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**Original**

# Cutter head forces and load cell scanning

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**Abstract** Among the machinery found in wood manufacturing industries, routers and planers are the most commonly used. These tools, which many times are mounted on metal cylinders, actually operate only briefly, i. e., when a chip is cut from a piece of wood under process. The rest of the time the knife follows the cylinder surface and a cycloid is formed relative to the work piece, which in turn is fed into the machine. A number of knives are mounted on the cutter, which ascertain that the planed surface will become sufficiently planed and does not show too a wavy pattern. This works fine for high revolutions and low feeding speeds even if problems sometimes occur. Factories, however, naturally want to increase the overall manufacturing speed, which means that at the same time more defects are introduced at the planed surface. These defects are the result of the cutting process. In this paper, we examine, by use of a load cell, how the cutting forces vary during the formation of a wood chip. Wood is not an isotropic material and knots and other anomalies make the evaluation harder. In order to simplify the conditions, experiments are also shown from the cutting of a plastic polymer material as well as Medium Density Fibreboard (MDF). It is shown that the work piece vibrated intensely which littered all output data from the cell. Experience from the experiments however made it possible to design a computerised filter which saved only those registrations which were of interest while the others were set to zero. For beech, the forces were found to be of the magnitude 50 N/cm opposite to the feeding direction while the tranverse forces changed signs and had a magnitude of about 5 N/cm.

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## Introduction

When furniture and other products are manufactured on an industrial level, machining is necessary, both for speeding up the process and for reasons of quality. A number of such machines use rotating tools, e. g., circular saws, routers and planers. In this paper we focus on the planing process, i.e., where the work piece is moved and the tool only follows a circular pattern. In a planer the actual tool, i.e., the device that actually cuts the wood, consists of a single knife. However, a number of such knives are mounted on a cylinder which in turn is firmly attached to the spindle of the machine. The knives can be demounted e.g., when they are to be sharpened. The planing process with such rotating cutters has been examined in the literature for several years; for example, in a book by Kollman and Côté (1984) there are references dating back 70 years. Defects at the planed surface must emanate from the actual cutting of the wood; hence, it is important to study the movement of one knife in operation.

Consider Fig. 1. Using ordinary trigonometry for the circle, with radius b, shows us the values for $x$ in the horizontal direction and $y$ in the vertical direction. Note that they start at point $P$ . The work piece was fed into the machine with an assumed speed of $f$ . After a time $t$ the piece travelled the distance $ft$ which is called $c$ in Fig. 1. $c$ corresponds to a certain length along the periphery of a much smaller circle with a radius of $a$ and, hence, $c$ equals $a\phi$. The coordinates $x$ and $y$ can therefore be expressed as:

$$x = \alpha\varphi + b\sin\varphi \quad (1)$$

$$y = b - \cos\varphi \quad (2)$$

The cutter head rotated with a speed $n$ and therefore one revolution was $1/n$ . After that time the work piece travelled the distance $f/n$ . Hence:

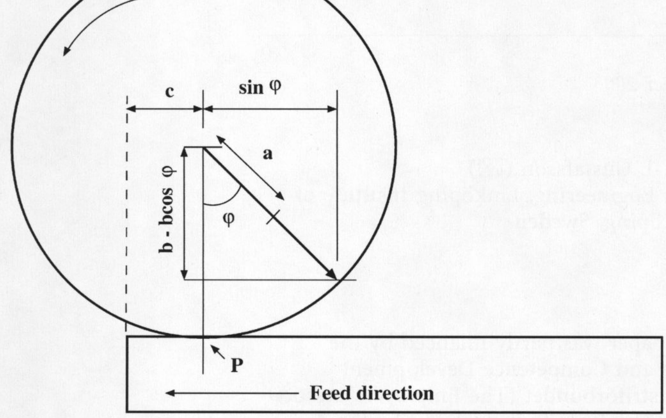


**Fig. 1.** Peripheral milling geometry

$$a\varphi = \frac{f}{n} \tag{3}$$

and for an angle $\phi$=2$\pi$:

$$a = \frac{f}{2\pi n} \tag{4}$$



Another common approach is to assume that the cutter is transported by use of a pineon (Koch 1964). Equations 1, 2, 3 and 4 were put into a small LINUX C-program and values generated for $0 \leq \phi \leq 4\pi$ (see Fig. 2). For pedagogic reasons the other values have been chosen as $f$=10 m/s, $b$=0.05 m and $n$=50 r/s.

