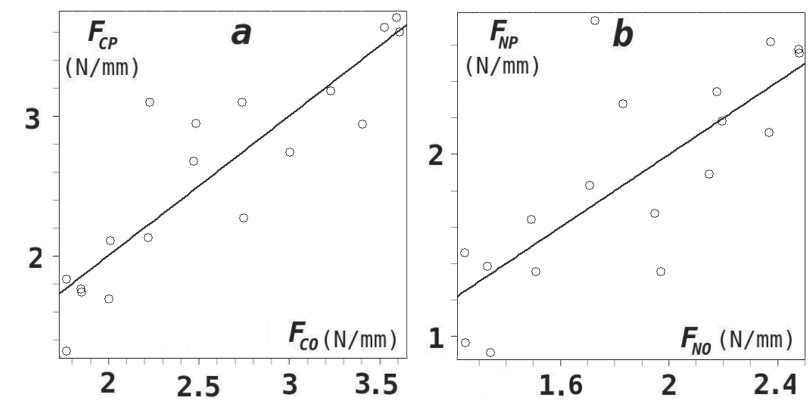


Figure 7. For up- routing of Oak (*Quercus petraea*): a) plot of the main cutting force observed F_{CO} against the main cutting force predicted F_{CP} according to equation (3), b) plot of the normal force observed F_{NO}, against normal force predicted F_{NP}, according to equation (4).

Figure 7a and 7b shows that for values of both F_C and F_N, some uncontrolled variation took place, because the distribution of residuals is not randomly dispersed below and above the diagonal line.

As shown in figure 8 the dependence $F_C=f(\varphi_V)$ present one maximum at 88.1º and one minimum at -27.5º, the dependence $F_N=f(\varphi_V)$ present one maximum at 53.4º and one minimum and -27.2º.

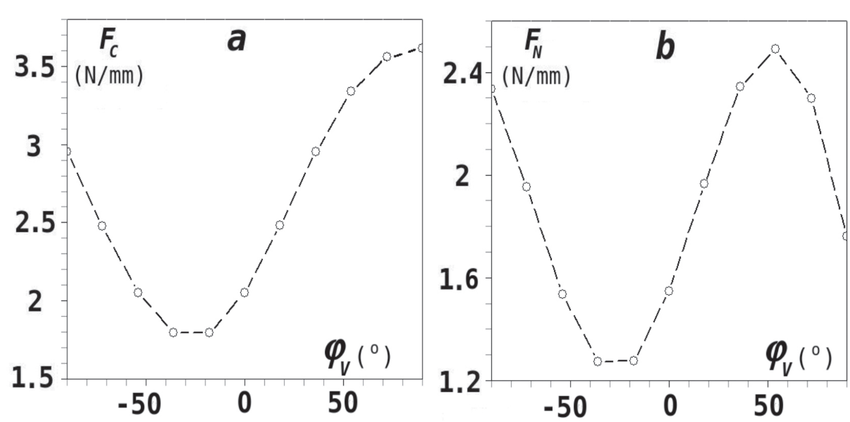


Figure 8. Plot of: a) main F_C, and b) normal F_N, cutting forces vs. wood grain orientation angle φ_V, according to equation (3) and (4) for up-routing of Oak (*Quercus petraea*).

For ***down-routing of Oak wood***, the relation between the main force and the wood grain orientation angle $F_C=f(\varphi_V)$, according to equation (3), following estimators were evaluated: e_1=1.02903, e_2=1.92949, e_3=28.90508, e_4=-0.10714. The quality of the fit was characterized by the quantifiers: S_K=4.3, R=0.77, R^2=0.59, S_D=0.52 N/mm. The coefficients of relative importance took values as follows: C_{RI1}=442.3, C_{RI2}=583.2, C_{RI3}=148.3, C_{RI4}=10.7. Measured and fit data are shown in figure 9a.

For down- routing of Oak wood, the relation between the normal cutting force and the wood grain orientation angle $F_N=f(\varphi_V)$, according to equation (4), following estimators were evaluated: f_1=0.79738, f_2=1.63725, f_3=29.99704, f_4=0.08593. The quality of the fit was characterized by the quantifiers: S_K=4.1, R=0.86, R^2=0.74, S_D=0.41 N/mm. The coefficients of relative importance took values as follows: C_{RI1}=420.1, C_{RI2}=664.2, C_{RI3}=270.4, C_{RI4}=11.3. Measured and fit data are shown in figure 9b.

