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Comparative analysis between using an articulated arm robot and a conventional machine in milling applications

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Abstract. The scope of this article is to perform a comparative analysis between low force milling operations performed by an articulated arm industrial robot and a conventional milling machine on an aluminium workpiece. The research sought to compare the machining force levels, tool behaviour and surface aspect in order to identify the nature of stiffness limitations for industrial robots. The expected force levels under normal circumstance were up to 100 N. The experiments were conducted using a Kawasaki FS 10 E articulated arm robot with six degrees of freedom. The experimental data was collected using a Kistler 9257B dynamometer. The experimental procedures were first conducted using the industrial robot approach. Several milling passes were performed using both full radial tool engagement and a lateral depth of cut equal to 2/3 of the tool diameter. The machining force values were compared for each axis, with focus on both machining force levels, variations and resulted surface aspect. Regarding tool behaviour and machining results, these aspects were observed directly during and after each operation. The main conclusion of the experimental procedures was that the biggest stiffness issues appeared along Z axis and also appeared with greater chip thickness.

1. Introduction

Historically, the field of industrial robots has appeared in the context of emerging flexible manufacturing systems area in order to first help and, after a few decades, to take over in certain production categories. The industrial robot, along with CNC machines, is one of the first industrial equipment's designed specifically to replace, rather than assist, human labour in production processes. Industrial robots have to offer certain advantages, such as both kinematic and programming flexibility, good integration with other automation-specific equipment, suitable for extended sensor system, implementation of multi-robot applications and, in certain configurations, collaborative work with human operators [1]. These aspects have determined a certain path of evolution for industrial robotics, with larger degrees of integration in some applications (such as welding and painting in automotive industry, palletizing, machine tending, etc.) and some applications with lower degrees of industrial robot's integration. Among various industrial process categories, the material processing field has the lowest rate of robotic integration, with the applications in which the robot is directly involved in performing the machining applications still being relatively rare. While machining represents a field in which robots are overlapped with CNC machine-tools – which are generally better equipped for such tasks – there are still a large number of secondary operations that are traditionally performed manually, and which are very well suited for robotic integration. Thus, considering these aspects, there is still much room for research and development regarding robotic machining applications, with



directions such as adaptive force feed-back and artificial vision systems having a very dynamic evolution.

Some of the most restricting issues regarding the wider integration of industrial robots in machining applications always have been linked to the overall stiffness of the robot's mechanical structure and the path accuracy, both being lower than those of machine tools by at least one order of magnitude. While machine tools can perform machining operations with tolerances of 0.001 mm, industrial robots that can be integrated in this industrial field have only recently reached levels around the 0.05 mm value [2].

2. Research scope and focus

Regarding the nature of the relation between the tool and the part in robotic machining operations with respect to attachment and spatial frames of reference, there are two possible approaches [3]:

- The part can be clamped on a work post using fixturing elements. The end-effector and the corresponding tool are manipulated by the industrial robot around the part in order to perform the required operations (see figure 1). This approach is used for large or heavy parts, as well as in applications that require repetitive machining operations on identical parts in quick succession (such as clamping multiple parts on the same fixture at the same time).
- The part can be manipulated by the robot, with the tool being placed on a work post inside robot's workspace (see figure 2). This approach is suitable for small to medium sized parts, where it could benefit from having several tools placed around the robot for various operations.

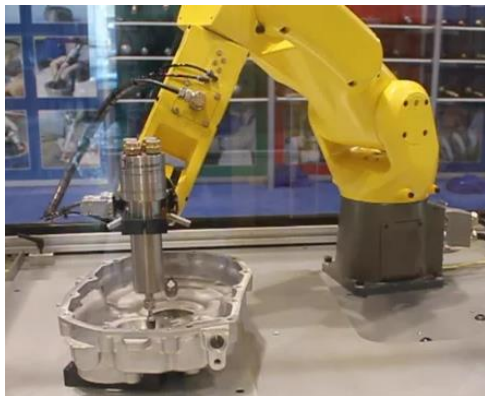


Figure 1. The part being clamped on a work post and the tool being manipulated by the robot in a machining application.



