Analysing the influence of a radial compliant tool in robotic milling operations

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Abstract. This article presents the experimental research performed by the authors in the field of robotic low force milling operations using radial compliant end effectors in order to identify the general advantages and limitations offered by this approach when compared to conventional (non-compliant) tools. The experiments were conducted using a Kawasaki FS 10E articulated arm robot with six axes. The experimental data was collected using a Kistler 9257B dynamometer for three different materials: aluminium, plastic and wood. For each material, several different milling operations were performed: chamfering, slotting and lateral milling. The evaluation for the two approaches was done by analysing the tool behaviour during machining operation, by measuring the machining forces generated by the milling process and by observing the surface quality resulted after machining. The experimental results led to the conclusion that the main limitation for radial compliant end effectors usage lies with slotting operations and with materials that have hard to remove chips. The results obtained in this work will be used, together with further experimental research, to identify the limitations and opportunities of available robotic equipment in milling applications with respect to machined materials, feeds and speeds, as well as trajectory planning.

1. Introduction
Robotics represent one of the most dynamic fields in the industrial area both regarding the number of applications that integrate industrial robots and regarding research and scientific development. Because industrial robotics as a concept covers a very wide area due to high flexibility with respect to the application in which the robot is integrated, the various robotized industrial processes have different levels of development and prevalence. For example, applications such as welding, painting and material handling occupy most of the market, mainly due to their integration in production lines and link to industries such as automotive, packaging and food processing [1]. There are also fields such as laser cutting and machining which have low robotic integration levels but are very dynamic in the research field [2].

This article is oriented towards studying certain aspects linked to robotic machining applications – the type of applications in which the machining operations are performed by the robot itself. The approach used in the research implies the usage of an articulated arm industrial robot with six degrees of freedom that manipulates an end-effector equipped with a milling tool around a part mounted on a work post in front of the robot.

Regarding robotic machining applications, the most widespread operations performed are deburring, flashing, drilling and polishing. These are applications with low machining forces and are generally using end-effectors with radially or axially compliant spindles. The research domain is,
however, focused mainly on machining with integrated spindles, using adaptive force feedback systems with control loops and machining complex shaped parts with more conventional operations such as chamfering, lateral milling and slot milling. Taking into account these considerations, the work presented in this article aims at drawing a line between the capabilities of a robotic system equipped with a compliant end-effector and a robotic system equipped with an end-effector that includes a rigid spindle.

2. Research scope and focus
The focus of this article is oriented towards industrial machining operations performed by industrial robots. In order to further define the scope of the research work, the range of robotic machining operations can be divided with respect to the level of machining forces, into the following domains:

- Operations that require low machining forces, of up to 100 N;
- Operations that require medium machining forces, in the range of 100-1000 N;
- Operations that require high machining forces, with values above 1000 N.

As stated before, the inherent advantages of industrial robots make them more suitable for finishing tasks, such as polishing or deburring. These are operations that are generally performed at the end of the manufacturing workflow and have good levels of industrial robot integration. The other category of operations in the field of machining are the part-shaping operations, such as milling, turning or drilling. While the previously mentioned operations, from programming point of view, are based on tool position and orientation control, the second category of operations are based mostly on force and torque control. For applications that integrate force control techniques, there are two approaches: passive force control and active force control. Passive force control uses features such as radial and axial compliance of the end-effector, as shown in figure 1 [3]. Active force control requires a closed control loop (basic structure shown in figure 2) for providing feedback to the controller, based on equipment such as force / torque sensors.

![Figure 1. ATI RC340 radially compliant end-effector (passive force control).](image1)

![Figure 2. Active force feedback closed control loop.](image2)

Taking into account the above considerations, the scope of the research is to evaluate the influence of a radial compliant end-effector on milling applications for various materials. The robotic end-effectors with radial or axial compliance are generally used as a passive force control system in finishing operations that require following complex contours or shapes with irregularities, such as deburring or polishing [4]. Primary machining operations, such as slotting and lateral milling are generally performed with rigid tools. The purpose of the research was to evaluate the results of a radially compliant end-effector used for milling operations in order to better understand the behaviour of compliant systems and to analyse the opportunities for extending the applications range for this type of tools. The research was performed for applications that require low machining forces, with a passive force control system integrated with an end-effector mounted on the robot’s flange. The machining force levels were recorded using a Kistler dynamometer mounted on a work post placed in robot’s workspace, the machined parts having been clamped to the dynamometer upper plate.
3. Experimental equipment and procedure

For experimental procedures an articulated arm, six degrees of freedom industrial robot model Kawasaki FS10E was used (see figure 3). The Kawasaki FS10E industrial robot is controlled by a Kawasaki D controller.