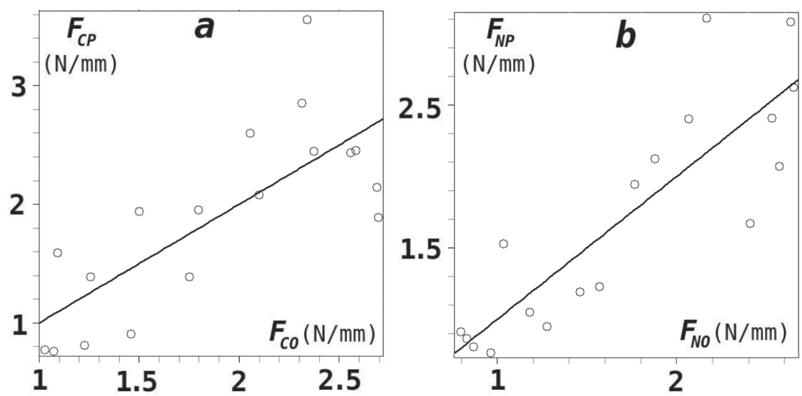


Figure 9. For down-routing routing of Oak (*Quercus petraea*): a) plot of the main cutting force observed F_{CO} against the main cutting force predicted F_{CP} according to equation (3), b) plot of the normal force observed F_{NO}, against normal force predicted F_{NP}, according to equation (4).

Figure 9a and 9b shows presence of uncontrolled variation for both F_C and F_N, decreasing approximation quality.

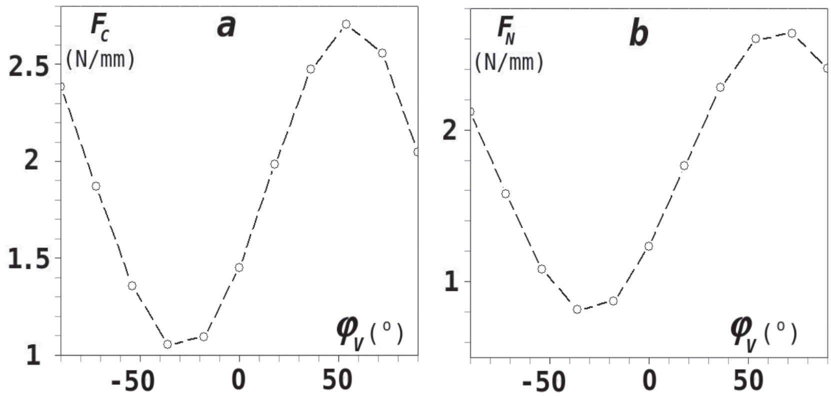


Figure 10. Plot of: a) main F_C, and b) normal F_N, cutting forces vs. wood grain orientation angle φ_V, according to equation (3) and (4) for down-routing of Oak (*Quercus petraea*).

As shown in figure 10 the dependence $F_C=f(\varphi_V, a_{Px})$ present one maximum at 56.4º and one minimum at -28.9º, the dependence $F_N=f(\varphi_V, a_{Px})$ present one maximum at 64.9º and one minimum and -30.1º.

Up- and down- routing of the Douglas fir wood

For ***up-routing of Douglas fir wood***, the relation between the main force and the wood grain orientation angle $F_C=f(\varphi_V, a_{Px})$, according to equation (1), following estimators were evaluated: c_1=1.06678, c_2=0.49252, c_3=40.67751, c_4=6.64741, c_5=1.65046. The quality of the fit was characterized by the quantifiers: S_K=5.13, R=0.82, R^2=0.67, S_D=0.38 N/mm. The coefficients of relative importance took values as follows: C_{RI1}=820.3, C_{RI2}=72.8, C_{RI3}=117.2, C_{RI4}=375.2 C_{RI5}=139.5. Measured and fit data are shown in figure 11a.

For up-routing of Douglas fir wood, the relation between the main force and the wood grain orientation angle $F_N=f(\varphi_V, a_{Px})$, according to equation (2), following estimators were evaluated: d_1=0.48208, d_2=-0.69556, d_3=-2.83177, d_4=11.21805, d_5=9.05516. The quality of the fit was characterized by the quantifiers: S_K=4.96, R=0.89, R^2=0.79, S_D=0.38 N/mm. The coefficients of relative importance took values as follows: C_{RI1}=168.8, C_{RI2}=136.5, C_{RI3}=3.8, C_{RI4}=1061.2, C_{RI5}=868.1. Measured and fit data are shown in figure 11b.

