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# CUTTING FORCES IN BASIC AND REAL LIFE WOOD MACHINING PROCESSES
## Review Paper

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## Abstract

The data available in the literature concerning wood cutting forces permit to build models or to simulate the main wood machining processes (milling, sawing, peeling etc.). This approach contributes to a better understanding of formation of wood surfaces and chips and the data may be helpful to optimize cutting geometry, reduce tool wear, improve tool material, and to size tool-machines.

The models may also be useful for industrial application in two ways: (1) providing data to optimise the settings for a given operation (batch approach) and (2) building predictive models that could be the basis of an online control systems for the machining processes (interactive approach). A prerequisite for this is that numerous machining tests on different wood materials are performed based on experiences with different kind of tools and experimental devices. With potential industrial applications in focus, the emphasis of this review was on the wood peeling process, which is a very demanding special case of wood cutting. Though not so many industrial machines are equipped with expensive force sensors, there is a lot of high quality information available about cutting forces which may be useful to improve the scientific or technologic knowledge in wood machining. Alternative parameters, such as vibration or sound measurements, appear to be promising substitutes in the praxis, particularly to feed online control systems of any wood cutting process.

**Keywords**
cutting forces; online control; peeling process; physico-mechanical model; sound; vibrations; wood industry; wood machining

## Introduction

### *Why to measure cutting forces?*

In the course of cutting process analysis, very often cutting forces are chosen as the main output for physical description of the process. The other possibilities – like vibration, sound, temperature, cutting power, deformation, surface quality and chip quality measurements – are usually neglected. The main reason: measurement of cutting force is a powerful tool allowing to build physico-mechanical cutting models for a better understanding of the phenomena observed during cutting. These models permit to design or optimise processes, machines, tools and wood preparation.

Cutting models have been first developed on scientific basis in order to describe the formation and typology of chips related to given cutting forces levels (Kivimaa 1950; Franz 1958). The model of Merchant (1945), written for orthogonal cutting of metal, was adapted to wood by McKenzie (1960).

Other models aiming at the analysis of the wood-tool interaction during machining, were focusing more particularly on the influence of the cutting geometry (clearance and rake angles), wood characteristics (species, density, moisture content, and temperature), and processing parameters (cutting speed, depth of cut) on the level and stability of cutting forces (Kivimaa 1950; McKenzie 1960).

Some authors preferred a mechanical approach based on the cutting forces and evaluated the stress fields induced by the cutting process into the wood and into the tool, considering the friction on the surface between the wood and tool. The resultant cutting forces were divided into two categories: (1) forces exerted by the rake face and (2) forces exerted by the clearance face of the tool (Thibaut 1988). When introducing the tool deflection (Decès-Petit 1996), the assessment of the cutting plan displacements became possible.

Some models have been elaborated to predict cutting forces, to understand the mechanical behaviour of the materials tested (McKenzie 1962; Eyma et al. 2004) and other to characterise the machinability of different wood materials (see Kivimaa et al. as quoted by Scholtz and Troeger 2005). Another important target of these models was a diminishing expensive experimentation efforts under consideration of all parameters of processing and materials.

Cutting forces have been frequently measured to size motors for machine tools to decrease energy consumption and to optimise processing parameters – such as cutting speed (Liska 1950; Sinn et al. 2005) –, depth of cut (Axelsson et al.1993), feed rate (Ko et al. 1999) and upward/downward milling (Palmqvist 2003; Goli et al. 2003). The cutting forces have also been used to optimise the tool geometry, e.g. rake, wedge and clearance angles, tool edge direction (Woodson and Koch 1970; McKenzie and Karpovich 1975; Komatsu 1976; Stewart 1977; Komatsu 1993; Boucher et al. 2004), and the tool head design (e.g. the chip space, Heisel et al. 2004; Heisel et al. 2007).

Cutting forces have often been measured to compare the cutting properties of different tool materials, e.g. steel, carbide, diamonds, thermal treated tools, and coated tools (Stewart 1991; Darmawan et al. 2008). Also the machined wood was in focus considering the grain orientation and the structure (Axelsson 1994; Cyra and Tanaka 1999; Goli et al.2003), the heterogeneity (Mothe 1988), the moisture content (Kivimaa 1950), the temperature of steamed or frozen wood (Marchal et al. 1993, Lundberg and Axelsson 1993), the mature or the juvenile wood (Gonçalves and Néri 2005), the tension or the normal wood (Vazquez-Cooz and Meyer 2006), and the type of wood based materials. In the latter case, often modified MDF (Kowaluk et al.2004) or not modified MDF (Ko et al. 1999) was investigated.

The avoidance of dust and noise, and the improvement of the productivity (reduction the tool changing time, increase of the cutting speed, of the feed rate and of the cutting depth for a given surface quality) were also frequently in focus. Important results were obtained with this regards concerning predicting the tool edge wear (Fischer 1999; Fischer 2004), online controlling the wear (Huang, Y.-S 1994; Cyra and Tanaka 1999), predicting the chip geometry and fragmentation (Franz 1958), and online monitoring the wood surface quality (Cyra and Tanaka 1999; Palmqvist and Johansson 1999; McKenzie et al. 2001).

In some specific cases, the measurements of cutting forces helped to quantify the efficiency of auxiliary devices used to assist the cutting processes – e.g. ultrasonic-assisted cutting (Sinn et al. 2004) – or to improve the use of a pressure bar (Mothe and Marchal 2001).

***How to measure cutting forces?***

Two main approaches are known to measure cutting forces.

