

Circular and quasi-circular paths for the industrial robots measuring with the Renishaw Ballbar QC20-W

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Abstract. Realized measuring with the Renishaw Ballbar QC20-W on industrial robots requires a special approach to measurement and creating of a circular path. In the article, two methods of the circular path creation are compared through experimental measurements. The first method is based on creating a circle using standard program commands in the FANUC programming environment. In the second method, the circular path is created as a polygon that represents the most accurate approximation of a circle required for a Ballbar measurement. The measurement methodology, the analysis of measurement data and results are presented in the article.

Keywords: Industrial robot, Renishaw Ballbar, Circular path

1 Introduction

Trends in increasing production flexibility are one of the reasons for an annual increase in the number of industrial robots in automation [1]. However, in the process of improving the competitiveness of an enterprise, it is also important to ensure the reliability of machinery, including industrial robots [2]. Predicting the future state of the technical equipment, reducing downtimes and avoiding major technical problems are goals of implementing technical diagnostics and predictive maintenance methods.

Diagnostics of industrial robots is a specific area in industrial robotics, with which the measurement of performance criteria is closely related. Performance criteria, together with the payload, shape and size of the workspace, specify properties of the industrial robot [3, 4]. During the life cycle of a robot, various factors may cause varying performance criteria Nubiola and Bonev [5] report five factors that change performance criteria:

- Environmental factors (temperature, humidity),
- Parametric factors (e.g., manufacturing and assembly errors),
- Factors related to measurement (caused by the limited resolution of the motor encoders),
- Factors related to calculations (e.g., rounding),
- Factors related to application (e.g., installation errors).

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Reviewers: *Janusz Mielniczuk, Dominik Wilczyński*

By applying technical diagnostics methods, it is possible to ensure long-term monitoring of the robot condition. With sufficient data collection and evaluation of trends in diagnostic quantities changes, it is possible to avoid a malfunction of the robot or the emergence of defective products.

Measuring performance criteria is a complex task. In scientific publications, various measuring devices and corresponding measurement methods are used to measure industrial robot performance criteria. However, many of them represent a complicated measurement process that is more determined by laboratory conditions than in real production [6, 7].

If the performance criteria measurement is part of the industrial robot monitoring diagnostics in a real production process, it is important that the measurement itself can be conducted in the shortest time and in the simplest way [8, 9]. In this direction, it is possible to use CNC machine tools diagnostics, where the Renishaw Ballbar measuring device is commonly used for quick checks of its performance and also to evaluate errors and its sources.

This article discusses the comparison of two circular path methods needed to diagnose an industrial robot using the Renishaw Ballbar QC20-W measuring device. Individual measurements were performed on FANUC robots.

2 Preparation for measurement

The Renishaw Ballbar measuring device is one of the most effective tools used in the predictive maintenance of CNC machine tools. The Renishaw Ballbar QC20-W measuring system consists of the precision linear displacement sensor for measuring distance deviations between a pair of balls located at its ends. The measurement process is based on measurement of deviations of radius during circular movement (or part of the arc). Measured data are recorded and processed in the Renishaw Ballbar 20 software and used to calculate the total machine accuracy value in accordance with valid international standards [10, 11].

From the evaluation of the test in the Renishaw Ballbar 20 programme, it is possible to identify 21 different errors that indicate the machine condition, where the circular motion is formed by two mutually perpendicular axes. Conversely, the circular path in the case of the use of an industrial robot with serial or parallel kinematics is the result of the simultaneous movement of multiple robot joints [12, 13]. For this reason, the robot condition can not directly be evaluated on the basis of identified errors as in the case of a CNC machine tool. The use of the Renishaw Ballbar measuring device on an industrial robot requires a special approach not only to measuring and analysing data but also to preparing a measurement consisting of the circular path creation.

2.1 Creating a circular path in the FANUC robot programming environment

In the FANUC robot programming environment, the circular path can be created in several ways. One of these is the use of a special software extension to generate shapes (square, hexagon, circle, etc.) designed especially for cutting operations such as waterjet, laser, and the like [14]. This software extension accelerates and simplifies programming because the path creation program is generated automatically by entering the centre position and shape dimension. In the case of creating a circle, it is the centre of the circle and its diameter. However, this is a paid extension that FANUC robot control systems do not have.

The second way to create a circular path is to use standard programming commands that include the basic configuration of FANUC robots. In this respect, this is a versatile way of creating a circular path that can be used on any FANUC robot. Therefore, even within this article, the circular path is created in this way, based on connecting two semi-circles (Fig.