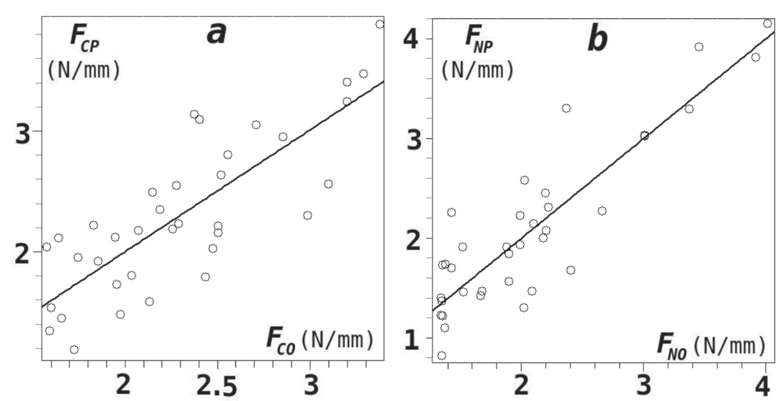


Figure 11. For up- routing case of the Douglas fir (*Pseudotsuga menziesii*): a) plot of observed main F_{CO} and b) normal F_{NO} cutting forces vs. forces predicted main F_{CP} and normal F_{NP} cutting forces, according to equations (1) and (2) respectively.

Figure 11a and 11b shows large uncontrolled variation for F_C and F_N, decreasing approximation quality.

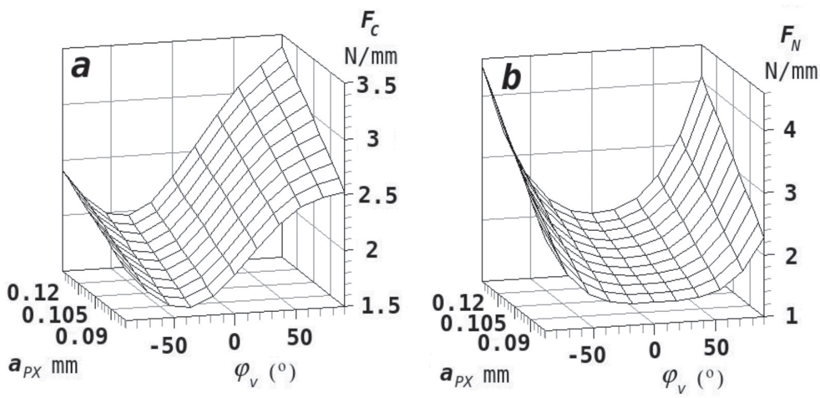


Figure 12. Plot of: a) main F_C, and b) normal F_N, cutting forces vs. wood grain orientation angle φ_V, and maximum chip thickness a_{PX}, according to equation (1) and (2) for up-routing of the Douglas fir (*Pseudotsuga menziesii*).

The dependencies $F_C=f(\varphi_V, a_{Px})$ and $F_N=f(\varphi_V, a_{Px})$, shown in figure 12a and 12b, present one maximum at 90º and one minimum at -40.59º and 2.82º respectively.

As shown in figure 12 the dependence $F_C=f(\varphi_V, a_{Px})$ present one maximum at 90.0º and one minimum at -40.6º, the dependence $F_N=f(\varphi_V, a_{Px})$ present one maximum at 90.0º (the same of F_c) and one minimum and 2.8º.

For ***down-routing of Douglas fir wood***, the relation between the main force and the wood grain orientation angle $F_C=f(\varphi_V, a_{Px})$, according to equation (1), following estimators were evaluated: c_1=1.08949, $_{c2}$=0.68076, c_3=4.07237, c_4=7.23075, c_5=2.13259. The quality of the fit was characterized by the quantifiers: S_K=8.26, R=0.74, R^2=0.54, S_D=0.4 N/mm. The coefficients of relative importance took values as follows: C_{RI1}= 545.8, C_{RI2}=89.2, C_{RI3}=1.7, C_{RI4}=287.1, C_{RI5}=38.1. Measured and fit data are shown in figure 13a.