As shown in Fig. 2 the tools moved in a cycloid, or trochoid, pattern. According to Selby (1972), at least four types of such curves can be elaborated upon, depending on the rate between $a$ and $b$. Furthermore, the curves will look different, depending on the basis of the coordinate system and the direction of the rotating cutter head. Therefore, there are certain differences between the mathematical expressions from Kollman and Côté (1984) and from Martellotti (1941).

The knife clamped to the cutter head cut a wood chip from the work piece. The formation of this wood chip has also been shown by Kollman and Côté (1984) and the details shown in Fig. 3. One important factor, however, when the chip formation is examined, is the feed for each cut of the knife, $e$ . If the number of cutting edges was $i$ the feed can be calculated as:

$$e = \frac{f}{ni} \tag{5}$$

Hence, it is possible to describe the movement of the knives and the cutting of the chip in closer detail; it should therefore be an interesting task to compare the mathematical expressions with real measurements from the cutting process.

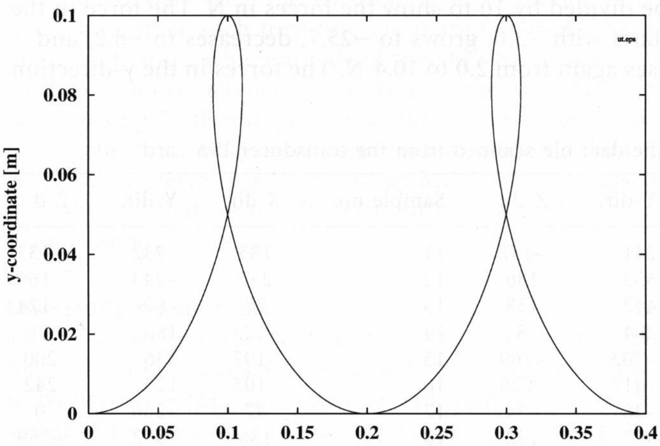


**Fig. 2.** The cycloid movement of the peripheral cutter head tool

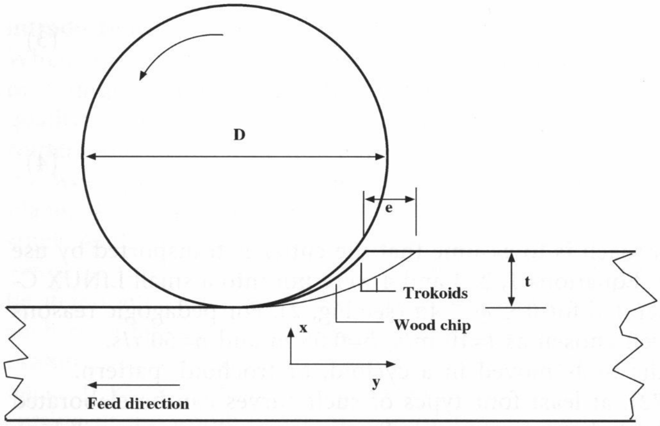


**Fig. 3.** The formation of a wooden chip

## The load cell and scanning process

When the basis for the cutter head movement was developed, there were only a few ways to examine the process in detail under realistic planing or routing conditions. The introduction of computers, fast scanning devices and probes have increased these possibilities (see e.g., Eyma et al. 2001 for a recent study). We used a commercial product, a Gamma FT 3774 tranducer, or load cell, which in the first experiments was clamped to a 3-axis NC Modig 6000 milling machine and, in the second series of tests, to a Cincinnati Milacron TT15. The transducer communicated with a so-called ISA card installed in an ordinary personal computer. A computer program, written in C, collected the readings and stored them in an ordinary text file. In this case, 4000 consecutive readings were stored for each experiment. In Table 1 the first 20 readings are shown from one of our first experiments.