Figure 2. The part being manipulated by the robot and the tool being placed on a work post in a machining application.

In the case of manufacturing using machine tools, the only approach possible is the one illustrated in figure 3, due to the kinematic limitations of the machine. The second approach (the one illustrated in figure 4) can only be used with industrial robots. Because the research is targeted at a comparative analysis which involves a series of similar experimental procedures performed both using an industrial robot and a machine tool, the first approach was used.

Another aspect to be taken into account is the placement of the force/torque sensor. The force/torque sensor role in the flexible manufacturing cell can be to function as an element of a closed control loop (as stated before) or it can be used to measure force/torque levels for research purposes. In both cases, there are two possible placements of the sensor for a machining application [4]:

- Mounted at the interface between the tool and the machine performing the manufacturing operations. This approach has the main advantage that it measures the machining forces acting on the tool. It also has the capability of measuring the force levels with respect to the tool coordinate system. The main disadvantage is that the weight of the sensor puts a higher level of load on a robot's wrist.

- Mounted between the work post and the part mounted on the work post. This approach measures the machining forces acting at the work post level and has the advantage of the sensor being mounted on a more rigid support.

Due to the kinematic flexibility of a robot, the advantage of measuring the force levels with respect to the tool coordinates is very important. Nevertheless, this approach is not used for machine tools due to the specific attaching interface of the tool to the main spindle. Thus, for the research presented in this paper, the second approach was used.

3. Experimental equipment

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.



Figure 3. Kawasaki FS10E articulated-arm robot and Kawasaki D controller.

The parameters of the Kawasaki FS10E industrial robot are specified in table 1.

Table 1. Kawasaki FS10E parameters.

Parameter		Value	
Architecture		Articulated arm	
DOF		6	
Joint limits and speeds	Joint	Limits	Speed
	1	$\pm 160^\circ$	200 °/s
	2	$-105^\circ - 140^\circ$	140 °/s
	3	$-155^\circ - 120^\circ$	200 °/s
	4	$\pm 270^\circ$	360 °/s

	5	$\pm 145^\circ$	360 °/s
	6	$\pm 360^\circ$	600 °/s
Payload		10 kg	
Wrist load	Joint	Torque	Inertia
	4	21.5 N·m	0.63 kg·m ²
	5	21.5 N·m	0.63 kg·m ²
	6	9.8 N·m	0.15 kg·m ²
Repeatability		± 0.1 mm	
Weight		170 kg	
Acoustic level		< 70 db	

In order to perform a second series of measurements using a machine tool and to provide the required data for a comparative analysis, a TOS FN32 mill was used, which is illustrated in figure 4. The mill has a vertical main spindle which provides the Y and Z axes, while the machine table provides the X axis movement. The maximum speed of the main spindle is 1000rpm.



Figure 4. TOS FN32 mill.

The robot arm was equipped with a 1.5kW milling spindle, shown in figure 5. The spindle is attached to the robot flange through an ATI QC41 automatic tool changer.



Figure 5. Milling spindle and inverter.

In order to perform the machining operations, a milling tool was attached to the end-effector spindle. The parameters of the milling tool are shown in table 2.

Table 2. Milling tool parameters.

Parameter	Value
Model	ATI 9150-RC-B-24065
Tool diameter	3/8''
Length	5/8''
Shank diameter	1/4''
Materials	Aluminium, soft materials, plastics

The force values required for the analysis were recorded using a Kistler 9257B dynamometer (shown in figure 4). 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 in table 3.

Table 3. Kistler 9257B parameters.