![Kawasaki FS10E articulated-arm robot and Kawasaki D controller.](image)

The parameters of the Kawasaki FS10E industrial robot are specified below:

- No. of axes: 6;
- Joint limits: J1: ±160°; J2: -105° – 140°; J3: -155° – 120°; J4: ±270°; J5: ±145°; J6: ±360°;
- Joint speeds: J1: 200 °/s; J2: 140 °/s; J3: 200 °/s; J4: 360 °/s; J5: 360 °/s; J6: 600 °/s;
- Payload: 10 kg;
- Joint torques: J4: 21.5 N·m; J5: 21.5 N·m; J6: 9.8 N·m;
- Joint inertia: J4: 0.63 kg·m²; J5: 0.63 kg·m²; J6: 0.15 kg·m².

The robot arm is equipped with an ATI RC340 radially compliant end-effector. The end-effector is attached to the robot flange through an ATI QC41 automatic tool changer. Both the end-effector and the automatic tool changer are illustrated in figure 4.

![ATI RC340 radially compliant end-effector and ATI QC41 automatic tool changer.](image)

The diagram that shows the relation between compliance air pressure and radial contact force at tool-part interface is illustrated in figure 5. The functional parameters of the end-effector are specified below:

- Motor type: air turbine;
- Idle speed: 40000 rpm;
- Max. Torque: 0.08 Nm;
- Power: 340 W;
- Weight: 1.2 kg;
- Compensation: max. ±7.5 mm, recommended ±3 mm;
- Compliance force: 12.7-42 N at 1-4.1 bar;
- Spindle air pressure: 6.2-6.5 bar;
- Collet size: 6 mm;

![Figure 5. ATI RC-340 radial contact force diagram.](image)

In order to perform the machining operations, a milling tool was attached to the end-effector spindle. The tool type was chosen in order to be suitable for all used materials. The parameters of the milling tool are shown below:
- Model: ATI 9150-RC-B-24065;
- Tool diameter: 9.525 mm (3/8’’);
- Length: 15.875 mm (5/8’’);
- Shank diameter: 6.35 mm (1/4’’);
- Materials: Aluminium, soft materials, plastics;
- No. of teeth: 6.

Regarding the experimental procedures, the general machining parameters that were used were based on the machinability of the used materials and the fixed spindle speed of the end-effector (40000 rpm). Thus, a cutting speed $V_c=167-227$ m/min and a feed/tooth $f_z=0.014-0.031$ mm were used as starting parameters. Because the spindle has a fixed speed, the feed for each experimental step was adjusted so that the feed/tooth parameters remain within the recommended values for each material. In order to perform the machining operations with a rigid spindle, a 1.5 kW milling spindle was used, with a maximum speed of 24000 rpm, which is shown in figure 6.

![Figure 6. Milling spindle and inverter.](image)
The force values required for the analysis were recorded using a Kistler 9257B dynamometer (shown in figure 8). The dynamometer was mounted on the work post in front of the robot, acting as a support for the machined part. The advantage in this case is linked to the low payload of the Kawasaki FS10E robot arm (10 kg.), as the force sensor does not put additional load on the robot wrist (as in the case of placing it between the tool and the robot flange). The device is capable to measure forces on three orthogonal directions, corresponding to the X, Y and Z axes of the reference frame. The parameters of the Kistler dynamometer are shown below:

- Maximum values for measured forces (Fx, Fy, Fz): -5…5 kN;
- Overload (Fx, Fy, Fz): -7.5…7.5 kN;
- Overload (Fz, for Fx and Fy ≤0,5Fz): -5…10 kN;
- Threshold: <0.01 N;
- Rigidity (Cx, Cy): >1 kN/μm;
- Rigidity (Cz): >2 kN/μm;
- Natural frequency: 3.5 kHz;
- Operating temperature: 0…70 °C;
- Weight: 7.3 kg;
- Clamping area: 100x170 mm.