The computer program scanned the ISA card at 4000 Hz and saved 4000 values, so that each data file contained only values scanned during 1 s. The values in Table 1 for the x- y- and z-directions show the registered force in 0.1 N, which implies that they must be divided by 10 to show the forces in N. The force in the x-direction, therefore, starts with −3.0, grows to −25.7, decreases to −8.2, and then changes and increases again from 2.0 to 10.4 N. The forces in the y-direction

**Table 1.** The first part of the data file scanned from the transducer ISA card

| Sample no. | X-dir. | Y-dir. | Z-dir | Sample no. | X-dir | Y-dir. | Z-dir. |
|---|---|---|---|---|---|---|---|
| 1 | −30 | 241 | −147 | 11 | 183 | −232 | −133 |
| 2 | −257 | 352 | 186 | 12 | 237 | −243 | −169 |
| 3 | −82 | 442 | 138 | 13 | 77 | −82 | −124 |
| 4 | 20 | 284 | 8 | 14 | −123 | 186 | 11 |
| 5 | 104 | −203 | −169 | 15 | −197 | 336 | 200 |
| 6 | 190 | −417 | −225 | 16 | −105 | 127 | 242 |
| 7 | 89 | −28 | −54 | 17 | 47 | −266 | 0 |
| 8 | −177 | 397 | 192 | 18 | 136 | −352 | −259 |
| 9 | −283 | −332 | 237 | 19 | 126 | −12 | −236 |
| 10 | −82 | −7 | 36 | 20 | 43 | 281 | 14 |

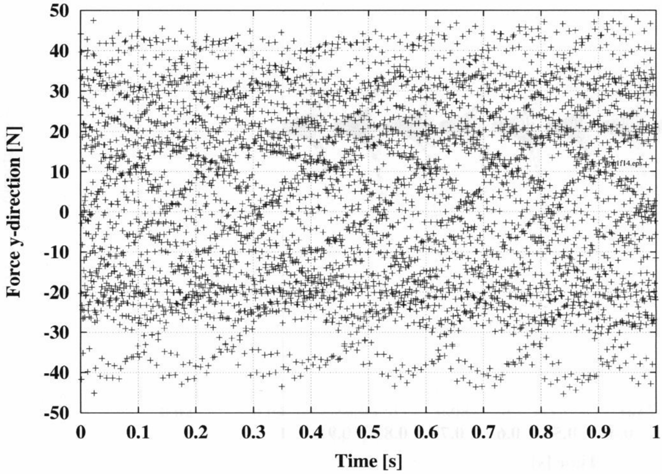


**Fig. 4.** Registered forces when cutting MDF in the y-direction during one second



show the same pattern, i.e., the forces fluctuate quickly from a positive direction to a negative direction, and the same for the z registrations. Note that, because of the scanning speed, just 0.00025 s occurred between two readings. It is, therefore, hard to find any correlation between the theory shown above and our first experiment. From the 60 values shown in Table 1 and the fact that 11,820 values remain unshown, there might be other data in the file which makes it easier to explain the situation. It is not meaningful to show all these values in a table, but all those values valid for the y-direction are depicted in Fig. 4, showing the force as a function of time.

From Fig. 4 it is obvious that the y-forces have the maximum absolute values of about 50 N. A slightly discernable wavy pattern is also present, but in many other aspects the registrations seem hard to interpret. In this first experiment a revolution speed of 5000 rpm was used and the work piece was made of 19 mm MDF. Such material is mostly used in the formation of large boards when tables, doors and other such furniture are manufactured. The board consists of wood fibres, not chips, which are glued together by so-called dry pressing (see Walker 1993 for a more detailed description of the manufacturing process). The reason for choosing MDF was that we assumed this material to have a higher degree of homogeneity in comparison to ordinary wood. Aguilera et al. (2000) also reported successful experiments from cutting MDF. From the discouraging results in Fig. 4 it is obvious that we had to start cutting more slowly, with a material of even higher homogeneity.

## Case study number one

Tt was shown previously that MDF was probably too inhomogeneous a material for evaluation purposes in an initial state and that a slower revolution speed had to be used. We therefore chose to cut more slowly, with a plastic material. The speed of the rotating milling cutter was set to 600 rpm and one revolution therefore took about 0.1 s. Although this was a short time, there were about 400 readings during one revolution, which seemed to be sufficient. In Fig. 5 the y-registrations are shown as a function of time.

