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Cauwenberg, J.W.G.; Hijink, J.A.W.; van de Molengraft, G.J.G.

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Measurements on the dynamic behaviour of modular milling tools

J.W.G. Cauwenberg, Ir. J.A.W. Hijink
G.J.G. van de Molengraft

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SUMMARY
To compare newly designed modular tooling—systems, a number of these systems have been used in order to compare the dynamic behaviour. The tools were measured dynamically, and three different cutting tests were performed. As a result of these tests a certain correlation between dynamic flexibility and cutting performance could be found.

1. INTRODUCTION
In modern production, flexibility is an important topic. In order to obtain a flexible production system, the tooling of the manufacturing cells must be extensive and easy to change [1]. Especially for the less used diameters and greater depths it is not useful, and expensive, to keep special tools in stock. In these cases the use of a modular tooling system is customary. Out of a great number of components a tool can be composed.

One can distinguish two clamping and locking systems in the available modular tooling systems, the central— and the radial—approachable systems. The disadvantage of a central—approachable clamping system is the fact that one has to take apart the complete tool in order to mount a new tool—head on the tool or to lengthen or shorten the tool. In the past years several new systems, in which the parts individually can be mounted or demounted, have been developed. Most of these systems have radial— approachable clamping devices.

The question arises which of the systems to choose for a flexible machining system and/or the workshop. Next items are of interest in the process of selection:
- availability,
- number of different elements/tools,
- ease of assembly,
- reproductiveness,
- stiffness,
- dynamic stability,
- price.

Of these items the aspect of dynamic stability is important [2]. It is dealt with in this report.

2. SELECTION OF THE MODULAR TOOLING SYSTEMS
The machines we have the tooling systems selected for, are CNC machining centres with ISO—taper 40. For most modular tooling systems, the standard system diameter D = 50 mm. With \( l_{\text{max}} = 6 \times D \) the maximum tooling length becomes about 300 mm. For a number of machining centres, this length even was exceeding the allowable length in the magazine. Because of the more often use of a smaller length, it was decided to do dynamic measurements for a tool—length of 200 mm. Due to interests and availability, the makes noted in Table 1 were selected, and the
Measurements on the dynamic behaviour of modular milling tools

Figure 1. Dynamic Flexibility of Modular Tools [3]
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<table>
<thead>
<tr>
<th>System</th>
<th>Make</th>
<th>Clamping principle</th>
<th>diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>URMA</td>
<td>axial - symmetric</td>
<td>55</td>
<td></td>
</tr>
<tr>
<td>ABS</td>
<td>radial - symmetric</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>Flexibore</td>
<td>radial - symmetric</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>Modulock</td>
<td>radial - symmetric</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>Varilock</td>
<td>radial - symmetric</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>Variobore</td>
<td>radial - symmetric</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>Widaflex</td>
<td>radial - symmetric</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>GM 300</td>
<td>radial - symmetric</td>
<td>50</td>
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<tr>
<td>CKB</td>
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<td>50</td>
<td></td>
</tr>
<tr>
<td>Multibore</td>
<td>radial - asymmetric</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>MBM</td>
<td>radial - asymmetric</td>
<td>55</td>
<td></td>
</tr>
</tbody>
</table>

Table 1. The available tooling systems

necessary parts were put at our disposal by the manufacturers. For all of these systems, it is possible to mount and dismount all of the assembly parts separately.

In a preliminary research [3] a number of tools was measured dynamically by exciting the tools in a radial direction. In order to avoid any influence of the stiffness of the machine-headspindle, a special test-rig was used. The dynamic flexibility found for a tool length of approximately 200 mm was varying from 1.1 to 2.2 \( \mu \text{m}/\text{N} \), with one bad exception of 5 \( \mu \text{m}/\text{N} \). When elongating the tools to a length of approximately 300 mm the dynamic flexibility was much more scattering and varies from 3.6 to 12.0 \( \mu \text{m}/\text{N} \). In Figure 1 the results of these measurements are shown. Because of the different lengths and mass distributions, the flexibility is shown as a function of \( \Sigma(l*M) \), where \( l \) is the distance to the centre of gravity and \( M \) is the mass of each part.

Examining the modal analysis results, one could conclude that especially the damping and the stiffness of the cone have a dominant influence on the results. To examine the tools, with a composed tool-length of about 200 mm, under cutting conditions [4], three different cutting tests were performed.