(1) Direct measurements by sensors directly placed on the tool or in strategic points on the frame. Strain gauges and piezo electric sensors are common. Strain gauges technology is cheap but not always efficient. Dynamometers, specifically designed for measuring cutting forces of wood, have some drawbacks especially for trials involving very small forces, which is quite often the case in wood machining. Sometimes, the ground noise and the signal cannot be differentiated. Such devices need a very meticulous set-up including an important management of wiring. Nevertheless, they are highly sensitivity to temperature and moisture. Another limiting factor is their low stiffness because they are based on deformation measurements. Piezo electric sensors are more expensive and much stiffer. They are reliable on several decades of forces values, are easy to maintain, and, – despite a drift of about 0.01 N/s in case of static test – are well adapted for dynamic and semi-static mechanical measurements.

(2) Indirect measurement are also available, which are based on non-contact displacement sensors with eddy current technology to measure distances, displacements. The forces are then computed via an inverse function of transfer (Costes 2007).

***Which cutting force components to consider?***

When measuring cutting forces, for the case of orthogonal cutting, the resultant force is usually decomposed in two ways: (1) in two orthogonal components: parallel and normal forces (Figure 1) and (2) in two facial components: rake and clearance forces (Figure 2).

The first decomposition seems often suitable from the technological point of view. The parallel force gives information on the torque and consequently the energy consumption. The normal force describes the plunging or cutting refusal tendency as well as the tool wear (Palmqvist 2003). The thickness of the damaged layer arisen during planing is also described (Hernandez and Rojas 2002). Force variations are linked up with the roughness of the wood surface.

The second decomposition makes it possible to propose a model directly linking the facial component forces to mechanical characteristics of wood. Such a model is much more powerful than the first one for the physical understanding of the underlying phenomenon, and at the same time, it is of some interest for optimising cutting geometry. On the other hand, two main hypotheses are necessary to use such a facial decomposition: (1) The sharpness of the tool is very good, i.e. the radius of the tool tip is low enough to neglect the "front" forces on the tool tip compared to the two facial components. (2) There is only Coulomb friction between tool and wood.

Franz (1958) and Kivimaa (1950) and many other authors favoured obviously the first approach. Few authors adopted the second way: Dippon et al. (1999) for orthogonal cutting of MDF, Thibaut (1988) and Thibaut and Beauchêne (2004) for the study of 0/90° cutting mode on green wood (peeling or slicing). Fischer (2004) mixed the two approaches in order to describe the phenomena at the mesoscopic scale just behind the cutting edge and, considering the forces under and above the cutting line. This author proposed a global approach of wood machining with specific trajectories of the tools into wood materials when milling, sawing or drilling.

***From the basic to the industrial praxis***

Measurement of cutting forces during wood machining is nowadays easy to realise at laboratory scale and physical models of cutting can be constructed which are capable of simulating the process. Different authors developed specific devices. These are necessary: (1) In the case of a **batch processing** for the prediction of machinability of some given wood materials and/or setting-up of specific machining operation. (2) In the case of an **interactive processing** to build a predictive model, then a monitoring system based on measurement of forces. These can be applied to adjust online process parameters (the cutting speed and/or the cutting geometry) based either on an open loop (help to the decision system for operators) or on a closed loop (adaptive control) control.

Nevertheless, in this last case, cutting forces do not always appear to be the most suitable inputs because of the specific and very expensive design of the machine-tools. Moreover, the integration of gauges in the internal structure of a device often reduces a machine's rigidity. Substitute outputs for control purposes must then be found.

To illustrate all these aspects, this paper is focused on the peeling process because it is an industrial process following a fundamental cutting mode (0°/90°). A direct transfer of the results from the laboratory scale to the industrial one is possible.

The peeling process requires keeping very accurate settings all along the machining operation. Actually, the cutting forces being the lowest among all wood processes (mode 0°/90°, green wood), the tool balance is very sensitive to any change – even minor – of settings and of wood properties. Critical cutting plan displacements easily occur inducing veneer thickness variation because of the high transverse deformability of green and often heated wood blocks stressed by the knife. Moreover, the action of the pressure bar modifies forces equilibrium and its settings interlink with the knife's settings. In peeling process the final product (the veneer) being the chip, a carefully setting of all parameters is very important in order to obtain both a good quality chip and machined surface, but also to reach as fast as possible the steady state and to keep it.

## Model of cutting forces to simulate the process

### *Mechanics of peeling process*

Thibaut (1988) and Thibaut (1995) proposed a system of mechanistic models for describing the basic processes in rotary veneer cutting. The experimental analyses were performed by a microlathe (Figure 3). This device permitted to record cutting forces and to visualise the lateral section of the piece of wood during the process (Butaud et al. 1995). The models of Thibaut explained and reproduced most of the experimental observations resulting from numerous peeling trials of various species like chestnut (Movassaghi 1985; Thibaut 1988), Douglas-fir (Movassaghi 1985; Mothe 1988), oaks (Marchal 1989), beech, walnut and poplar (Deces-Petit 1996), numerous tropical woods (Thibaut 1988; Beauchêne 1996).

The main experimental observations may be summarised as follows after the analysis of the forces exerted by the tool (the resultant rake force $F_a$, the resultant clearance force $F_d$) and by the pressure bar ($F_b$), and also considering their respective tangential (or parallel) and radial (or normal) components X and Y (Figure 2):

The chip flows above the rake face of the tool via a shearing deformation along a nearly radial plane (zone 2 in Figure 4), and does not show any shortening as compared to cutting length, which is in strong disagreement with classical metal machining experiments and theories like that of Merchant.

The compression and rubbing action of the pressure bar – most of the experiments were performed with a nosebar; the action of a round bar would be slightly different – and the clearance face of the tool result in radial compressive stresses which can reach very high values (crushing of the cells – zones 1 in Figure 4) near the contact zone, and remain in the elastic domain farther from the tool (zone 4 in Figure 4).

The radial wood displacement at the tip level leads to unexpected changes of the final thickness of the veneer due to this compression state (Figure 5).

In front of the tool tip, the radial tensile stresses resulting from both tool and bar actions may lead to lathe checks (in mode I), particularly for thick veneer and dense wood (zones 3 in Figure 4, Figure 6a).