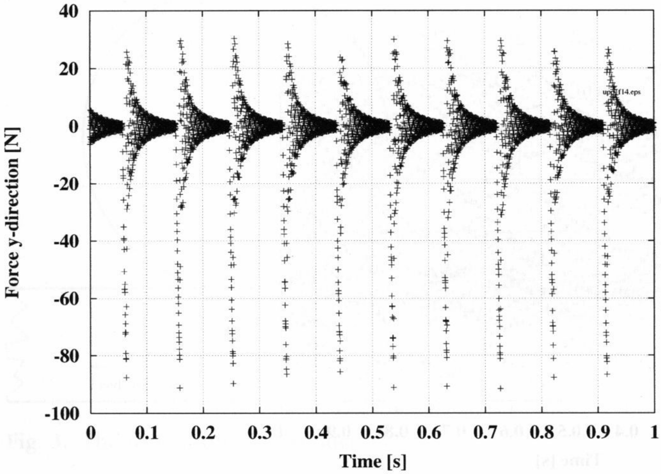


**Fig. 5.** Registered forces in N in the y-direction for a polymer plastic material. Speed 600 rpm

It was then possible to follow the process in more detail. It is obvious that the forces in the y-direction grew rapidly on a regular basis. It was of course assumed that those forces were registered when the tool actually was cutting. However, it is also obvious that the impact of the cutting knife set the work piece into vibration and that the amplitude of these vibrations declined until a new impact was made. This explains the discouraging results in Fig. 4 and it is plausible that the useful registrations were covered by vibrational litter. However, the registrations shown in Fig. 5 started when the knife did not cut anything. This is explained by the procedure used during the experiments. Firstly, the router was started while at the same time the scanning process was idle. Secondly, when it was observed that cutting actually occurred, the scanning started but because of the revolution speed it was difficult to start the scanning in the precise moment of impact. By a detailed examination of the data file it is, however, possible to find the exact time when the the tool really started to do something. In Fig. 6 the monitored values for the first 450 readings in the x-direction are shown, i.e., perpendicular to the transversal feeding direction. When the registrations started, the sensor showed that the force varied between positive and negative values in the range of - 1 to + 1 N. The amplitude, however, decreased until about 0.05 seconds passed and the force increased to about 10 N. A number of subsequent readings were positive but for 0.06 s the force became negative.

The same experiment was run for the y-direction which is described in Fig. 7. Here, forces of the same magnitudes are likewise shown up to about 0.05 s when the force became negative and increased to a value of about 90 N. In the z-direction a similar pattern was found but the values after the impact were much smaller with a maximum of approximately 1 N. This is explained by the fact that the tool only worked at the edge of the work piece, and in theory, no forces at all should have emerged in the z-direction. In Fig. 6 and Fig. 7 it is obvious that the moment when the tool gripped the work piece was determined with a high degree of accuracy. The problem was to find the moment when the tip of the tool no longer cut anything and the force readings only emanated from vibrations in the

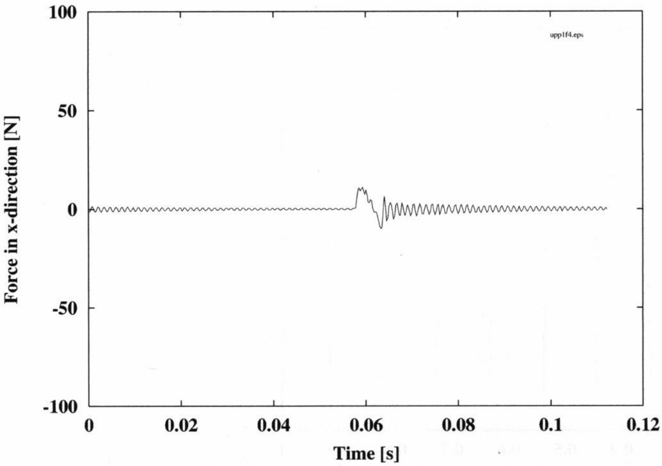


**Fig. 6.** Registered forces N in x-direction for the first revolution in case study one

experimental setup. Because of the high scanning rate and the possibility to see exactly when the tool hit the work piece surface, we were able to calculate the average time gap between two knife impacts to 0.09469 s. The revolution speed has, therefore, been evaluated to 10.56 rps or 633.7 rpm. In this experiment the depth of each cut, i.e., $t$ in Fig. 3, equaled 0.002 m, $b$ equaled 0.03 m and $\phi$ equaled 21.04 degrees. Each cut, therefore, took 0.0055 s which in turn resulted in 22 scanned registrations. It was therefore possible to implement a filter in a new LINUX C-program which started to print values to a file when the difference between two registrations were large; the program then stopped writing when the tool was above the work piece (Fig. 8).