These cutting tests are:
- Longitudinal cutting with a 4-cutter end mill in a Weldon-holder,
- Rough boring with a two-cutter boringhead,
- Finishing with a single cutter in a two-cutter boringhead.
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TOOL WITH WELDON-HOLDER

TOOL WITH TWO-CUTTER BORINGHEAD

Figure 2. The two types of modular tools used for the cutting tests

Figure 3. The measurement setup
For the available tools it was not possible to carry out the measurements with all the makes, and with an exact length of 200 mm. To publish the results, the tools were (randomly) given a number for the Weldon-holder. For the two-cutter boringhead the numbers were raised up with 10. In the following list the tool numbers and the tool length according to Figure 2 are given.

<table>
<thead>
<tr>
<th>Tool number (Weldon)</th>
<th>Length (mm)</th>
<th>Tool number (Two-cutter)</th>
<th>Length (mm)</th>
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<tbody>
<tr>
<td>1</td>
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<td>11</td>
<td>230</td>
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<tr>
<td>2</td>
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<td></td>
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<td>210</td>
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</tbody>
</table>

Table 2. The tool numbers with their length

3. MEASUREMENT SETUP

As a result of the cutting process, the accuracy and the roughness of the cut is very important. But when comparing tools it is not sufficient to measure only the roughness of the cut, also the cutting forces and the movements of workpiece and tool play an important role. To carry out the measurements, a Kistler dynamometer (type 9265 A) was mounted on a T-plate. A special plate was attached to the dynamometer in order to mount the block-type workpieces. To control the movements of the workpieces three accelerometers were fixed on the top plate of the dynamometer (see Figure 3).

The movements of the tool can not be measured directly, but two accelerometers (in the X- and Y-direction) were fixed on the Z-carriage as close to the head spindle as possible. To collect the measuring data, an 8-channel data acquisition system (HP 3566 A) was used. In this way the cutting data could be analysed in the time and frequency domain. The workpiece material used is C45, and the dimensions of the workpiece amount 97*97*60 mm.
<table>
<thead>
<tr>
<th>Tool</th>
<th>Ref.</th>
<th>Tool 1</th>
<th>Tool 2</th>
<th>Tool 3</th>
<th>Tool 4</th>
<th>Tool 5</th>
<th>Tool 6</th>
<th>Tool 7</th>
<th>Tool 8</th>
<th>Tool 9</th>
<th>Tool 10</th>
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</thead>
<tbody>
<tr>
<td>X-Y</td>
<td>1392</td>
<td>438</td>
<td>490</td>
<td>484</td>
<td>492</td>
<td>420</td>
<td>438</td>
<td>490</td>
<td>482</td>
<td>410</td>
<td>362</td>
</tr>
<tr>
<td>Y-Z</td>
<td>1392</td>
<td>484</td>
<td>464</td>
<td>470</td>
<td>496</td>
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<td>450</td>
<td>520</td>
<td>494</td>
<td>407</td>
<td>355</td>
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<tr>
<td>Y-X</td>
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<td>2.37</td>
<td>2.85</td>
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<td>2.69</td>
<td>3.45</td>
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<td>1.96</td>
<td>4.70</td>
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<tr>
<td>Y-Y</td>
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<td>2.67</td>
<td>2.37</td>
<td>2.85</td>
<td>2.85</td>
<td>2.85</td>
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<td>2.85</td>
<td>2.85</td>
<td></td>
</tr>
</tbody>
</table>

Table 3. Results for the cutting tests performed with the end mill.
4. END MILL CUTTING USING A WELDON—HOLDER

Although not primarily designed to cut in radial direction, sometimes it is necessary to use modular tools to cut in a longitudinal direction, for example with an end mill. For the dynamic behaviour of long tools this will be the worst case of using the tool.

As in the primary research the tools 1–10 were measured dynamically, but now in the head spindle of the machining centre (MAHO MC50). These measurements were carried out in the X— and Y—direction. In appendix 1 for a number of tools typical examples of the measured transfer functions in the X— and Y—direction are given in the Figures A1.1 and A1.2. For all the tools, differences were measured as well for the resonance frequency as for the dynamic flexibility. These values are listed in the upper part of Table 3.

For the cutting tests, a 4—cutter end mill (Vallorbe, F—1405, HSSCo8—M42) with a diameter of 16 mm was used. To determine the cutting conditions test runs with a short (60 mm) tool holder, called the reference tool, were carried out. For up— as well as for down—milling, the following cutting conditions could be used: cutting speed 24 m/min, feed per cutting—edge 0.06 mm, cutting depth 24 mm and a width of cut of 2.4 mm. In this way the stability of the measurement setup was proven to be satisfactory.