1). During the execution of the path thus created, the Tool Centre Point (TCP) of the robot stops at its end point after describing the first semi-circle and then re-starts to describe the second semi-circle (Fig. 1). This method of performing a circular path is inappropriate for measuring with the Renishaw Ballbar measuring device. The continuous path can be achieved by using the CNT (Continuous Termination) parameter with a value of 100 for the largest circumvention of the programmed point (Fig. 2b) [15]. The use of the CNT100 parameter, in the case of a circular path, ensures continuity of movement but can cause the circle to deform.

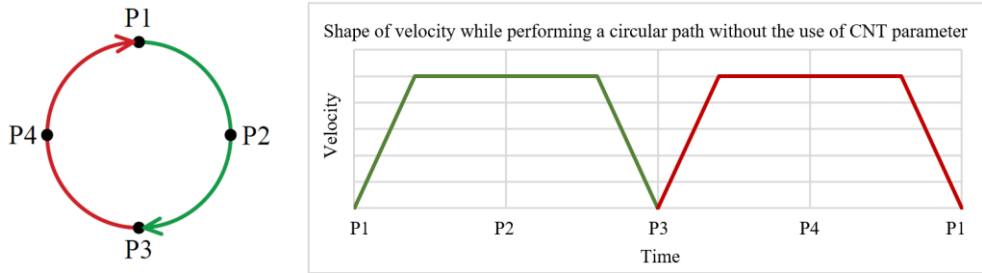


Fig. 1. Circular path consisting of two semi-circles

2.2 Approximation of the circular path

The two semi-circles problem solves a method based on the creation of an n-polygon, representing the approximation of the desired circle as precisely as possible. The so-created circular path for measuring with the Renishaw Ballbar measuring device was first tested on a CNC machine tool [16]. By comparing the approximate circular path and the circle created by circular interpolation commands, the result is a negligible difference, representing the deviation between two consecutive identical measurements.

The calculation of the polygon is based on the size of the desired circle of radius R , replaced by the corrected circle of the radius R_c formed by n-points (Fig. 2a). After the connection of these points with segments, an n-polygon represents the most precise approximation of the desired circle of radius R .

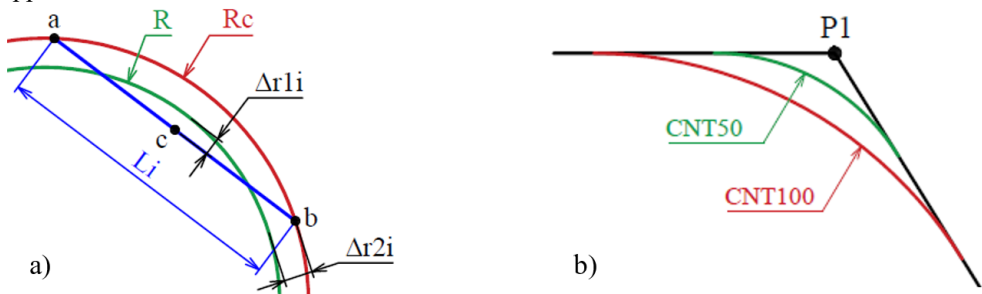


Fig. 2. Circular path approximation and CNT parameter

Coordinates of individual points can be entered in the FANUC robot control system to three decimal places, which is taken into account when calculating X and Y coordinates of polygon vertices, according to mathematical formulas (1) and (2).

$$X_i = \frac{\text{rint}(\cos(\alpha_i) \cdot R_c \cdot 1000)}{1000} \quad (1)$$

$$Y_i = \frac{n \cdot \text{int}(\sin(\alpha_i) \cdot R_C \cdot 1000)}{1000} \quad (2)$$

Variable α_i represents the angle between the centre line of the corrected R_C circle and the X-axis in a counterclockwise direction. This angle is determined by the relationship (3).

$$\alpha_i = \frac{\varphi}{n} \cdot i + \varphi \quad (3)$$

Where i takes values from 0 to n , with n being the number of points (polygon vertexes). φ represents the angle of the calculated circular arc. If the points are counted on the whole circle, then $\varphi = 360$.