The forces in the y-direction are about ten times larger than those in the x-direction. It is worth noting that the x-values are positive at the beginning of the incision but are negative at the end. The reason for such a behaviour might depend on conditions described by Martellotti (1941). Because of the feed in the x-direction the tool could have moved downward into the work piece and not

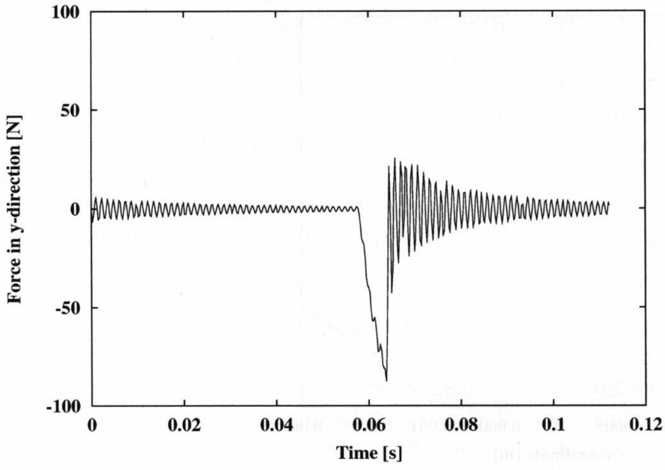


**Fig. 7.** Registered forces N in y-direction for the first revolution in case study one

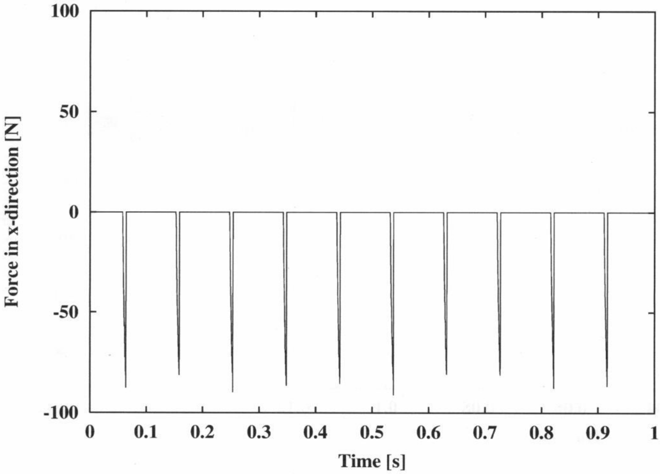


**Fig. 8.** Registered forces N in y-direction during 1 s with the filter applied

tangentially, which is assumed in Fig. 3. In order to examine this, equations 1 and 2 must be examined in closer detail. In our case, the Cincinnati milling machine was programmed to feed the work piece with 0.16 m/min. The radius of the tool was 0.03 m, so equations 1 and 2 were used in order to draw Fig. 9.

In Fig. 9 the curve is shown for three consecutive revolutions, and it is obvious that the tool started the incision in almost a tangential direction; therefore, the possible explanation above seems inapplicable. Note that the depth of the cut in the y-direction is 0.002 m, i.e., more than ten times the scale in the figure. Even if the tool, for a very short moment, was directed into the work piece, the overwhelming part of the cut should have resulted in forces in the opposite direction. During each second ten chips were cut, and furthermore, three experiments with identical conditions have been elaborated. Hence, it is possible to scrutinise thirty incision experiments. These experiments are not described here, but they all show