For lower thickness and softer wood, the tangential compression at the tool edge level may lead to discontinuous cutting with alternation of wood compression and relaxation in front of the tool tip. This behaviour is often called the Horner effect (Figure 6b).

***Simulation of the peeling process***

The models of Thibaut were embedded into a software for simulating the rotary cutting of a heterogeneous wood (Mothe et al.1997). The simulation works on a radial basis: starting from the initial conditions (tool edge tangential to the surface, veneer thickness = 0), the cutting forces are computed for each rotation at the same angular position (Figure 7), as the tool moves radially inwards. The radial wood displacement induced by the cutting forces is therefore computed, allowing predicting the actual veneer thickness at each turn.

It was assumed that wood properties remain constant – at least in a short distance – in both tangential and longitudinal directions and vary only along the radius. Beauchêne and Thibaut (1996) showed that most of the mechanical properties of wet wood depend strongly on the wood density and temperature for tropical homogeneous species. The stress-strain curves in radial compression, in radial tension, and in radial/tangential shear are all supposed to be predictable at a given temperature through the wood density profile from the tip of the pressure bar to the inner core.

***Force on the pressure bar ($F_b$)***

The radial component of $F_b$, $Y_b$, is related to the depth of wood crushed by the pressure bar which is the difference between the actual veneer thickness Ev and the horizontal gap Ch. The radial displacement is absorbed by the whole block of wood from the upper side of the veneer to the peeling lathe spindle (not considering the bolt bending).

The radial force may be computed with an iterative procedure: For increasing values of the load, the stress distribution is estimated along a plane uniformly loaded with the formula of Timoshenko and Goodier (1951). The radial displacements of elementary portions of wood are summed along the radius to compute the total wood displacement: The process is repeated until the total displacement is close enough to the bar penetration Ev - Ch.

Finally, an experimental model based on the pressure bar settings and the friction coefficient is applied for estimating the orientation angle of $F_b$ and therefore the tangential component $X_b$. Assuming that the compression load is identical on both the front and back faces of the pressure bar, the total force is redistributed on both faces proportionally to the respective lengths of contact, which are computed geometrically.

***Force on the tool clearance face ($F_d$)***

The clearance force $F_d$ depends mainly on the amount and stiffness of wood crushed by the clearance face. The depth and length of contact are computed geometrically based on the actual veneer thickness, the peeling radius, and the clearance angle. The radial component is then calculated by the same iterative procedure as for the pressure bar force.

However, experimental results show that $F_d$ remains rather high even if the clearance angle is large enough to minimise the contact. This can be explained by the crushing of cells rolling back the tool edge and rubbing the clearance face on a short distance. This second contribution to the radial component of $F_d$ can be estimated by the product of the contact length (supposed to be constant) and the stress generated by the cells crushing (supposed to be equal to the end of the elastic phase of the stress-strain curve in radial compression).

With the radial component of the clearance force being known, the angle of inclination of $F_d$ (given by the friction coefficient between wet wood and metal) can be used to compute the tangential component of the clearance force.

***Force on the tool rake face ($F_a$)***

The rake force $F_a$ increases quite linearly with wood density and veneer thickness. It depends mainly on the intensity of the stresses and their distribution along the main shearing plane.

**In absence of a pressure bar**, the radial force may be estimated by integrating along the stresses along the shear plane (supposedly radial). Considering that the wedge angle is usually close to 20°, the maximal shear deformation near the tool tip may be assumed to be constant (around 35%) whatever the lathe settings are. An exponential decreasing function is then used to describe the stress distribution and to compute the radial component of $F_a$.

**In the presence of a pressure bar**, the forces on both the back and front faces of the bar have to be considered. The radial component of the back face force contributes positively to the rake force, the veneer being compressed between the back face of the bar and the rake face of the tool (this force is null if the angle between the cutting plan and the back face is above 90°). On the other hand, the front face force contributes negatively by reducing the stresses along the shearing plane.

***Radial wood displacements due to the cutting forces***

The radial forces on the tool and the pressure bar lead to radial displacement of the wood block. As a main consequence, the veneer thickness (Ev) may be slightly different from the expected thickness.

The actual thickness depends on the current radial displacement and on the displacement resulted from the previous revolution. Assuming that the previous displacement and the cutting forces are known, the new displacements generated at the tool tip level by the radial components of the shearing force, the tool clearance force and the front face of the pressure bar force have to be computed. The force on the back face of the nosebar is assumed have no effect because it is equilibrated by the face force of the tool rake. In each case, this task is performed by summing along the radius the displacements of elementary layers of wood in accordance with the relationships between tension and compression stress-strain.

***Main calculation loop***

Considering that the cutting forces are needed for estimating the veneer thickness and that the thickness depends on the cutting forces, an iterative procedure has to be applied. The convergence is usually reached after less than five iterations for heterogeneous woods except when the properties change abruptly (e.g. near an annual ring limit) or when the pressure bar (being misplaced) leads the tool to plunge and rise alternately.

***Veneer quality***

The three main defects of a rotary cut veneer linked to the cutting process are lathe checks, roughness due to the Horner effect, and thickness variations. Only the last one has been actually predicted by the simulator, even if lathe checks and Horner effect could be predicted easily through cutting forces and tensile properties of wood.

For heterogeneous wood species, the continuous changes in wood density tend to make worse these defects. The most unfavourable case occurs when the wood density near the pressure bar and near the tool are strongly different, as shown for the two main cases in figure 6 frequently occurring when peeling softwoods.