For down-routing of Douglas fir wood, the relation between the main force and the wood grain orientation angle $F_N=f(\varphi_V, a_{Px})$, according to equation (2), following estimators were evaluated: d_1=0.51896, d_2=0.15756, d_3=12.28517, d_4=13.34601, d_5=2.75468. The quality of the fit was characterized by the quantifiers: S_K=4, R=0.76, R^2=0.58, S_D=0.33 N/mm. The coefficients of relative importance took values as follows: C_{RI1}=278.3, C_{RI2}=61.1, C_{RI3}=62.3, C_{RI4}=1943.5, C_{RI5}=116.2. Measured and fit data are shown in figure 13b.

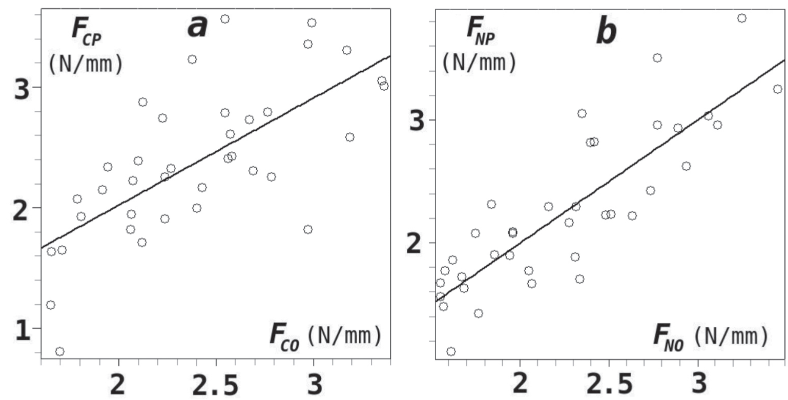


Figure 13. For down-routing case of the Douglas fir (*Pseudotsuga menziesii*): a) plot of main F_{CO} and b) normal F_{NO} cutting forces observed vs. forces predicted main F_{CP} and normal F_{NP} cutting foreces, according to equations (1) and (2) respectively.

Figure 13a and 13b shows an uncontrolled variation for F_C and F_N, decreasing approximation quality.

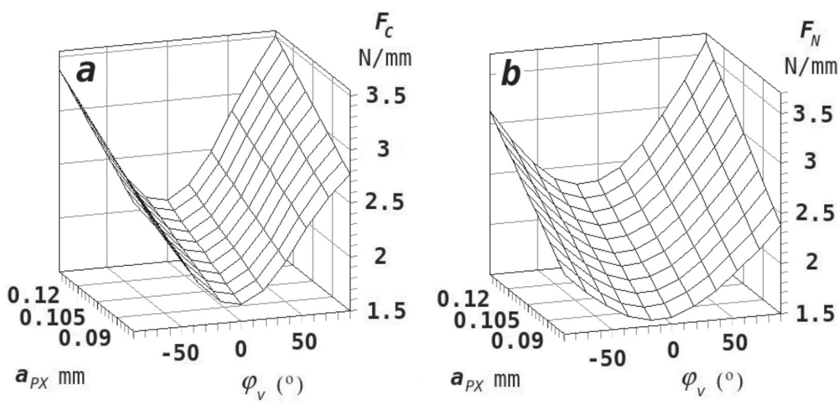


Figure 14. Plot of: a) main F_C, and b) normal F_N, cutting forces vs. grain orientation angle φ*V*, and maximum chip thickness a_{PX}, according to equations (1) and (2) for down-routing of the Douglas fir (*Pseudotsuga menziesii*).

As shown in figure 14 the dependence $F_C=f(\varphi_V, a_{Px})$ present one maximum at 90º and one minimum at -4.2º, the dependence $F_N=f(\varphi_V, a_{Px})$ present one maximum at 90º (the same of F_C) and one minimum and 12.4º.