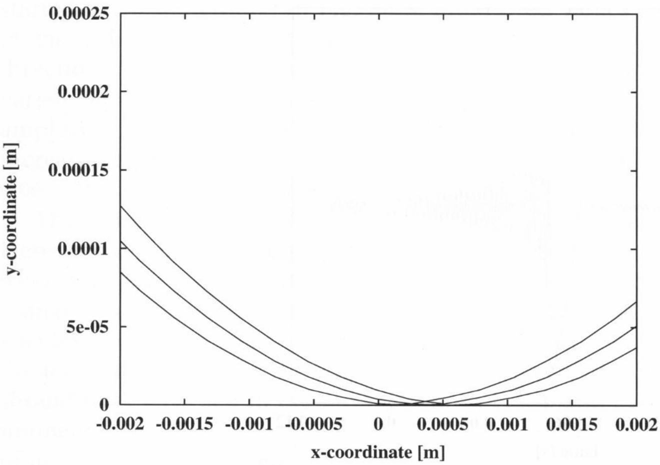


**Fig. 9.** Part of the trochoid curve for $\phi=6\pi$

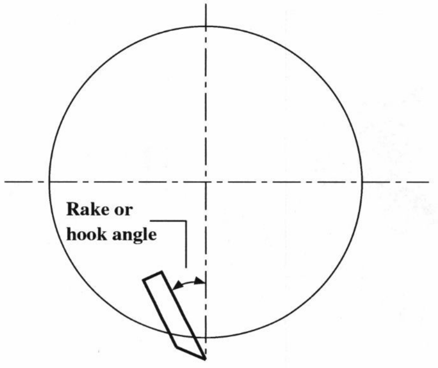


**Fig. 10.** Rake or hook angle for a cutter knife

the same facts: that about 15 values are positive in the start of each cut, and then the rest show either negative or small positive values. One other solution to this situation might be that the tip of the tool does not immediately start to cut in the work piece but instead is sliding for a moment on the surface, which of course results in forces pressing on the work piece. This behaviour, however, was not found to be of interest by Martellotti (1941) who examined the peripheral milling of brass. One common denominator in these three experiments was that the rake or hook angle (see Fig. 10) $\alpha$ was zero degrees.

When that angle was changed to 15 degrees the positive x-values became less frequent, about 11 instead of 16. The magnitude of the positive values were approximately the same but the negative values reached about 17 N when the rake angle was 15 degrees instead of about 10 N when a zero angle was used. The positive x-values should have increased in number if the feed of the work piece was increased, at least if it is assumed that the cutter knife was directed downward for a short moment. We have also examined such a case, but the fact is that the opposite behaviour was found, which is contradictory. As mentioned above, only up-milling has been examined, but we have also scrutinised values from down-milling. Fortunately, the positive x-values became larger and more numerous, which are in correspondence with what should have happened. In the y-direction the change in feed direction cannot be observed from variations in the forces. These are about the same no matter what feed was used. According to Martellotti (1945) the forces would then try to pull on the work piece instead of pushing on it as is natural when up-milling. It is obvious that we needed to examine a larger number of data sets in order to find a pattern between the forces in the x-direction, the y-direction and the position of the cutter knife. This is shown in Fig. 11 and it is obvious that forces of low absolute magnitude in the y-direction correspond with positive x-forces.

There are some values that do not follow the overall pattern, but they may be the result of vibrations in the experimental setup after each incision. In Figs. 12 and 13 the monitored forces are shown versus the time passed after the first detected impact.

Note that the forces were scanned in discrete steps and hence it is not possible to know exactly where the cutter head was located. In the computer filter it is assumed that the tool left the work piece 0.06 s after the moment when the impact was detected. It was mentioned previously that each incision had a duration of 0.056 s and therefore a few values did not remain in the computer filter. The forces in the x-direction, i.e., perpendicular to the feed direction, varied from

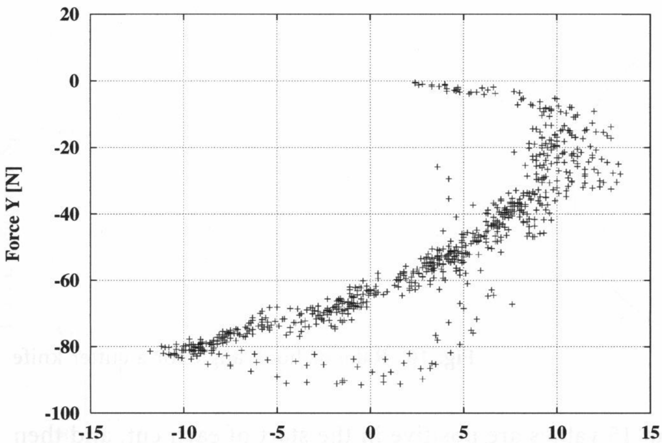


Fig. 11. Forces in x- and y- directions for up-milling with a rake angle of zero degrees