A virtual simulation of the peeling process is nowadays available to predict cutting forces, and consequently the adapted settings for given wood species. However, this model can be improved with better modelling of wet wood mechanical behaviour. With a view to deliver a more general model of the chip formation during peeling at the mesoscopic scale, Bonin (2006) attempted to implement a thermo-mechanical simulation of metal turning (Cordebois 1994; Ali, F. 2001) to wood peeling. An adaptation of the thermo mechanic model of Oxley (1989) has been tested based on a law of wood orthotropy (called the Bauschinger effect; asymmetry of the mechanical behaviour in compression and tension) and considering the deformation speed. This approach was unsuccessful because all the analytical models of the chip formation for metals are based on laws describing elastoplastic behaviour at high deformations. After having performed a great number of mechanical tests on beech green wood in transverse directions, Bonin (2006) concluded that hyperelasticity and compressibility of green wood like elastomers (Laraba-Abbes 1998) caused the differences. Bonin (2006) also built a new model relying on simplified assumptions (e.g. neglecting the increase of temperature during chip formation and the orthotropy in the transverse plan) based on thirty micropeeling tests. In this model, the slope of the cutting zone was in agreement with the experiments. Furthermore, forces occurring on the rake face of the tool were correctly predicted: for more than 95% of the predicted forces, the gap between experimented and predicted results was less than 20%.

**Dynamometric approach for optimising the process**

From this comprehensive description of the veneering process, several practical rules can be highlighted which are directly applicable to industrial processes. Just considering the two decompositions of $F_c$, the resultant cutting force exerted by the tool, the 4 components provide useful practical information on the process in progress:

(1) **$X_c$:** its mean value determines the lathe motor torque value. It must be as small as possible. Standard variation of $X_c$ is linked to the amplitude and possibly the frequency of lathe checking.

(2) $\mathbf{Y_c}$ is linked to the tool tip position: a negative value expresses a cutting refusal tendency when a positive one indicates a tool plunging tendency. In the normal case, the best settings are obtained when the tool dives a little (low positive $Y_c$ value); the cutting plan is then slightly lower than the theoretical one. As can be seen in Figure 8, a very small change on clearance angle can then induce huge effect upon the tool equilibrium, especially for very small veneer thicknesses (Marchal and Negri 1997).

(3) The ratio $\mathbf{F_a/F_d}$ describes the tool balance and also the wear pattern. In the normal case, $F_a/F_d$ is in the range of 2 to 3. $F_a$ and $F_d$, are computed as illustrated in Figure 2. These two forces are, respectively, a function of the veneer thickness and of the clearance angle. It is quite easy to act on the clearance angle to reach the right ratio. This ratio must be as insensitive as possible to cutting speed variation. There are for a given wood species two domains: one for low cutting speed and one for high cutting speed. At high speed, the clearance angle should be increased in order to avoid the huge increase of $F_d$ (Figure 9 in the case of walnut) due to the "Maxwell effect" and then to maintain the good balance of the tool. Cutting speed and clearance angle are interlinked settings. Remark to the Maxwell effect: Under high deformation speeds, free water contained in cells being only parthly evacuated from the maximum stress area, the free water still remaining induces an apparent increase in rigidity through Young's modulus because of its incompressibility (Costes and Larricq 2002).

(4) All the mean values and the variation of forces must be maintained at a level as low as possible in order to improve tool-life (minimizing the wear of the tool and machine fatigue).

Considering also the pressure bar, (1) The ratio $\mathbf{Y_b/F_a}$ can be used to survey the pressure bar efficiency for reducing lathe checking (Thibaut 1988). (2) The sum $\mathbf{X_c+X_b}$ should be minimized to decrease the power consumption and (3) the sum $\mathbf{Y_c + Y_b}$ should be minimized to decrease the flexion of the wood block at the end of the process.

These measurements and calculation are very useful for the process optimisation at the laboratory scale. However, there are not yet industrial machines equipped with force sensors which make possible the application of this knowledge neither for basic optimisation nor for online control of the process (Lemaster et al.2000a). Nevertheless, for high value added products, the process could be feasible.

## Cutting forces and alternative outputs to develop interactive processing

### *Power consumption*

Some alternative inputs were also investigated. The nearest measurement to forces is probably power consumption. Despite the fact that it is quite easy to implement directly a spindle to measure the power consumed by the cut, this information is significantly less pertinent. According to Lemaster et al. (2000a), this measurement integrates both the cutting forces and the dynamic aspects of the machine.

### *Artificial vision*

Operators on CNC often characterise the status of the process by visual inspection. Many defects of the machined surface or tool wear can be seen directly. Unfortunately, according to Januten (2002), direct methods to measure tool wear (also including computer vision) have not yet proven to be very attractive economically and technically. Lemaster and Stewart (2005) have developed a software able to distinguish different random defects from an optical profilometer signal. The algorithm proposed is based on fuzzy logic and Wavelets. This approach seems very promising, but it is still not yet fully developed.

### *Acoustic emission*

Several authors also applied acoustic emission (AE) as input data. AE is the stress waves (low energy and very high frequency i.e. from 100 kHz up to 1000 kHz) produced by the sudden internal stress redistribution of a material caused by changes in its internal structure (crack opening or growing, fibre breakage, etc.). Lemaster et al. (1982), Lemaster and Kato (1991), and Murase et al. (2004) proved the great potential of this technique to monitor wood cutting processes. According to the accepted indicators (Root Mean Square - RMS, count rate, cumulative count rate, etc.), AE is sensitive to the chip formation mechanism (shearing plan, sliding areas, cracks, splits etc.). However, Lemaster et al. (2000a) underlined the limitation of this technique which is the high sensitivity to background noise due to the device components such as roller bearings. Adding the high damping character of wood materials, it is necessary to place sensors very closed to the cutting area, which is often not applicable in industry.