The experimental process is oriented towards performing milling operations on three types of material: aluminium (grade 6032), plastic (polyamide) and fir wood. These materials have several common characteristics, among which the most influential on the machining process are the formation of chips that tend to stick to the milling tool and a tendency to locally melt (or, in the case of wood, a tendency of chip burning). Also, these are relatively soft materials, with high machinability, suitable for the machining applications that require low force levels. The materials were machined in succession, by first performing all planned operations on the aluminium part, then on plastic and last on wood. The operations performed were specific for the low machining forces range: chamfering, slotting and lateral surface finishing with low depth of cut. The experimental setup is illustrated in figure 7.
4. Experimental results

The first stage of the operations was done using the radial compliant ATI RC-340 end-effector. During the experimental procedures, a series of results were obtained. The most relevant results samples, on which the argumentation for the conclusions is made, are presented in table 1.

Table 1. Relevant results samples for machining with the radially compliant end-effector.

| Material         | Aluminium (grade 6032) | Plastic (polyamide) | Fir wood     |
|------------------|------------------------|---------------------|--------------|
| Operation type   | 0.5x45° chamfering     | 0.5x45° chamfering  | 0.5x45° chamfering |
| Path length      | 50 mm                  | 50 mm               | 50 mm        |
| Robot trajectory speed / feed | 100% / Vf=6800 mm/min | 100% / Vf=6800 mm/min | 50% / Vf=3400 mm/min |
| X axis           | max. value 34.58 N, average value 5.87 N | max. value 161.68 N, average value 31.89 N | max. value 90.06 N, average value 22.42 N |
| Y axis           | max. value 52.76 N, average value 7.50 N | max. value 88.71 N, average value 13.56 N | max. value 103.85 N, average value 14.89 N |
| Z axis           | max. value 32.90 N, average value 5.10 N | max. value 61.58 N, average value 10.04 N | max. value 74.95 N, average value 12.06 N |
| Observations     | Medium surface quality, relatively constant spindle speed, very low tool deflection (see figure 8). The force levels were within robot specifications regarding load on arm and especially wrist loads. The highest machining forces were on the Y axis, corresponding to the feed direction. Also, the machining forces were below the maximum level at which the compliance system will cause the tool to depart from the programmed path, which means that the operation can be performed without compliance-related issues. | Less than average surface quality, constant spindle speed, some tool deflection. For this operation, the forces were at higher values due to the plastic chips melting locally and sticking to the teeth. Because plastic is a softer material, it didn’t cause the spindle to stall, but caused significant tool deflection and, as a consequence, poor surface quality. The tool deflection was caused by the force levels exceeding the level at which the compliance system causes the tool to deflect. The plastic operations were performed along the X axis, and thus the highest machining forces were on this direction. | Good surface quality, variations in spindle speed, tool deflection (see figure 12). The operations performed on wood were done with the feed direction along the Y axis – this being the direction with the highest machining forces. The quality of the surface was good due to wood having good machinability characteristics, but the high force levels caused tool deflection and variations in spindle speed. For this experimental run, the robot trajectory speed was set to 50% due to the high tendency of chip burning. |
| X axis           | max. value 39.00 N, average value 10.03 N | max. value 173.55 N, average value 21.64 N | max. value 12.24 N, average value 3.26 N |
| Y axis           | max. value 46.11 N, average value 9.94 N | max. value 80.87 N, average value 16.19 N | max. value 13.15 N, average value 3.11 N |
| Z axis           | max. value 27.07 N, average value 9.11 N | max. value 64.45 N, average value 11.19 N | max. value 24.57 N, average value 3.80 N |
Observations

Lower surface quality, variable spindle speed, spindle stalled after 20 mm (see figure 9). In this case, having a higher material removal rate, the machining forces were at higher values than for the previous operations. The relative lack of system rigidity (caused by both robot architecture and the compliance system) caused lower surface quality. The force values exceeded both the level at which the compliance causes the tool to deflect and the allowable load on the spindle.

Poor surface quality, constant spindle speed, significant tool deflection (see figure 10). These results largely confirmed the conclusions from the previous run, with relatively high peak machining force values, tool deflection due to the compliance system and, consequently, poor surface quality. The tool radial compliance determined the spindle to be pulled towards the part, generating thicker chips and higher force values.

Good surface quality, variations in spindle speed, spindle stalled after 25 mm. This pass confirmed the observations from the previous runs. The issues were caused by the very high spindle speed, which caused the wood to burn locally and hinder the cutting process, thus causing the spindle to stall.

