# CUTTER-HEAD FORCES AND LOAD CELL SCANNING

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## Abstract

Among the machinery in wood manufacturing industries routers and planers are most commonly used. The tool, which many times is mounted on a metal cylinder, actually operates only under a very short moment, i. e. when the chip is cut from the 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. An number of knives are mounted on the cutter which ascertain that the planed surface will become sufficiently plane and does not show too a wavy pattern. This works fine for high revolution, and low feeding, speeds even if problems sometimes occur. The factory, however, naturally wants to increase the overall manufacturing speed and at the same time more defects are introduced at the planed surface. These defects are the result of the cutting process and in this paper it is examined, by use of a load cell, how the cutting forces vary during the formation of the wood chip. Wood is not an isotropic material and knots and other anomalies will make the evaluation harder. In order to simplify the conditions experiments are also shown from cutting in a plastic polymer material, and medium density fibre board, MDF. It is shown that the work piece is set into severe vibration which litter all output data from the cell. Experience from the experiments made it possible to design a computerised filter which saved only those registrations which are of interest while the others are 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 sign and had a magnitude of about 5 N/cm.

## Introduction

When furniture and other products are manufactured on an industrial level machining is necessary both for speeding up the process and for quality reasons. 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 have been examined since many years and in e.g. [1] references are shown which are now 70 years old. Defects at the planed surface must emanate from the actual cutting of the wood and hence it must be important to study the movement of one knife in operation. Consider firstly Figure 1. Using ordinary trigonometry for the circle shows us the values for $x$

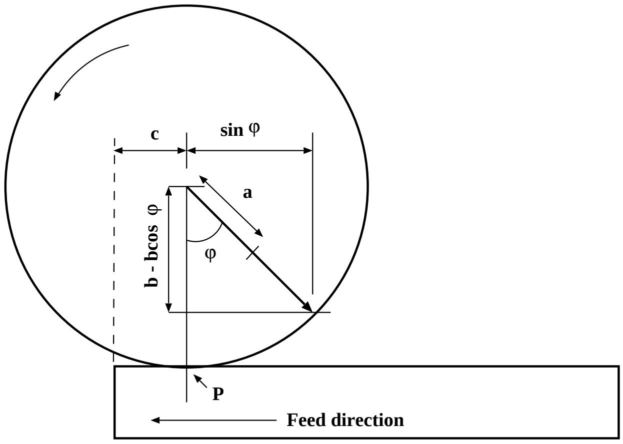


Figure 1: Peripheral milling geometry.

in the horisontal direction and $y$ in the vertical ditto. Note that they start in the point $P$. The work piece is fed into the machine with the assumed speed of $f$. After a time $t$ the piece has travelled the distance $ft$ which is called $c$ in Figure 1. $c$ corresponds to a certain length along the periphery of a much smaller circle which radius is set to $a$ and, hence, $c$ equals $a\varphi$. The co-ordinates $x$ and $y$ can therefore be expressed as:

$$x = a\varphi + b\sin\varphi \tag{1}$$
$$y = b - b\cos\varphi \tag{2}$$

The cutter-head rotates with the speed $n$ and one revolution therefore takes the time $1/n$. After that time the work piece has travelled the distance $f/n$. Hence:

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

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

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

Another common approach is to assume that the cutter is transported by use of a pineon, see e.g. [2] p. 114. The equations 1 to 4 have been put into a small LINUX C-program and values been generated for $0 \leq \varphi \leq 4\pi$, see Figure 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 Figure 2 the tools moves in a cycloid,