***Sound and vibrations***

Experienced operators are very sensitive to sound or vibrations emitted by the process of milling or sawing (Marchal et al. 2000). Only a few works were carried out with acoustic or vibratory sensors as sources of information for wood machining. Nagatomi et al. (1999) found a high correlation between probability of sound pressure level (SPL) larger than a suitable threshold and surface roughness of peeled veneers of sugi. However, this relation was obtained within a very large domain of frequencies (some Hz to 100 kHz) which is not congruent with the operator’s ability with an audible range from 20 Hz to 20 kHz. In numerous other works based on AE or SPL measurements to build an online control system (Tanaka et al. 1997; Nagatomi et al.1993; Murase and Harada 1995), the threshold value determination has never been clearly explained. This value is always more or less linked to experimental settings applied (device, wood species, cutting conditions, moisture content, etc.) which is not enough flexible to meet industrial requirements. Iskra and Tanaka (2006) used dynamical thresholds to analyse (one-third octave band analysis) both SPL and sound intensity during routing of Japanese beech. This constituted a great improvement of the approach previously described because the criterion was polyvalent and consequently better adapted to industrial environment constraint.

Iskra and Tanaka (2005) obtained a significant and high correlation coefficient between surface roughness and sound intensity allowing them to adapt feed rate during routing with regard to the value of sample grain angle. However, the frequency band selected for computation was probably only optimal for the experimental setup considered. Lemaster et al. (2000b) used accelerometers and obtained similar results for tool wear monitoring during routing. Instead of a global RMS value (computed on a large frequencies domain), the authors proposed power spectrum density (PSD) as criterion to determine the most promising band for computation. The great potential of spectral analysis was confirmed by Denaud et al. (2005). During peeling, the authors identified a peak on fast Fourier transform (FFT) spectra (obtained from both microphone and accelerometers as indicated in Figure 10). It corresponds to the vibratory signature of the average lathe check frequency of the veneer. This phenomenon is almost periodic for homogeneous species. However, the peak detection would be only possible by characterising the mechanical behaviour of the lathe which is a delicate and an expensive operation. To bypass this difficulty, Denaud et al. (2007a) developed a method to identify the signature of lathe checks on the temporal signal emitted from the same sensors. This needs only a local RMS averaging via a peak detection algorithm which did not require any threshold (see Figure 11). This approach seemed very promising to get check distributions along the veneer, however, its efficiency for slightly checked veneers was not characterised.

To sum up, vibration or sound measurements seem to be the most promising ways to substitute measurements of cutting forces in a search for an online control system of a cutting process. However, there are some ambiguities concerning a threshold, a correlation coefficient, a frequency band domain or a peak on a spectral analysis. Hitherto, empirical and preliminary limits are set with this regard.

As a response, Denaud et al. (2007b) initiated new experiments. These authors tried to avoid any check formation and estimated PSD from a "reference cutting trail" under conditions of a high pressure rate of the pressure bar (20% of the veneer thickness here). In this manner, they took account of the dynamical behaviour of their device. Such settings produced inevitably unacceptable variations of the veneer thickness which, however, did not affect notably the PSD.

The ratio between measured and reference signal helped avoid natural frequencies of the lathe. By this way, the default signature characterisation was greatly simplified as shown in Figure 12 for the same domain of frequencies. The highest peak was at 152 Hz which corresponds to an average distance of almost 3.3 mm between two consecutive checks. Moreover, according to the results of Denaud et al. (2007b), this approach is also suitable for relatively low pressure rates. In the end, this could lead to an online control of the pressure rate of the pressure bar which is always a compromise to obtain a veneer with small lathe checks and constant thickness.

## Conclusion

For a long time, cutting force measurement has been the only successful and most powerful measurement for producing output data for advanced analytical research on wood machining processes. It is still matchless and helps improve knowledge about wood surface formation and tool wear. Its main asset is that it takes into consideration the contact between tool and wood and thus enables computation of the strains inside the wood pieces, the wood chips, and the tools. However, cheaper sensors with more operating comfort are needed in the industrial praxis. Against this background, accelerometers and microphones, which can be integrated easily into the machine, are promising sensors for the near future. On the other hand, the signal treatment is more difficult in the case of these sensors.

Measuring wood cutting forces makes a sense definitively for basic research. The same is true in industrial applications, particularly in batch processes. In such cases, preliminary tests on specific machining benches are necessary in order to optimise cutting geometry and any other cutting parameters, before launching a new production.

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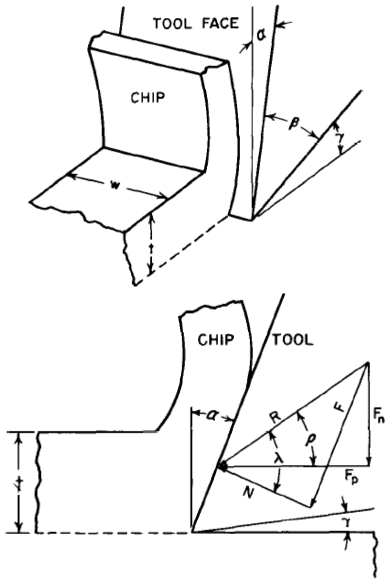



α — *Rake angle: angle between the tool face and a plane perpendicular to the direction of tool travel.*

β — *Sharpness angle: angle between the tool face and back.*

γ — *Clearance angle: angle between the back of the tool and the work surface behind the tool.*

t — *Thickness of chip before removal from the workpiece.*

w — *Width of undeformed chip.*

$F_n$ — *Normal tool force: force component acting perpendicular to parallel tool force and perpendicular to the surface generated.*

$F_p$ — *Parallel tool force: force component acting parallel to tool motion in workpiece, i.e., parallel to cut surface.*

R — *Resultant tool force: the resultant of normal and parallel tool force components.*