Due to chatter, cutting with a 200 mm modular tool holder under these conditions was impossible, therefore the following cutting conditions were used for the experiments: speed 24 m/min, depth of cut 10 mm, width of cut 1 mm, and a feed per cutting—edge of 0.03, 0.04 and 0.05 mm respectively.

In Appendix 2 the measured results for tool 2 and down—milling with a feed of 0.03 mm are shown. In Figure A2.1 the cutting forces are represented. The power—spectrum of the accelerations of the dynamometer and the Z—carriage are presented in the figures A2.2 and A2.3.

To present the results, the resultant cutting force was calculated. Because the cutting was performed in the Y—direction (downward), especially the acceleration of the dynamometer and the Z—carriage in Y—direction were used to compare the different tools.

The results for some tools and different cutting conditions are presented in Appendix 2.

From all the cuts the roughness value Rₐ was measured at different positions of every cut.

In Table 3 the results are compiled for all the measurements carried out. From this table one can make the following general conclusions:

- The mean frequency of the dynamometer and Z—carriage is higher than the resonance frequency of the tool when down—milling and is equal to this resonance frequency when up—milling.
- The accelerations and the resultant force are lower when down—milling.
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<table>
<thead>
<tr>
<th>Tool</th>
<th>Tool 11</th>
<th>Tool 12</th>
<th>Tool 13</th>
<th>Tool 14</th>
<th>Tool 15</th>
<th>Tool 16</th>
<th>Tool 17</th>
<th>Tool 18</th>
<th>Tool 19</th>
<th>Tool 20</th>
<th>Tool 21</th>
<th>Tool 22</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed (um/rev)</td>
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<td>320</td>
<td>54</td>
<td>47</td>
<td>31</td>
<td>359</td>
<td>175</td>
<td>68</td>
<td>57</td>
<td>84</td>
<td>53</td>
<td>34</td>
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<tr>
<td>Dynamic Force Fx (N)</td>
<td>0.3</td>
<td>438</td>
<td>33</td>
<td>37</td>
<td>51</td>
<td>402</td>
<td>176</td>
<td>35</td>
<td>69</td>
<td>75</td>
<td>56</td>
<td>48</td>
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<tr>
<td>Dynamic Force Fy (N)</td>
<td>0.4</td>
<td>680</td>
<td>25</td>
<td>38</td>
<td>50</td>
<td>414</td>
<td>143</td>
<td>23</td>
<td>76</td>
<td>70</td>
<td>58</td>
<td>49</td>
</tr>
<tr>
<td>Dynamic Force Fz (N)</td>
<td>0.2</td>
<td>343</td>
<td>55</td>
<td>47</td>
<td>32</td>
<td>366</td>
<td>181</td>
<td>71</td>
<td>59</td>
<td>65</td>
<td>55</td>
<td>35</td>
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<tr>
<td>Dynamic Force Fy (N)</td>
<td>0.3</td>
<td>453</td>
<td>33</td>
<td>38</td>
<td>53</td>
<td>408</td>
<td>182</td>
<td>36</td>
<td>71</td>
<td>75</td>
<td>57</td>
<td>50</td>
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<tr>
<td>Dynamic Force Fz (N)</td>
<td>0.4</td>
<td>700</td>
<td>25</td>
<td>38</td>
<td>52</td>
<td>422</td>
<td>147</td>
<td>25</td>
<td>79</td>
<td>70</td>
<td>60</td>
<td>51</td>
</tr>
</tbody>
</table>