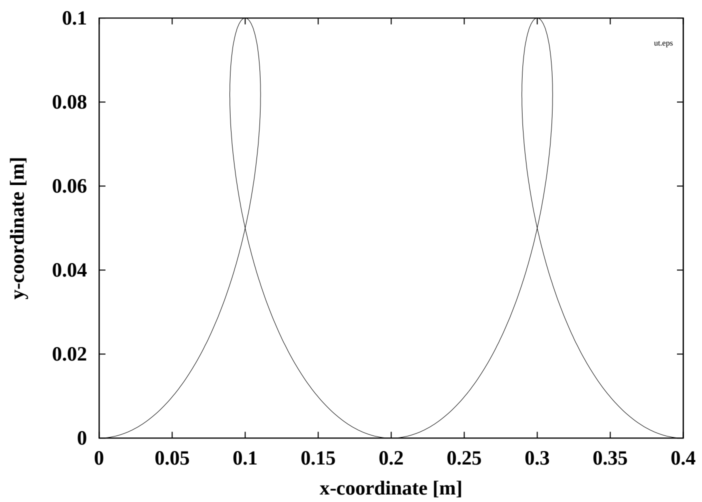


Figure 2: The cycloide movement of the peripheral cutter-head tool

or trochoid, pattern. According to [3], p. 371, at least four types of such curves can be elaborated depending on the rate between $a$ and $b$. Further, the curves will look different depending on the basis of the co-ordinate system and the direction of the rotating cutter-head. Therefore, there are certain differences between the mathematical expressions in e.g. Refs. [1] and [4]. The knife clamped to the cutter-head will cut a wood chip from the work piece. The formation of this wood chip has also been shown in [1] p. 518 and the details shown in Figure 3 were found there. One important factor, when the chip formation is to be examined, is the feed for each cut of the knife, $e$. If the number of cutting-edges is $i$ 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 close detail and it should therefore be an interesting task to compare the mathematical expressions with real measurements from the cutting process.

## The load cell and scanning process

When the basis for the cutter-head movement was developed only small possibilities existed in examining the process in detail under realistic planing

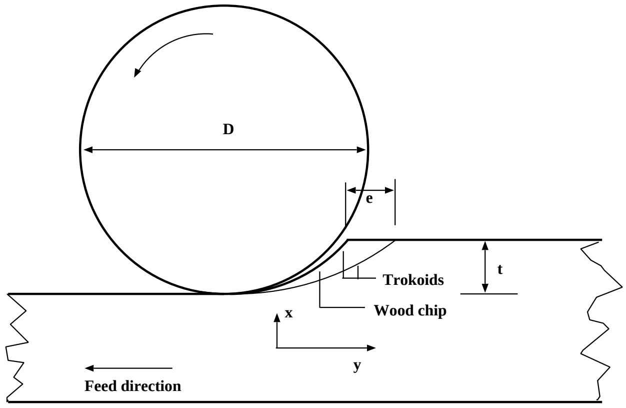


Figure 3: The formation of a wooden chip

or routing conditions. The introduction of computers, fast scanning devices and probes have decreased these calamaties, see e.g. [5] for a recent study. We have 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 communicates with a so called ISA card installed in an ordinary personal computer. A computer program, also written in C, collects the readings and stores them in an ordinary text file. In this case 4000 consecutive readings were stored in each experiment. In Table 1 the first 20 readings are shown in one of our first experiments. The computer program scans the ISA

| 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 |

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

card at 4000 Hz and saves 4000 values so each data file contains 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, changes sign and grows again from 2.0 up to

19.0 N. The forces in th y - direction show the same pattern, i.e. the forces fluctuate fastly from the positive to the negative direction and the same applies for the z registrations. Note that, because of the scanning speed, just 0.00025 s passes 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 remain unshown, it might however dwelve other data in the file which makes it easier to explain the situation. It is not suitable to show all these values in a table but all those valid for the y-direction are depicted in Figure 4 showing the force as a function ot time.

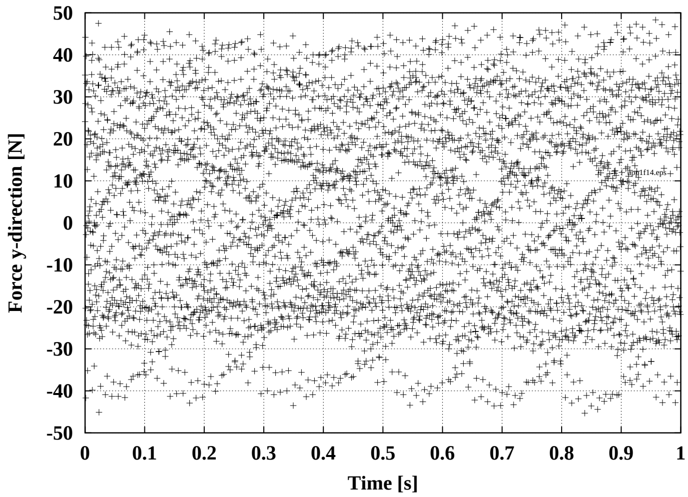


Figure 4: Registered forces when cutting in MDF in the y-direction during one second.