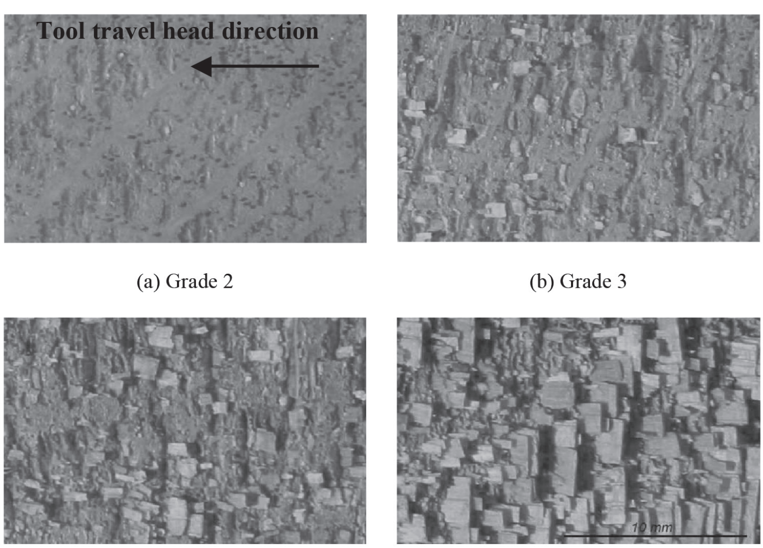
The statistical indexes clearly show how the residuals for down-routing case are a little larger than for up-routing. The fit quality in some case is higher for F_C instead than F_N and in some others the opposite so it cannot be established a clear rule. As regards maximums and minimums locations their values are reported in table 2. As regards Oak wood the maximums of F_C processing in up and down-routing case are shifted of about 30°, while the minimums are around the same value. Looking at F_N it presents a better alignment between maximums and minimums if compared to F_C. For Douglas fir maximums and minimums does not change varying a_{Px}, it means that the grain orientation variation due to varying a_{Px} is completely compensated by the corrections applied. As regards F_C the maximums between up and down-routing processes are both at $\varphi_V = 90°$ while minimums are shifted of about 35°. For F_N the maximums are both at $\phi V = 90°$ while minimums present a little shift of about 10°.

Table 2. Maximums and minimums for main F_C and normal F_N cutting forces when up- and down- routing Oak (*Quercus petraea*) and Douglas fir (*Pseudotsuga menziesii*).

	Oak		Douglas fir	
	max (°)	min(°)	max (°)	min(°)
F_C down-routing	56	29	90	-4.2
F_C up-routing	88	27	90	-41
F_N down-routing	65	30	90	12,3
F_N up-routing	53	27	90	2,8

These shifts, acting differently between up and down-routing techniques are possibly due to differences in the cutting process that when starting from the thicker or from the thinner part of the chip result in different cutting mechanics according to the mechanical properties of the machined specie itself. One important difference to be highlighted between up and down-routing is the appearance, when down-routing against the grain, of a particular defect described by Goli *et al.* (2002) and called "Tilted grain". This defect was not previously analyzed and it is not reported from the surface quality reference standard ASTM D1666-87.

This defect formation mechanism consists of a wood lamella that is picked-up by the tool edge when the tool impact at the maximal chip thickness. The lamella is lifted up and broken by transverse tension and bended until it is broken at the base and tilted on the other side. A classification of this defect as presented in Goli *et al.* (2004a) is reported in figure 15 while the formation mechanisms are described in Goli *et al.* (2004b).



(a) Grade 2 (b) Grade 3

(c) Grade 4 (d) Grade 5

Figure 15. Tilted grain classification on Oak (*Quercus petraea*) wood (as already published in Goli (2004a).

The relations $F_C = f(\varphi_V)$ and $F_N = f(\varphi_V)$ shown in figure 8, 10 and figure 12, 14 are not very well correlated between each other for the same φ_V, and does not have the minimum at $\varphi_V = 0^o$, and maximum at $\varphi_V = 90^o$ in all cases, what contradicts informations from papers Afanasev (1961), Amalitskij and Lûbčenko (1977), Beršadskij (1967), Orlicz (1982) and is consistent with works Axelsson *et al.* (1993), Porankiewicz *et al.* (2007) and Porankiewicz *et al.* (2011).

The minimum of the FC and FN cutting forces were at similar φ_V, for Oak up- and down- routing, at about φ_V~30º. For the F_N cutting force, for Douglas fir up- and down- routing the minimum were at about φ_V~0º, what can not be said about the F_C cutting force, where significant difference were noticed. The maximum of the F_C and F_N cutting forces for Douglas fir up- and down- routing was not well defined, what suggests that this cutting forces measurements experiment, especially for down-routing, seem to be coupled with uncontrolled variations.