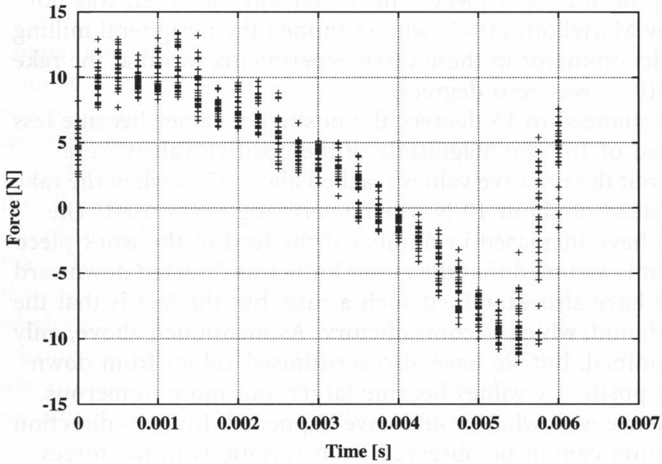


Fig. 12. Forces in x-direction versus time for up-milling with a rake angle of zero degrees

about + 15 N to about - 12 N, while the forces in the y-direction were located between zero and about - 95 N.

The thickness of the work piece was 19 mm, and hence the forces are less than about 50 N/cm. Kollman and Côté (1984) show that values from - 2 to 8 kp/cm result when cutting in birch, and these values correspond well with the ones found here.

Up to now we have only shown values from cutting a MDF and a polymer. The reason for doing this was that such materials were supposed to be homogeneous compared to real wood. Experiments were also conducted with beech and pine and the next section shows values from those experiments.

## Case study number two

When cutting beech the forces for the Y-direction varied from - 60 to about 100 N, and a wavy pattern was discernable. Between the levels - 20 up to 20 N,

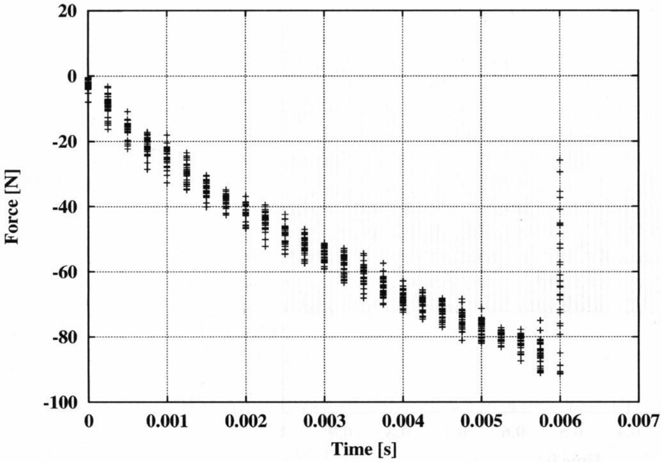


**Fig. 13.** Forces in y-direction versus time for up-milling with a rake angle of zero degrees



however, the values were scattered in a more even distribution. The experiment showed up-milling with a rake angle of zero degrees but with a revolution speed of 5000 rpm, or about 83 incisions each second. Unfortunately, these did not show up in an easily recognisable pattern. Once again a closer study had to be performed. It is likely that the maximum values emanated from periods when the cutter knife operated in the wood. The first such high values showed up after 0.00950 s, the second time after 0.02050 s and the third time after 0.03150 s, or each 0.011 second. Only four consecutive readings have increasing values and each chip was, therefore, actually cut during about 0.00075 s. The computer filter which was elaborated for cutting plastic was then applied on the values valid for beech. Note that, this time, the y-values were positive due to another orientation of the load cell. The result is shown in Fig. 14, which should be compared with Fig. 8.