From Figure 4 it is obvious that the y-forces have 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 medium density fibre board, MDF. Such material is mostly used in the form of large boards when tables, doors and other such furniture are to be manufactured. The board consists of wood fibres, not chips, which are glued together by so called dry pressing, see e.g. [6] p. 465 for a more detailed description of the manufacturing process. The reason for choosing MDF was that we assumed this material to have a high degree of homogenity compared to ordinary wood. The authors to [7] also reported sucessfull experiments from cutting in MDF. From the discouraging result in Figure 4 it is obvious that we had to start cutting more slowly and in a material of even higher homogenity.

## Case study number one

Above it was shown that MDF probably is too an inhomogenous material for evaluation purposes in an initial state and that a slower revolution speed must be used. We have therefore chosen to cut slowly in a plastic material. The speed of the rotating milling cutter was now set to 600 rpm and one revolution therefore will take about 0.1 s. Even if this is a short time there should be about 400 readings during one revolution which seemed to be sufficient. In Figure 5 the y - registrations are shown as a function of time. Now it was

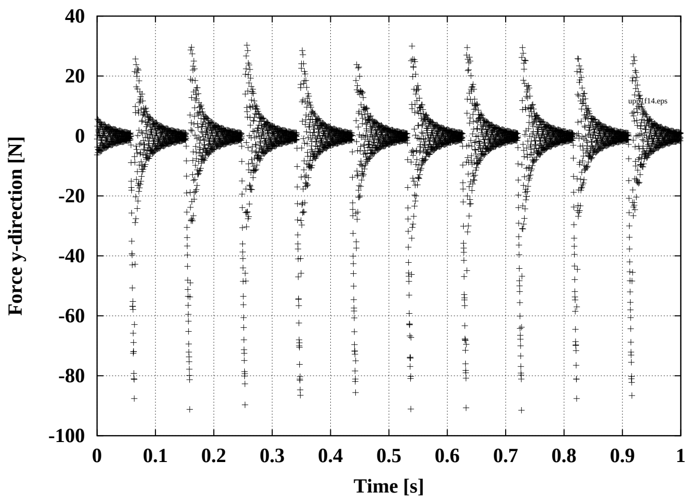


Figure 5: Registered forces in N in the y-direction for a polymer plastic material. Speed 600 rpm.

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 is 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 sets the work piece into vibration and that the amplitude of these vibrations decline until a new impact is made. This explains the discouraging result in Figure 4 and it is plausible that the useful registrations were covered by vibrational litter. However, the registrations shown in Figure 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 precice 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 Figure 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 shows that the force varies between positive and negative values in the range of - 1 to + 1 N. The amplitude, however, decreases until about 0.05 seconds have passed when the force increases to about 10 N. A number of readings are after this positive but for 0.06 s the force turns negative. The same study has been

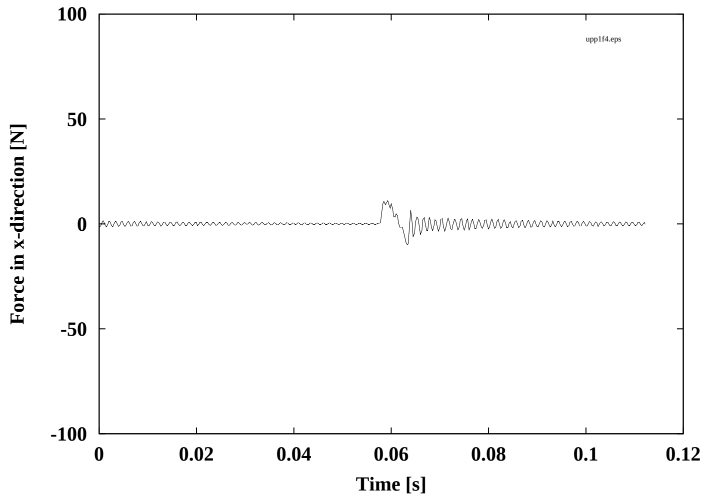


Figure 6: Registered forces N in x - direction for the first revolution in case study one.