Comparison between observed cutting forces and literature

The measured data were compared with the data computed for the same cutting conditions with the Wood Cutting (W_C) program developed by Porankiewicz (2012). The measured data appear to be sensibly lower than the data computed according to W_C as can be observed in figure 16.

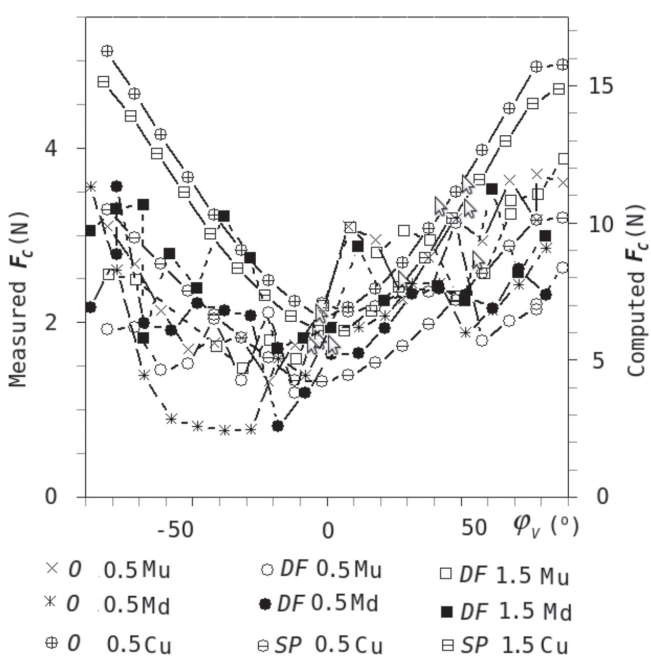


Figure 16. Plot of main cutting force F_C vs. orientation angle φ_V, for measured (M) and computed (C) data, according to Wood Cutting (Porankiewicz 2012), for the same cutting conditions, *O* - Oak (*Quercus petraea*), *DF* - Douglas fir (*Pseudotsuga menziesii*), *SP* - Scotch pine (*Pinus sylvestris*) d - down-routing, u - up-routing.

The W_C allow the calculation of the cutting forces only for up-routing operations and consider the trend to be the same when machining with or against the grain. As can be observed from table 3 the best significant correlation coefficient *R* is obtained for up-routing against the grain orientation φ_V (from -90 to 0°) and for down-routing with the grain orientation (φ_V from 0 to 90°). This observations allow to state that the trend of measured values and computed values of the main force F_C, in the mentioned ranges were correlated, what clearly shows the asymmetry of the forces when machining with or against the grain.

Table 3. Pearson linear correlation coefficient *R*, standard error S_R for *R* and significance level *SL* for different grain orientation φ_V ranges intervals, between measured data and computed data, according to W_C (Porankiewicz 2012) *O* - Oak (*Quercus petraea*); *DF* - Douglas fir (*Pseudotsuga menziesii*); *SP* - Scotch pine (*Pinus sylvestris*).

For whole range of variation of the orientation angle φ_V, from -90° to 90°, there is no significant the correlation between measured values and computed values of the main force F_C is poor. The values of computed main cutting force F_C were larger then measured F_C values, so more work seems to be necessary to find and eliminate a source of uncontrolled variation. It is possible that the source of a some part of uncontrolled variation lay in the use of piezoelectric sensors mounted on the Kistler platform, what was mentioned for routing in the Fromentin (2007) work.

CONCLUSIONS

The analysis of results obtained after fitting with non-linear multi-variable equations allowed to verify that the maximums and minimums of both the main cutting force F_C and the normal cutting force F_N are not located at a grain orientation φ_V = 90º and φ_V=0º respectively. This contradicts several works done in the past and listed in this paper. The main cutting force F_C and the normal cutting force F_N machining Oak with up-routing and down-routing techniques present the same minimums but different maximums while for Douglas fir the behavior is opposite. The observed shifts in the maximums and minimums can be ascribed to different surface formation mechanics that results also in different surface quality and typical surface defects. Tilted grain for example is a defect arising only when down-routing against the grain. It was verified an asymmetry of the cutting forces when machining with- or against- the grain when routing Oak and Douglas fir. This contradicts several authors and imposes the development of asymmetrical models. When down-routing against the grain the appearance of tilted grain could result in very large asymmetries in the cutting forces plotted according to grain orientation.

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