Table 4. Results for the cutting tests performed with a two—cutter boring head

<table>
<thead>
<tr>
<th>Tool</th>
<th>Tool 11</th>
<th>Tool 12</th>
<th>Tool 13</th>
<th>Tool 14</th>
<th>Tool 15</th>
<th>Tool 16</th>
<th>Tool 17</th>
<th>Tool 18</th>
<th>Tool 19</th>
<th>Tool 20</th>
<th>Tool 21</th>
<th>Tool 22</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed (um/rev)</td>
<td>0.2</td>
<td>1010</td>
<td>1070</td>
<td>770</td>
<td>710</td>
<td>1030</td>
<td>1693</td>
<td>1110</td>
<td>1040</td>
<td>1110</td>
<td>1270</td>
<td>1024</td>
</tr>
<tr>
<td>Dynamic Force Fx (N)</td>
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<td>1450</td>
<td>1270</td>
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<td>1675</td>
<td>2241</td>
<td>2370</td>
<td>1334</td>
<td>1720</td>
<td>2030</td>
<td>1468</td>
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<tr>
<td>Dynamic Force Fz (N)</td>
<td>0.2</td>
<td>6.0</td>
<td>2.1</td>
<td>1.1</td>
<td>3.6</td>
<td>6.7</td>
<td>2.6</td>
<td>1.7</td>
<td>9.2</td>
<td>6.4</td>
<td>4.0</td>
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<td>Dynamic Force Fy (N)</td>
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<td>7.8</td>
<td>3.3</td>
<td>1.3</td>
<td>5.6</td>
<td>6.0</td>
<td>3.9</td>
<td>2.5</td>
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<td>Dynamic Force Fz (N)</td>
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<td>3.4</td>
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<td>2.7</td>
<td>2.2</td>
<td>9.1</td>
<td>5.3</td>
</tr>
</tbody>
</table>

Table 5. Results for the cutting tests performed with a single cutter in a two—cutter boring head

-8-

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- The roughness values are lower for up-milling.
- A correlation between accelerations, resultant force and roughness can hardly be found.
- For up-milling there is a reasonable correlation between the flexibility of the tool and the roughness, for down-milling this correlation can not be found.

The differences between the tools are considerable, when comparing the tools the numbers 2, 7 and 4 do give the best results.

5. BORING WITH A TWO-CUTTER BORING HEAD

For this test we have chosen boring heads with an adjustable reach up to a diameter of 70 mm. Because of the different designs, it was not possible to use the same inserts for all the tools. Where available the same tool geometry (CCMT 120408) was used. A different tool geometry was used for the tools 15 (PDI-481204), 17 (TCMT16T308 UR), 19 (CNMG 120408C) and 21 (CCMT 120404).

The tests were performed with a cutting speed of 2 m/s and a width of cut of 3 mm. The starting diameter of 62 mm was machined on a lathe. Before boring, the position of the workpiece was justified with help of the measuring sensor of the machining centre. The feeds used were 0.2, 0.3 and 0.4 mm/revolution. Although the accelerations have been measured, the results of these measurements are not used to compare the tools because of irrelevancy.

In Appendix 3 the measurement results for some tools are given.

As can be seen in Table 4, the dynamic forces in X- and Y-direction and the thrust force in Z-direction are documented, as well as the roughness $R_a$ of the hole in length direction. For a feed of 0.2 mm, chatter occurred for the tools 11 and 19. From Table 4 it can be concluded that for the tools 11 and 15 the forces are abnormally high compared with the other tools, this resulting in a high roughness. For tool 21 the roughness is high, although the cutting forces are low, a somehow different tool-geometry can be the reason. When selecting the better tools for this operation one would prefer the tools 13, 12, 17 and 19.

6. FINISH-BORING WITH A SINGLE CUTTER IN A TWO-CUTTER BORING HEAD

In order to simulate the often used single-point finish-boring, the two-cutter boring heads were used with one insert adjusted for the finishing diameter (69 mm). The cutting was performed with a cutting-speed of 8.5 m/s and a feed of 0.07 mm. The width of cut was 0.1 mm. With exception of tool 19, inserts with the same cutting-edge geometry (Sandvic, TCMT 120404 UF CT515) are used for all the tools. As with rough-boring the accelerations were measured, but not used to compare the tools.

In Appendix 4 the cutting forces for some tools are given.
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<table>
<thead>
<tr>
<th></th>
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</tbody>
</table>

Table 6. Qualitative presentation of the dynamic– and cutting– tests
For these measurements only the dynamic force in X- and Y-direction and the roughness is documented in Table 5.

For the forces as well as for the roughness the results are very much alike for all the tools. Three tools, 11, 17 and 19, give bad results for the roughness. The tools 16 and 22 have a higher dynamic force, but this does not result in a higher roughness.

7. CONCLUSIONS

In order to compare the stability of modular tooling-systems, it is not sufficient to measure the tools with modal analysis techniques only. However, when comparing all the results, the tools with the better cutting test results (2+12, 3+13 and 8+18) also have the lowest flexibility.

In Table 6 the results of the dynamic measurements and the cutting tests are represented in a qualitative way.

There is a good correlation between the cutting test with the end mill and the boring-tools, maybe with exception of tool (7+17).

A relation between clamping principle and stability could not be established.

When comparing the new measurements with the preliminary results, it is surprising that these results are contradictory, because in the preliminary research the tools 1 and 5 did have the better measuring results.