elaborated for the y - direction which is found in Figure 7. Here, forces of the same magnitudes are likewise found up to about 0.05 s when the force turns negative and increases to a value of about 90 N. In the z - direction a similar pattern have been found but the values after the impact are 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 emerge in the z - direction. From the Figures 6 to 7 it is obvious that the moment when the tool grips into the work piece can be decided upon with high accuracy. The problem will be to find the moment when the tip of the tool no longer cuts anything and the force readings only emanate from vibrations in the experimental setup. Because of the high scanning rate and the possibility to see exactly when the tool hits the work piece surface we were able to calculate the average time gap between two knifw 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 Figure 3 equals 0.002 m, $b$ equals 0.03 m and $\varphi$ will become 21.04 degrees. Each cut will, hence, take 0.0055 s which in turn results in 22 scanned registrations. It has therefore been possible to implement a filter in a new LINUX C-program which starts to print values to a file when the difference between two registrations are large and then stops writing when the tool must have been above the work piece,

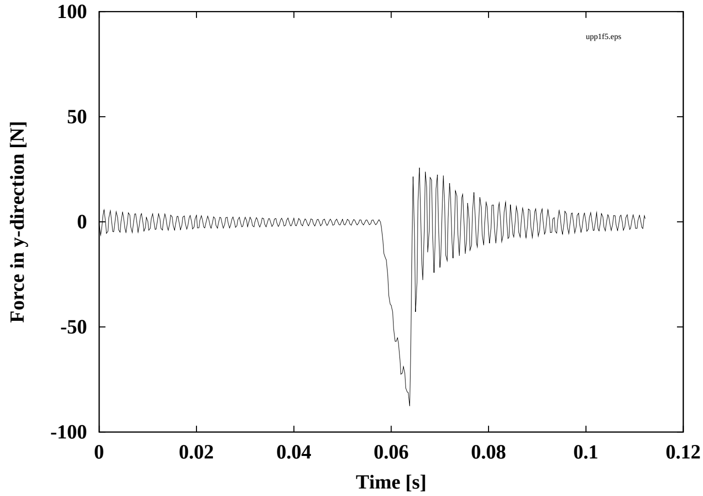


Figure 7: Registered forces N in y-direction for the first revolution in case study one.

see Figure 8. The forces in the y - direction are about ten times larger than those in the x - direction. Interesting to note is that the x - values are positive in the beginning of the incision while they are negative in the end. The reason for such a behaviour might depend on conditions described in [4]. Because of the feed in the x - direction the tool could have moved downward into the work piece and not tangentially which is assumed in Figure 3. In order to examine this the equations 1 and 2 must be depicted in close 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 the equations 1 and 2 have now been used used in order to draw Figure 9. In Figure 9 the curve is shown for three consecutive revolutions and it is obvious that the tool must start the incision in almost a tangential direction, and the possible explanation above seems therefore not to be applicable. 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 is directed into the work piece the overwhelming part of the cut should result in forces directed in the opposite direction. During each second ten chips are cut, and further, three experiments with identical conditions have been elaborated. Hence it is possible scrutinize thirty incision experiments. These are not shown here but they all point to the same facts, that about 15 values are positive in the start of each cut and then the rest show negative, or small positive values. One other solution to this calamity 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 in [4] where peripheral milling of brass was