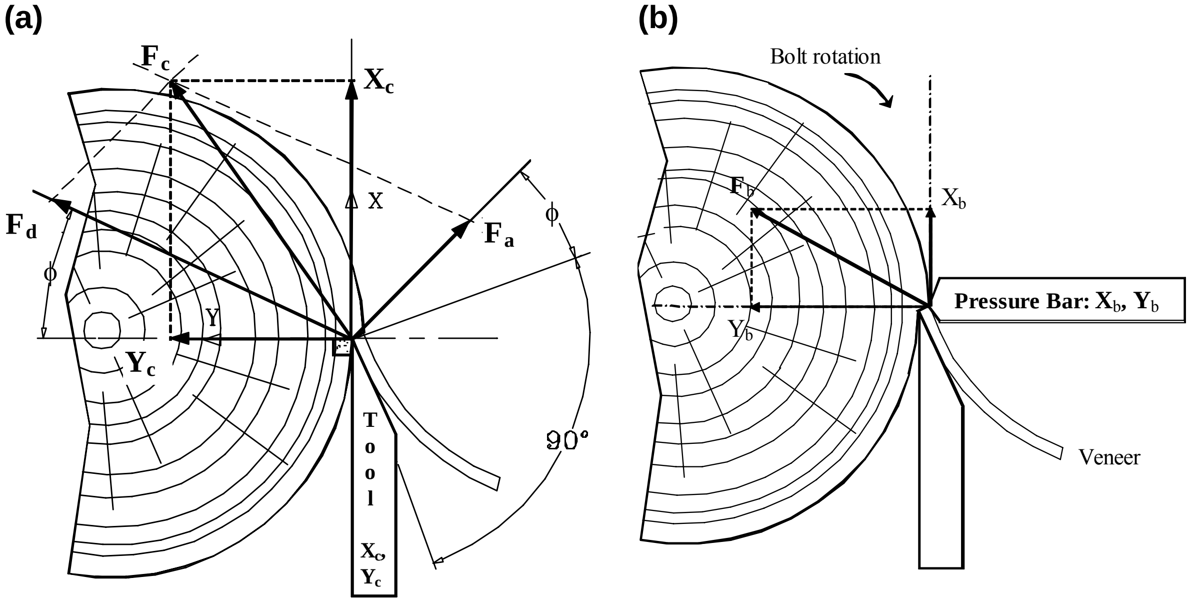
P — *Angle of tool force resultant: the angle whose tangent is equal to the normal tool force divided by the parallel tool force.*

F — *Friction force: force component acting along the interface between tool and chip.*

N — *Normal to the friction force: force component acting normal to tool face.*

λ — *Angle between resultant tool force and the normal frictional force; the angle whose tangent is equal to the friction force divided by the normal friction force.*

Figure 1 Orthogonal decomposition of the cutting force (in Woodson and Koch, 1970)




$$F_a = \frac{X_{c.} \cos\phi + Y_{c.} \sin\phi}{\sin(\beta + 2\phi)}$$

$$F_d = \frac{X_{c.} \cos(\phi + \beta) - Y_{c.} \sin(\phi + \beta)}{\sin(\beta + 2\phi)}$$

*With ß = bevel angle ; $\phi$ = steel/wood friction angle*

Figure 2: Cutting and pressure bar forces in peeling processes. (a) orthogonal and facial components of the resultant cutting forces $F_c$ (b) orthogonal components of the resultant pressure force $F_b$ (in Butaud et al 1995)

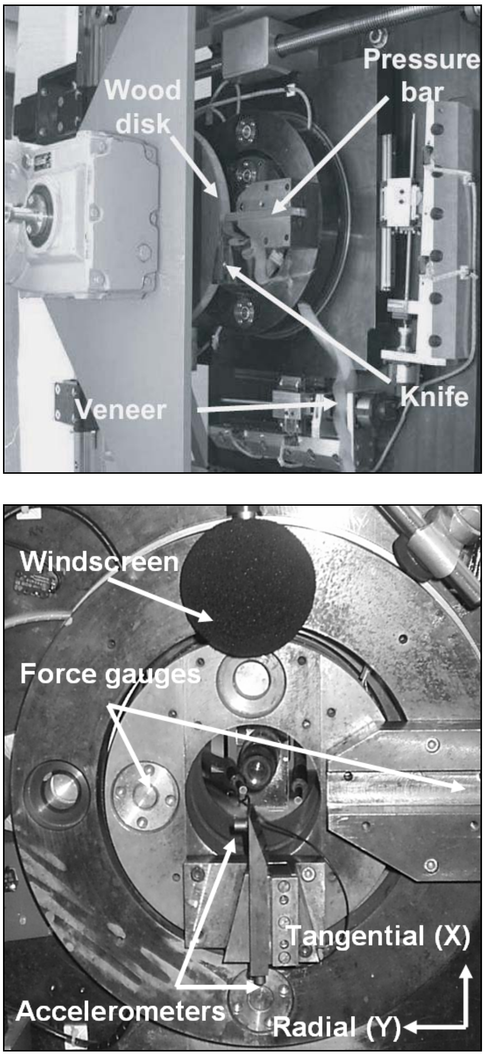



Figure 3 The instrumented microlathe in ENSAM

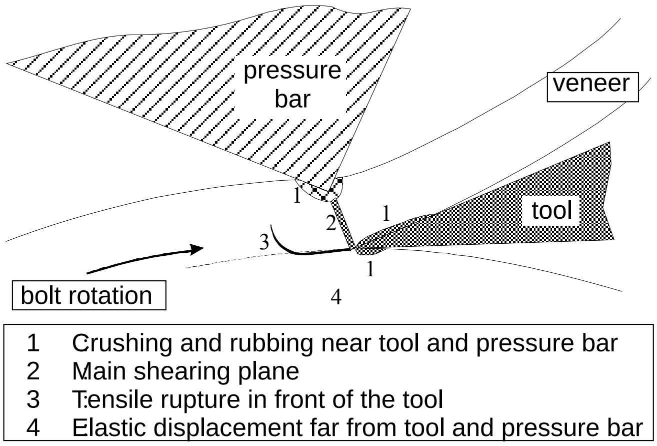



Figure 4 Basic processes in veneer cutting (in Beauchêne 1996)