Furthermore, one must realise that the dynamic stability of a tool is only one reason for choosing a tooling-system.

References


Appendix 1. The transferfunctions of tool 6 and 9

In order to have an impression of the dynamic stiffness of the tools, the tools were mounted in the head spindle of the machining centre, and excited with a puls by means of a small hammer. Two accelerometers (in X- and Y-direction) were mounted at the end of a dummy end mill.

The transfer functions of the tools are measured in the X- and Y-direction. The differences in the transfer function must be due to the dynamic behaviour of the Z-carriage in the mentioned directions.
Figure A1.1 The transfer functions of tool 6
Figure A1.2  The transfer functions of tool 9
Appendix 2. The test results of end mill cutting

During these tests 8 signals were recorded, the cutting forces in X−, Y− and Z−direction, the accelerations of the dynamometer in X−, Y− and Z−direction, and the accelerations of the Z−carriage in the X− and Y−direction.

It is not useful to present all the measurements in this paper, but for an impression the complete results for tool 2 for down milling with a feed of 0.03 mm are given in the figures A2.1, A2.2 and A2.3.

To compare the measurement for the tools it occurred that in particular the accelerations in the Y−direction, as well for the dynamometer as for the Z−carriage, and the calculated resultant cutting force were the most useful.

In the figures A2.4 – A2.17 the results are presented for the short reference tool and for the tools 1, 2, 3, 5, 8 and 9.

From these figures it can be seen that for a number of tools, the four cutting edges do not cut in the same order. For tool 9 for instance, only two cutting edges are cutting.
Figure A2.1 The cutting forces for tool 2, down-milling with a feed of 0.03 mm
Figure A2.2 The autopower spectrum of the accelerations of the dynamometer, tool 2, down-milling with a feed of 0.03 mm
Figure A2.3  The autopower spectrum of the accelerations of the Z–carriage, tool 2, down–milling with a feed of 0.03 mm
Figure A2.4  The measuring results for the short reference tool, down-milling with a feed of 0.05 mm
Figure A2.5 The measuring results for the short reference tool, up-milling with a feed of 0.05 mm
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Figure A2.6 The measuring results for tool 1, down-milling with a feed of 0.05 mm
Figure A2.7  The measuring results for tool 1, up-milling with a feed of 0.05 mm
Figure A2.8 The measuring results for tool 2, down-milling with a feed of 0.05 mm
Figure A2.9  The measuring results for tool 2, up-milling with a feed of 0.05 mm
Figure A2.10  The measuring results for tool 3, down—milling with a feed of 0.05 mm
Figure A2.11 The measuring results for tool 3, up-milling with a feed of 0.05 mm
Figure A2.12  The measuring results for tool 5, down-milling with a feed of 0.05 mm
Figure A2.13  The measuring results for tool 5, up-milling with a feed of 0.05 mm
Figure A2.14  The measuring results for tool 8, down-milling with a feed of 0.05 mm
Figure A2.15  The measuring results for tool 8, up-milling with a feed of 0.05 mm
Figure A2.16 The measuring results for tool 9, down—milling with a feed of 0.05 mm
Figure A2.17 The measuring results for tool 9, up-milling with a feed of 0.05 mm
Appendix 3. Some test results of boring with a two—cutter boring head

For the tools 11 and 12 all the measured results are given in the figures A3.1—A3.6. The accelerations of the dynamometer and the Z—carriage are low, and therefore not used to compare the tools.
Figure A3.1  The cutting forces for tool 11
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Figure A3.2 The autopower spectrum of the accelerations of the dynamometer
Figure A3.3 The autopower spectrum of the accelerations of the Z-carriage
Figure A3.4 The cutting forces for tool 12
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Figure A3.5 The autopower spectrum of the accelerations of the dynamometer
Figure A3.6  The autopower spectrum of the accelerations of the Z-carriage
Appendix 4. Some test results of finish-boring with a two-cutter boring head

The results for finish-boring are confusing, a relation between cutting forces and the measured roughness does not exist. For the tools 11, 12, 17, 18 and 22 the cutting forces are given in the figures A4.1-A4.5. Together with table 5 one can see that high dynamic forces do not always give a high roughness.
Figure A4.1 The cutting forces for tool 11
Figure A4.2  The cutting forces for tool 12
Figure A4.3 The cutting forces for tool 17
Figure A4.4 The cutting forces for tool 18
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Appendix 4

Figure A5.5 The cutting forces for tool 22