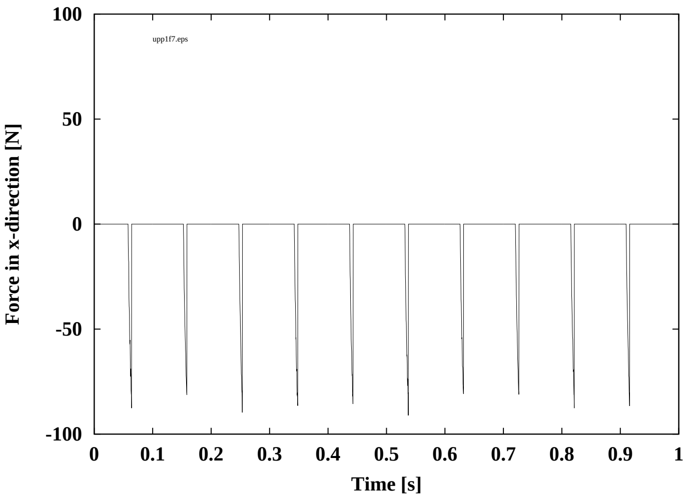


Figure 8: Registered forces N in y - direction during 1 s with filter applied.

examined. One common denominator in these three experiments was that the rake or hook angle, see Figure 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 are approximately the same but the negative values reach up to about 17 N when the rake angle is 15 degrees instead of about 10 N when a zero angle is used. The positive x - values should increase in number if the feed of the work piece is increased, at least if it is assumed that the cutter knife is directed downward for a short moment. We have also examined such a case but the fact is that the opposite behaviour was found which contradicts this. Above, only upmilling has been examined but we have also scrutinized values from downmilling. Fortunately, the positive x-values now became larger and more numerous which are in correspondence with what should happen. 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 is used. According to theories found in [8] the forces will now try to pull on the work piece instead of pushing on it as is natural when upmilling. It is obvious that we must 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. In Figure 11 this has been done 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 Figures 12 and 13 the monitored forces are shown versus the time passed after the first detected impact. Note that the forces are scanned in discrete steps and hence it is not possible to know exactly where the cutter head was

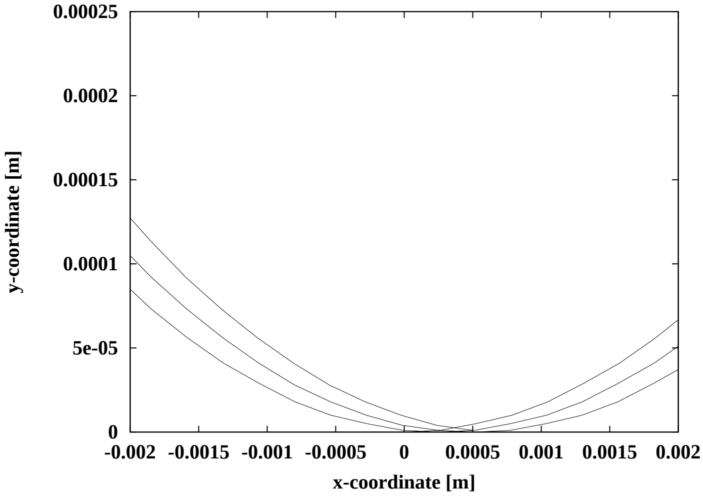


Figure 9: Part of the trochoid curve for $\varphi = 6\pi$

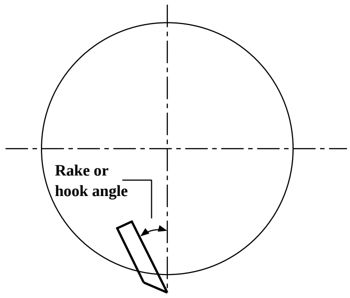


Figure 10: Rake or hook angle for a cutter knife.

located. In the computer filter it is assumed that the tool has left the work piece 0.06 s after the moment when impact was detected. Above it was mentioned that each incision had a duration of 0.056 s and therefore a few values are not stuck in the computer filter. The forces in the x - direction, i.e. perpendicular to the feed direction varied from 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. In [1] p. 519 values from -2 to 8 kp/cm are shown when cutting in birch wood and they therefore correspond well with the ones found here.
Up to now we have only shown values from cutting in a MDF and a polymer. The reason for doing this was that such materials were supposed to be homogenuous compared to real wood. Experiments have also been elaborated when cutting in beech and pine and the next case shows values from those