Parameter	Direction	Value
Maximum values for measured forces	F_x, F_y, F_z	-5...5 kN
	F_z (for F_x and $F_y \leq 0.5F_z$)	-5...10 kN
Overload	F_x, F_y, F_z	-7.5...7.5

		kN
	F_z (for F_x and $F_y \leq 0.5F_z$)	-7.5...15 kN
Threshold		<0.01 N
Rigidity	C_x, C_y	>1 kN/ μm
	C_z	>2 kN/ μm
Natural frequency		3.5 kHz
Operating temperature		0...70 °C
Weight		7.3 kg
Clamping area		100x170 mm

The experimental procedures were performed using an aluminium (grade 6032) plate. In order to introduce a variation linked to the lateral depth of cut (a_e), the machining operations were performed for full slotting and for a tool lateral engagement of 2/3 of the diameter. The experimental setup is illustrated in figure 6.



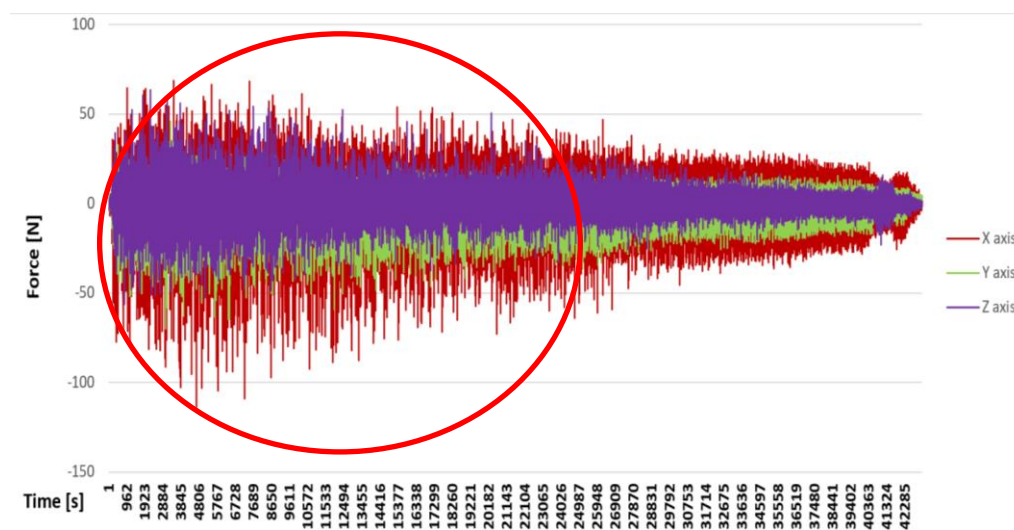
Figure 6. Experimental setup.

4. Experimental results

The first stage of the operations was done by performing the machining operation using the Kawasaki FS10E articulated arm robot. The second stage of the operations comprised of performing the machining operations. The most relevant machining results are presented in table 4.

Table 4. Relevant experimental results.

Machine	Kawasaki FS10E robot	TOS FN32 mill
Operation type	slot milling, $a_p = 1$ mm, $a_e = 9.5$ mm	slot milling, $a_p = 1$ mm, $a_e = 9.5$ mm
Path length	124 mm	124 mm
Trajectory speed / feed	10% / $V_f = 180$ mm/min	$V_f = 75$ mm/min
X axis	max. value 113.77 N, average value 9.82 N	max. value 97.14 N, average value 31.8 N
Y axis	max. value 70 N, average value 5.74 N	max. value 47.61 N, average value 21.95 N
Z axis	max. value 63.17 N, average value 5.31 N	max. value 38.3 N, average value 11.57 N
Observations	Long stabilization period, good surface quality, some chatter at the beginning of the path (see figure 7).	Constant cutting behaviour, very good surface quality, balanced machining force values on all three axes (see figure 8).
Operation type	lateral milling, $a_p = 1$ mm, $a_e = 6.33$ mm	lateral milling, $a_p = 1$ mm, $a_e = 6.33$ mm
Path length	124 mm	124 mm
Robot trajectory speed / feed	10% / $V_f = 180$ mm/min	$V_f = 75$ mm/min
X axis	max. value 47.08 N, average value 8.07 N	max. value 85.27 N, average value 25.02 N
Y axis	max. value 61.03 N, average value 6.41 N	max. value 108.61 N, average value 42.7 N
Z axis	max. value 59.72 N, average value 5.23 N	max. value 77.45 N, average value 10.62 N
Observations	Relative constant cutting behaviour, with some variation of the machining force levels (see figure 9).	Good surface quality, no chatter. There were two areas with growing peak force values, at the beginning and at the middle of the cutting path (see figure 10). This was determined to be caused by low feed value, as the behaviour did not occur when growing the feed by 20%.