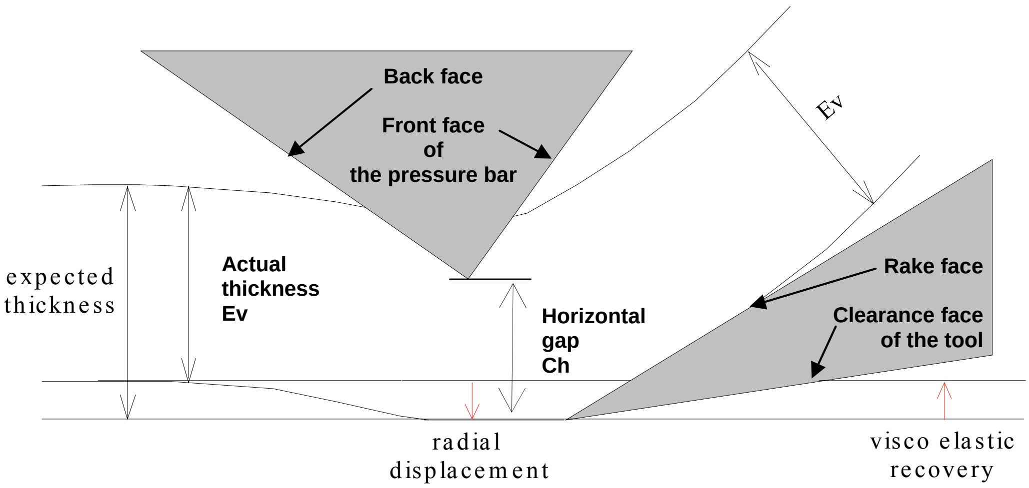



Figure 5 Consequence of the radial displacement of wood on veneer thickness at the tip level due to the cutting forces.

(a) (b)

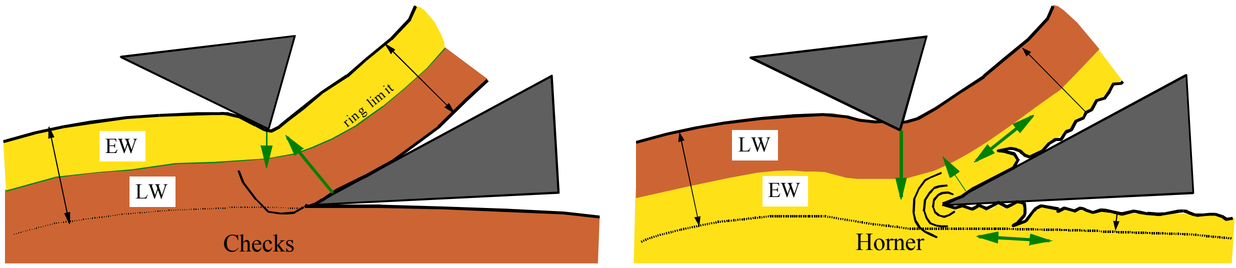



Figure 6 Specific problems encountered with heterogeneous species. (a) Ring limit crossing the veneer: the high density near the tool increases the risk of lath checks since the low density near the pressure bar prevents it to counteract. (b) Early wood/late wood transition: the soft wood around the tool is crushed at the tool tip and torn by the friction on the tool faces; the bar force is increased by dense wood and tends to reduce the veneer thickness by moving the cutting plane above the tool.

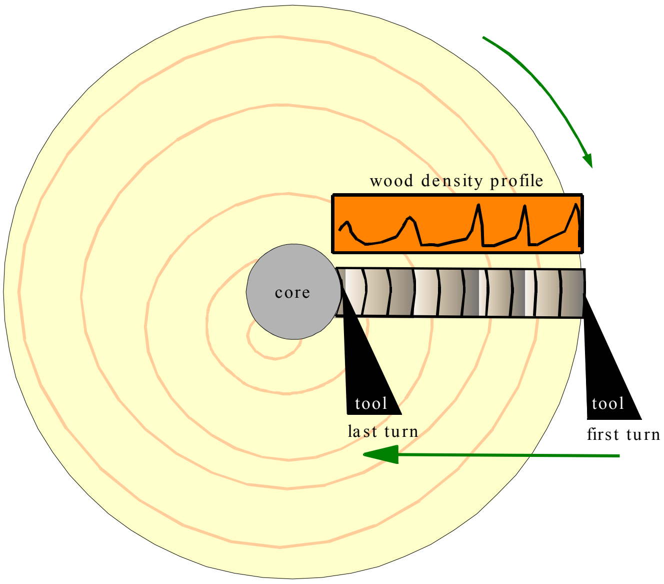



Figure 7  Work of the peeling simulator. The forces and wood displacements are computed at each turn at the same radial position. The wood density profile is the basis for predicting the mechanical properties along the radius.