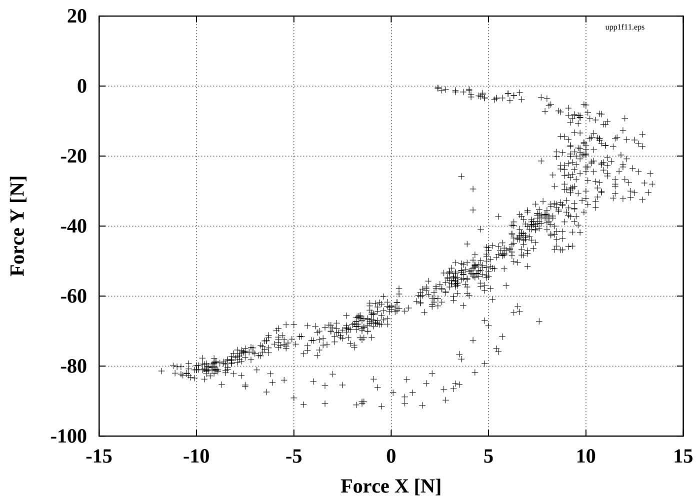


Figure 11: Forces in x - and y - directions for up-milling with a rake angle of zero degrees

experiments.

## Case study number two

When cutting in beech the forces for the Y-direction varied between - 60 up to about 100 N and a wavy pattern was discernable. Between the levels - 20 up to 20 N, however, the values were scattered in a more even distribution. The experiment showed upmilling 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 easy recognizable pattern. Once again a closer study had to be be performed of the data file. It is likely that the maximum values emanate from periods when the cutter knife operates 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 is, therefore, actually cut during about 0.00075 s. The computer filter which was elaborated for cutting in plastic was now applied on the values valid for beech. Note that, this time, the y - values are positive due to another orientation of the load cell. The result is shown in Figure 14, which should be compared with Figure 8. The figures show that the filter not worked well in this case. Above it was mentioned 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 scrutinized it is obvious that the vibrations in the work piece have a larger amplitude. The filter tries first to find a point where the vector sum of the x - and y - forces are less than 1 N. Unfortunately, such values did not

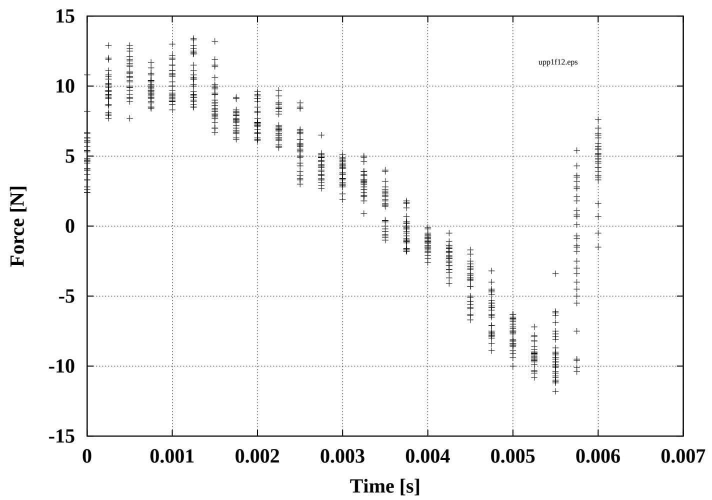


Figure 12: Forces in x - direction versus time for up-milling with a rake angle of zero degrees

exist before the first incision in the beech data file and therefore the first occasion after 0.00950 s was missed, see Figure 14. Another strategy must 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 Figures 6 and 7 and 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 start by finding these points and then scan the file once more and print e.g. five consecutive values before and two after each such "large value" point. All other values are set to zero. The result from this new filter design is shown in Figure 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.