**Figure 7.** Aluminium slot milling using the Kawasaki FS10E industrial robot. The stabilization period is encircled.

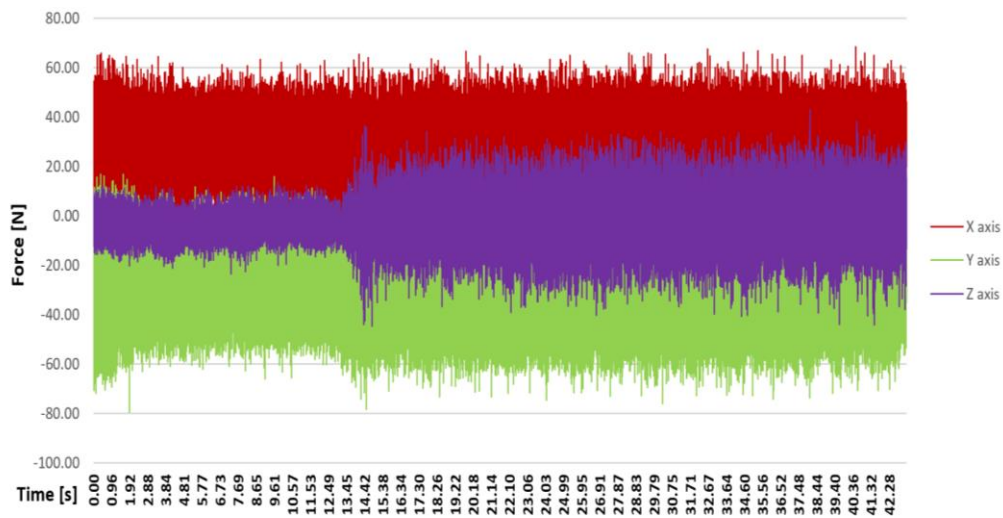


Figure 8. Aluminium slot milling using the TOS FN32 mill.

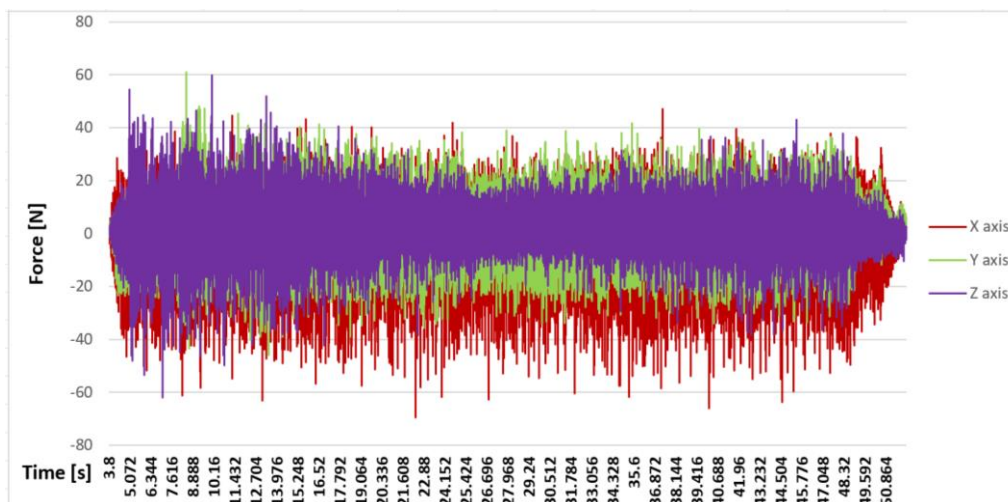


Figure 9. Aluminium lateral milling using the Kawasaki FS10E industrial robot.