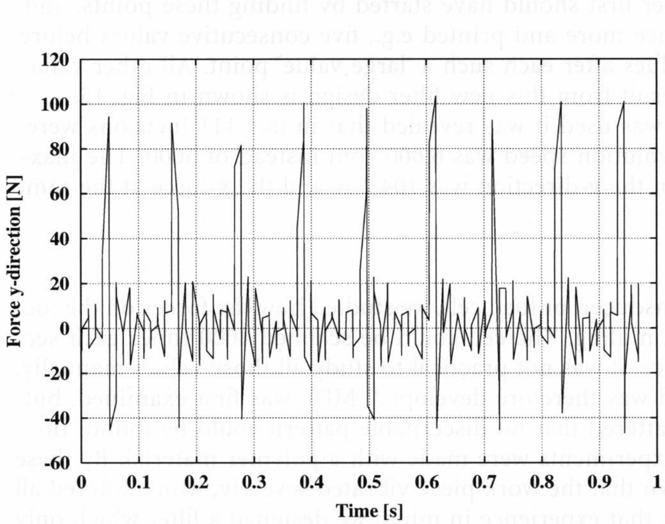


**Fig. 14.** Forces in y-direction versus time for up-milling with a rake angle of zero degrees in beech. Filter no. 1 applied.

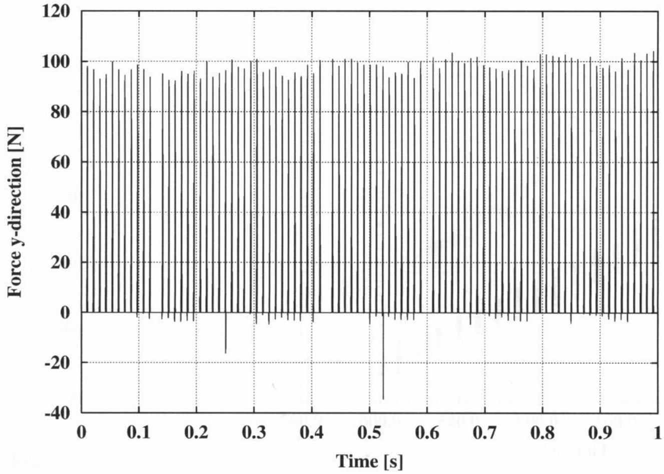


**Fig. 15.** Forces in y-direction versus time for up-milling with a rake angle of zero degrees in beech; filter no. 2 applied

The figures show that the filter did not work well in this case. It was mentioned previously that the revolution speed of the cutter head was 5000 rpm, which implies that one revolution takes 0.012 s. If the values in the data file are scrutinised, it is obvious that the vibrations in the work piece have a larger amplitude. The filter tried first to find a point where the vector sum of the x-and y-forces were less than 1 N. Unfortunately, such values did not exist before the first incision in the beech data file, and therefore the first occasion after 0.00950 s was missed (see Fig. 14). Another strategy had to be chosen. In the end of each incision both forces in the x and y directions were positive and larger than 10 and 90 N, respectively, compare with Figs. 6 and 7; note, once again, that the transducer placement was changed. The signs of the forces are therefore different. This fact implies that the filter first should have started by finding these points, and then scanned the file once more and printed e.g., five consecutive values before and two consecutive values after each such a 'large value' point. All other values were set to zero. The result from this new filter design is shown in Fig. 15.

When the new filter was used it was revealed that in fact 111 incisions were made and hence the revolution speed was 6,600 rpm instead of 5000. The maximum force registered in the y-direction was 104.2 N and the x-force at the same occasion 8.7 N.

## Conclusion

By use of a so-called transducer, or load cell, we studied how the forces on the tool varied under peripheral milling. The cell could be scanned 4000 times each second by a computer; hence, it was not practical to study all those values manually. A computerised method was therefore developed. MDF was first examined, but the readings were so scattered that no discernable pattern could be found. Instead, slow revolution experiments were made with a polymer material. By these experiments it was shown that the work piece vibrated severely, which littered all readings. However, with that experience in mind, we designed a filter which only printed the useful registrations and set all others to zero. For beech it was found that forces in the feed direction of the magnitude 50 N/cm were applicable for up-milling and with a rake angle of zero degrees. Forces also occured in the transverse direction of about 5 N/cm and these also changed signs during each incision. This behaviour could not, however, be explained fully.

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