Operation type:
- slot milling, $a_e$ 9.5 mm, $a_p$ 0.5 mm
- slot milling, $a_e$ 9.5 mm, $a_p$ 0.5 mm
- slot milling, $a_e$ 9.5 mm, $a_p$ 0.5 mm

Path length:
- 120 mm
- 100 mm
- 50 mm

Robot trajectory speed/ feed:
- 100% / $V_f$=6800 mm/min
- 100% / $V_f$=6800 mm/min
- 50% / $V_f$=3400 mm/min

X axis:
- max. value 44.43 N, average value 10.67 N
- max. value 144.96 N, average value 19.17 N
- max. value 45.36 N, average value 13.26 N

Y axis:
- max. value 50.87 N, average value 10.92 N
- max. value 75.59 N, average value 12.96 N
- max. value 42.65 N, average value 13.11 N

Z axis:
- max. value 24.84 N, average value 8.54 N
- Z axis: max. value, 54.32 N average value 8.98 N
- max. value 21.13 N, average value 7.90 N

Observations

Good surface quality, variations in spindle speed, spindle stalled after 15 mm. Again, the machining forces proved to be at high values, causing the spindle to stop turning. The lower surface was of relatively good quality due to the machined surface being normal to the Z direction, which provides better rigidity. For the slot milling operation, the compliance system proved to be a major disadvantage, because teeth on both sides of the tool engaged the workpiece and generated chatter.

Poor surface quality, constant spindle speed, some tool deflection, very high chatter (see figure 11). The tool compliance determined poor machining performance due to half of the tool perimeter being engaged with the part and the compliance system trying to compensate machining forces acting from opposing sides.

Poor surface quality, variations in spindle speed. The chatter generated due to the compliance of the end effector determined tearing the chips off the slot walls rather than cutting. The spindle stalled after 17 mm.
Figure 8. Aluminium chamfering force diagram.

Figure 9. Aluminium lateral surface finishing force diagram with spindle stall observable in the encircled area. Tool deflection and growing chatter zone is marked with a rectangle.

Figure 10. Plastic lateral surface finishing force diagram with the area in which thicker chips were generated encircled and the area with significant tool deflection marked with a rectangle.
Figure 1. Plastic slot milling with observable chatter, high variations in machining force levels and a loss of spindle speed in the middle of the path (encircled).

Figure 2. Fir wood chamfering. Although the first half of the path shows good behaviour, in the second part of the path the tool deflection can be observed due to chip burning. In this area the tool is not cutting the part, is only moving tangent to the part profile.

The second stage of the operations was done using the 1.5 kW milling spindle which does not integrate a radial compliance system. Because this end-effector has a maximum spindle speed of 24000 rpm, the robot trajectory speed was reduced accordingly in order to keep the same feed/tooth values as in the first stage of operations. The most relevant results samples are presented in table 2.

Table 2. Relevant results samples for machining using the end-effector without radial compliance.