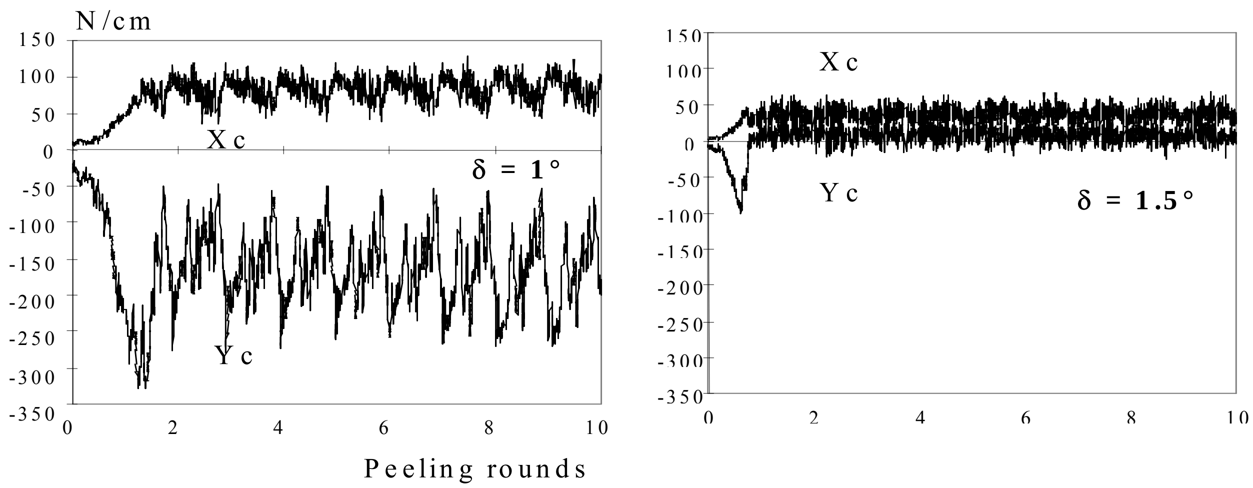



Figure 8 Experimentaly obtained diagrams. Influence of the clearance angle δ on the orthogonal cutting forces distribution (Marchal and Negri 1997) in the case of peeling thin veneers (evergreen oak; nominal thickness = 0.6 mm; cutting speed = 2 mm/s)

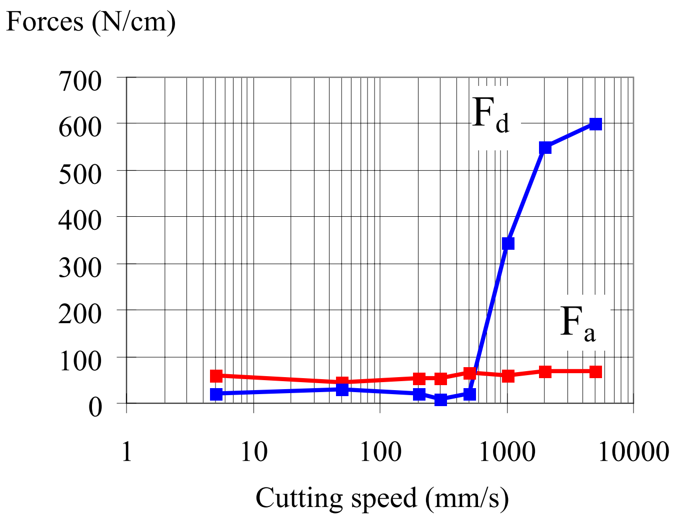



Figure 9 Evolution of the two facial components of the resultant cutting force with the cutting speed (Decès-Petit 1996). (Walnut; nominal thickness =1 mm; clearance angle = 0°)

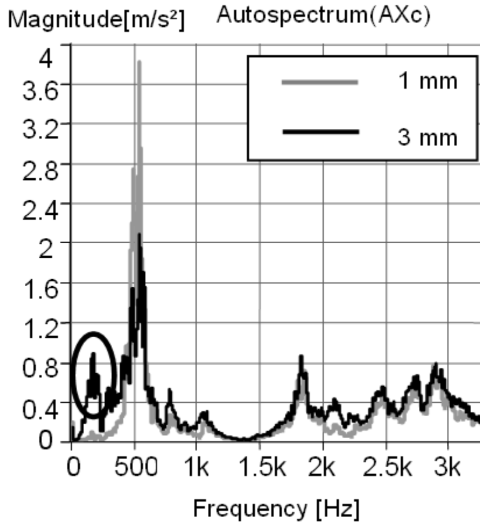



Figure 10 Lathe check signature (spectrum from knife accelerometer in tangential direction ($AX_c$). The signature (circled) is mainly visible for the higher thickness, only very small lathe check occurring when peeling in 1 mm (grey line). Poplar, without the pressure bar, Vc = 0.5m/s, well honed tool, clearance angle null, thickness of 1 mm: soft-checked veneer / thickness of 3 mm: hard-checked veneer)

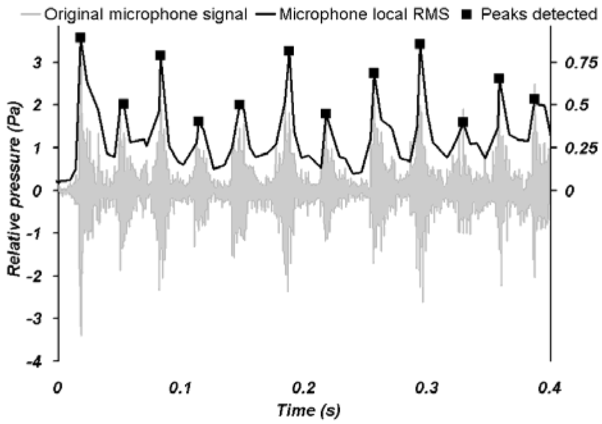



Figure 11: Original, preset, and peak detected from the microphone signal for a 3 mm thick beech veneer (Denaud et al 2007 a)

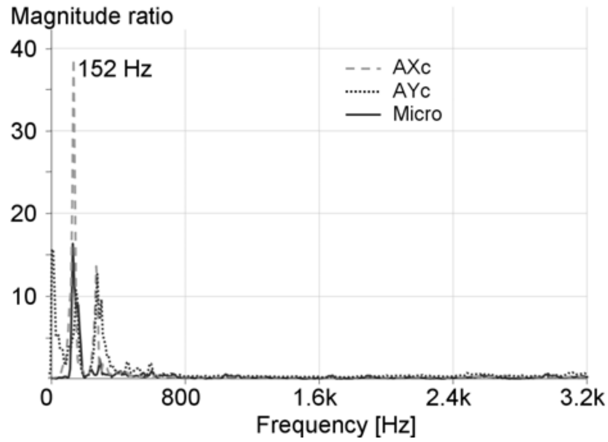



Figure 12 PSD ratio for microphone, $AX_c$ and $AY_c$ accelerometers (respectively in the tangential and radial direction) between 3 mm. Poplar veneer without pressure bar and reference signal.