## Conclusions

By use of a so called transducer, or load cell, it has been studied how the forces on the tool vary under peripheral milling. The cell could be scanned 4000 times each second by a computer and hence it was not practical to study all these values manually. A computerised method was therefore developed. First the material medium density fibre board, MDF, was examined but the readings were so scattered that no dicernable pattern could be found. Instead, slow revolution experiments were made in a polymer material. By these experiments it was shown that the work piece was set into severe vibration which littered all readings. However, by use of that experience it was possible

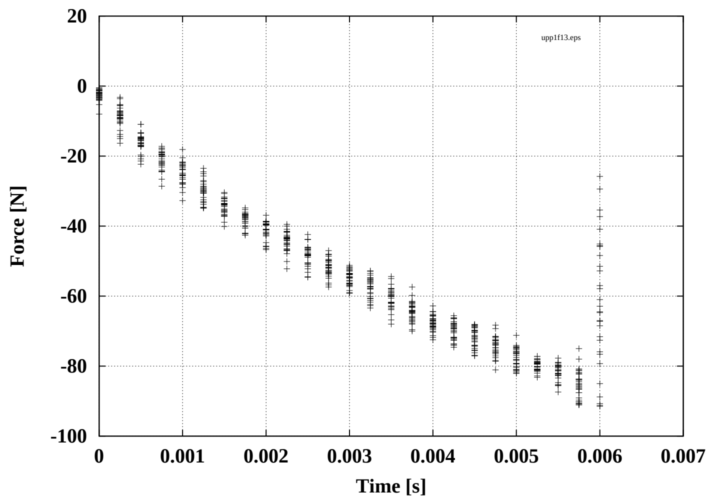


Figure 13: Force in y - direction versus time for up-milling with a rake angle of zero degrees

to design a filter which only printed the useful registrations and set all other to zero. For the species beech it was found that forces in the feed direction of the magnitude 50 N/cm were applicable for upmilling and with a rake angle of zero degrees. Forces also occured in the transverse direction of about 5 N/cm and these also changed sign during each incision. This behaviour could, however, not be explained to full satisfaction.


## Acknowledgement

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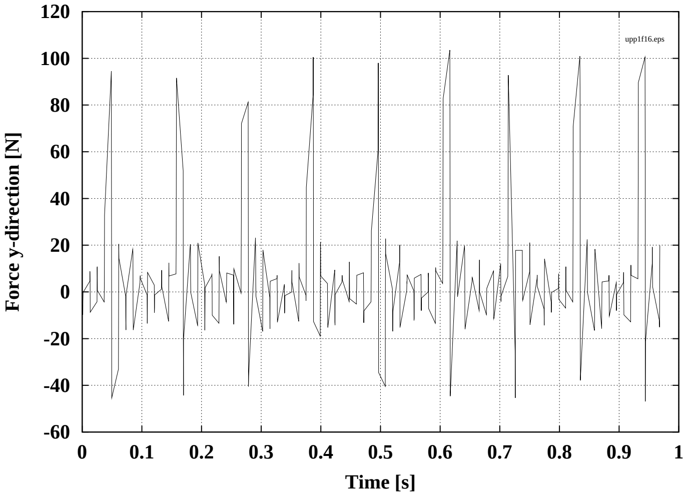


Figure 14: Force in y - direction versus time for up-milling with a rake angle of zero degrees in beech. Filter no. 1 applied.

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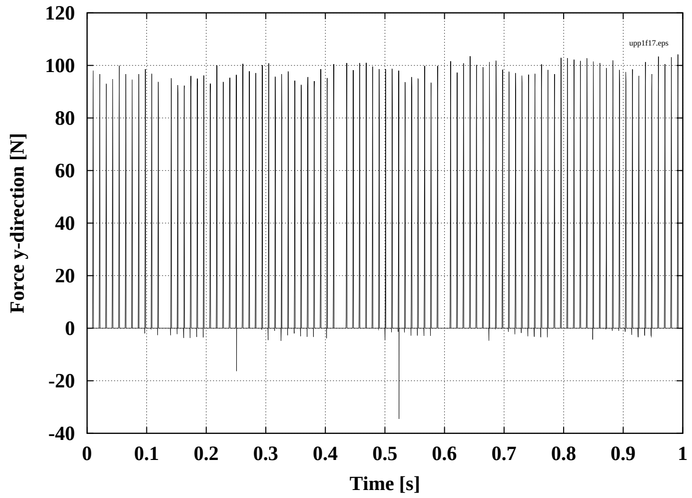


Figure 15: Force in y - direction versus time for up-milling with a rake angle of zero degrees in beech. Filter no. 2 applied.