| Material            | Aluminium (grade 6032) | Plastic (polyamide) | Fir wood   |
|---------------------|------------------------|---------------------|------------|
| Operation type      | 0.5x45º chamfering     | 0.5x45º chamfering  | 0.5x45º chamfering |
| Path length         | 50 mm                  | 50 mm               | 50 mm      |
| Robot trajectory speed / feed | Operation type | Path length | Robot trajectory speed / feed |
|-----------------------------|----------------|-------------|-------------------------------|
| 60% / V_r=4080 mm/min       | lateral surface finishing, a_z 0.2 mm, a_y 8 mm | 80 mm | 60% / V_r=4080 mm/min |
| X axis                      | max. value 56.88 N, average value 4.91 N | max. value 10.99 N, average value 1.56 N | max. value 22.94 N, average value 8.22 N |
| Y axis                      | max. value 35 N, average value 2.86 N | max. value 10.66 N, average value 2.23 N | max. value 19.06 N, average value 6.24 N |
| Z axis                      | max. value 31.58 N, average value 2.65 N | max. value 21.62 N, average value 7.05 N | max. value 25.38 N, average value 5.35 N |
| Observations                | Good surface quality, constant spindle speed. There were lesser force level variations and relative constant behaviour of the system during the operation, with a stabilization period at the beginning of the cutting path in which higher force values and more pronounced oscillations were registered. | Good surface quality, constant spindle speed, very short stabilization period. For aluminium this operation provided the best results, with constant force levels and no chatter. | Constant machining force levels, good surface quality, very short stabilization period at the beginning. No chatter. |
| X axis                      | max. value 46.71 N, average value 7.61 N | max. value 8.18 N, average value 1.31 N | max. value 16.87 N, average value 5.81 N |
| Y axis                      | max. value 58.89 N, average value 7.25 N | max. value 9.26 N, average value 2.47 N | max. value 17.98 N, average value 4.22 N |
| Z axis                      | max. value 52.43 N, average value 6.52 N | max. value 11.37 N, average value 3.31 N | max. value 8.65 N, median value 1.88 N |
| Observations                | Good surface quality, constant spindle speed, very short stabilization period. | Constant machining force levels, good surface quality, very short stabilization period at the beginning. No chatter. | Average surface quality, some chatter, noticeable force level variations. The highest variation in force levels was recorded along the radial section – the force levels were less stable than for the other two materials. |
| Operation type              | slot milling, a_z 9.5 mm, a_y 0.5 mm | slot milling, a_z 9.5 mm, a_y 0.5 mm | slot milling, a_z 9.5 mm, a_y 0.5 mm |
| X axis                      | max. value 113.77 N, average value 9.82 N | max. value 8.75 N, average value 1.4 N | max. value 20.44 N, average value 7.75 N |
| Y axis                      | max. value 70 N, average value 5.74 N | max. value 9.91 N, average value 2.65 N | max. value 20.29 N, average value 5.11 N |
| Z axis                      | max. value 63.17 N, average value 5.31 N | Z axis: max. value, 12.17 N average value 3.55 N | max. value 13.33 N, average value 3.14 N |
| Observations                | Good surface quality in the second part of the path, significant chatter in the first third. This operation required the longest stabilization period. | Constant machining force levels, good surface quality, very short stabilization period at the beginning. No chatter. | Average surface quality, some chatter, noticeable force level variations. |
time in order to reach a stable cutting behaviour (see figure 13, figure 14). The surface quality improved significantly after stabilization.

Figure 13. Aluminium slot milling with the stabilization interval marked by a rectangle.

Figure 14. An example of an aluminium slot milling operation that did not stabilize, but instead the tool was pulled towards the part, machining a much higher axial depth of cut that was programmed. Extreme chatter and very high force values were recorded.
5. Conclusions
The experimental results illustrated above were analysed by observing the machining force levels, by interpreting the diagrams generated from these values and by visual inspection of the parts after each operation. Based on this approach, the following conclusions were drawn:

- As expected, in the case of the end-effector with radial compliance, the lack of spindle rigidity caused issues in the form of spindle deflection – the tool was, in many cases, pushed away from the part, especially for aluminium (the hardest material used). This happened mainly in the cases where the force required to form the chip exceeded the equivalent force generated by the pressure in the compliance system. In the case of end-effector without compliance, this issue did not appear, the tool was not deflected for any of the operations performed.
There were experimental procedures during which the tool was pulled towards the part, because the force required to detach the chip from the part was higher than the rigidity of the system. This issue appeared along the X-Y axes in the case of the end-effector with radial compliance and along the Z axis in the case of the end-effector with rigid spindle. These observations showed that the radial compliance determined the lowest rigidity along the X and Y axes, while in the absence of spindle compliance, the lowest rigidity was determined to be along the Z axis and was caused by the elastic displacements in robot joints (mainly the 2nd, 3rd and 5th axes of the robot).

- The issue of the tool being pulled towards the part determined higher chip thickness. Thus, the chips were gradually harder to cut, and the tool was further pulled towards the part, generating even thicker chips. This eventually led to spindle speed loss (and spindle stall), an issue that was observed mainly in the case of using the radially compliant end-effector.

- In most of the cases, there were significant differences regarding machining force values between using the radial compliant end-effector and using the rigid end-effector. When the tool was pulled towards the part along the X-Y axes in the case of using the compliant end-effector, higher force values were registered due to higher lateral depth of cut and thicker chips. When the radially compliant spindle was deflected away from the part, lower machining forces were registered due to the force levels being partially damped by the compliance system acting like a spring.

- The radially compliant end-effector generated good results when using very low radial depths of cut and repeated quick passes for surface finishing. The pressure determined by the radial compliance on the part ensured the removal of surface irregularities.

6. References

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