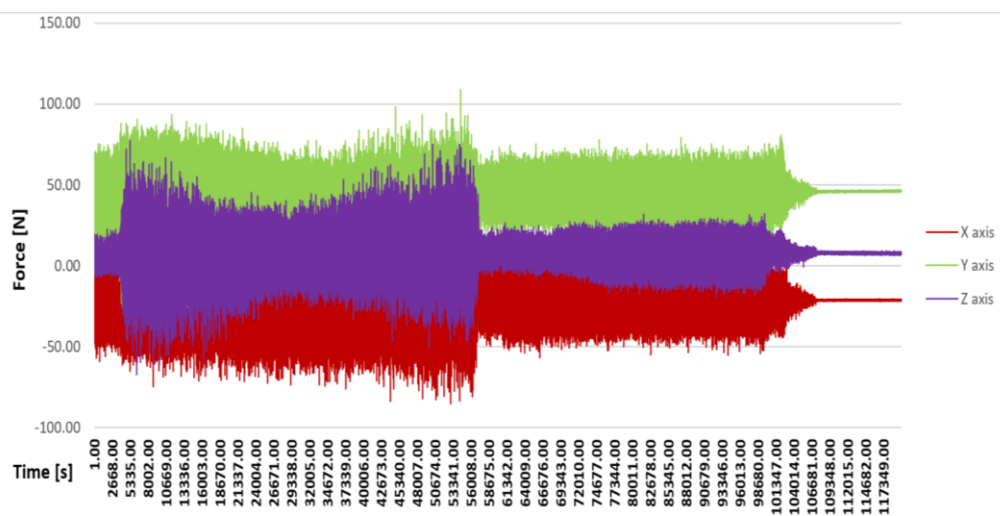


Figure 10. Aluminium lateral milling using the TOS FN32 mill.

5. Conclusions

As it was expected, the main differences between the milling operations performed using the articulated arm industrial robot and the operations performed using the milling machine tool are caused by the difference of stiffness inherent due to structural characteristics of the two machines. For the Kawasaki FS10E industrial robot, the lack of stiffness is determined mainly by the elastic displacement at the kinematic joint level. As a consequence, the lowest stiffness level is present along the Z axis of the part coordinate system, because for this direction the elastic displacement of the second, third and fifth axis are cumulated, the rotation axes for these joints being parallel to each other and perpendicular to the Z axis. However, by analyzing the corresponding diagrams, it can be observed that the highest force levels are registered along the X axis of the part coordinate system. This represents the feed direction and, consequently, it is the direction of occurrence for the primary machining forces.

For the machining processes performed using the industrial robot, there is a stabilization period that appears at the beginning of the path for each operation. This stabilization period is characterized by higher peak machining force values and higher variations in machining force levels. The stabilization period is longer for slot milling and significantly shorter for lateral milling. This issue generates a lower quality surface in the corresponding path segment (the surface quality improves significantly after the end of the stabilization period). After the stabilization period ends, the cutting is more stable for the slotting operation when compared to the lateral milling operation due to better tool engagement. For the machining operation using the milling machine tool, there is no stabilization period.

The feed value was lower in the case of machining operations performed using the milling machine tool in order to compensate for the higher spindle speed of the robot end-effector. The operations performed using the industrial robot were conducted at a spindle speed of 24000 rpm, while the operations performed on the machine tool were conducted at a spindle speed of 10000 rpm (the maximum possible value). The spindle speed of robot's end-effector could not be reduced because a significantly lower rpm was shown in the preliminary testing procedures to determine a spindle stall. Thus, the lower spindle speed for the operations performed using the milling machine tool generated higher machining force values, especially in the case of lateral milling.

6. References

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