To determine the radius of the corrected circle, a numerical method is used, which, based on geometric conversions, controls the deviation of the polygon from the desired circle using following formulas (4), (5), (6).

$$\Delta_{r1i} = \left| R - \frac{\sqrt{(X_i + X_{i+1})^2 + (Y_i + Y_{i+1})^2}}{2} \right| \quad (4)$$

$$\Delta_{r2i} = \left| R - \sqrt{x_i^2 + y_i^2} \right| \quad (5)$$

$$\Delta_{r\max} = \max(\Delta_{r1i} \cup \Delta_{r2i}) \quad (6)$$

From coordinate points thus determined, the length of the segment L_i connecting two adjacent points on the polygon is calculated according to the relation (7).

$$L_i = \sqrt{(X_i - X_{i+1})^2 + (Y_i - Y_{i+1})^2} \quad (7)$$

Consequently, during the measurement, it is important that the TCP of the robot pass continuously between individual segments connecting vertices of the calculated polygon. The flow path can be reached using the CNT parameter. As mentioned above, this is a part of the motion command in the robot control program that defines the size of the programmed point circumvention (Fig. 2b). This parameter can take values from 0 to 100. The CNT100 represents the largest circumvention, and vice versa, when defining the motion command with the CNT0, the TCP of the robot will stop at individual programmed points.

3 Conditions and measurement realization

The experiments were carried out on two FANUC industrial robots, namely the LR Mate 200iD/7L and the LR Mate 200iC, in order to compare two circular path creation methods.

The first method of circular path creation is a polygon made up of 512 points representing the most precise approximation of a circle with a radius $R = 100\text{mm}$. The selected radius corresponds to the corrected circle of size $R_C = 100.0026\text{mm}$ and the maximum length of the segment connecting two adjacent polygonal points $L_{\max} = 1.2281\text{mm}$, which was chosen so that the deviation from the actual circle R was as small as 0.0007mm . For the continuous transition between points of the polygon, movement command CNT100 and CNT75 parameters were used. These values are based

on results of previous experiments when lower values of the CNT parameter resulted in a significant prolongation of the measurement time and results could be affected by vibrations [15]. At the same time, previous experiments show the linear velocity value of the TCP of the robot at the polygon transition. Its size was set at 100 mm/s.

In the case of the second method, the required circle with a radius of 100mm is created using standard programming commands, such as connecting two semi-circles. The speed of the TCP point movement of the robot was chosen to approximate as closely as possible the identified velocity value in Ballbar 20 programme when measured with an approximated circle with CNT100 and CNT75 parameters values. For the FANUC LR Mate 200iC, speeds were 55.33 mm/s and 22.83 mm/s. In the case of the FANUC LR Mate 200iD/7L, speeds were 55.33 mm/s and 30.83 mm/s.

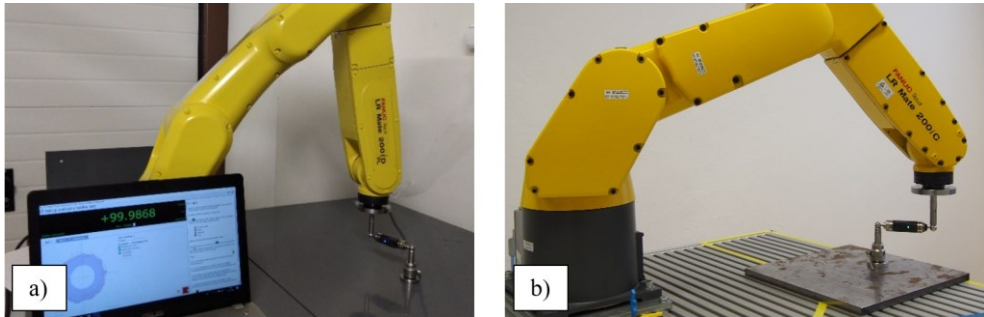


Fig. 3. Measurement performance on Fanuc LR Mate 200iD/7L (a) and FANUC LR Mate 200iC robots (b)

Measurements were performed in the XY plane with respect to the robot global coordinate system. The center of the circle has been chosen to accommodate robots at their workplaces so that its position is the same for both industrial robots. The measuring cycle was performed in a way that the TCP of the robot performs a circular path twice in a clockwise (CW) and twice in a counterclockwise (CCW) direction. For each velocity value and CNT parameter, 30 repetitive measurements were performed (Table 1. and Table 2.). Altogether, 240 measurement cycles were performed for the experiment. The load of the end of robot’s arm during the measurement is 438 g.

Table 1. Measurement conditions when using an approximated circle

Circle path created as a polygon consisting of 512 points					
FANUC LR Mate 200iD/7L			FANUC LR Mate 200iC		
CNT	TCP robot velocity	Repeat count	CNT	TCP robot velocity	Repeat count
100	100 mm/s	30	100	100 mm/s	30
75	100 mm/s	30	75	100 mm/s	30

Table 2. Measurement conditions for a circle using standard programming commands

Circular path created using standard programming commands			
FANUC LR Mate 200iD/7L		FANUC LR Mate 200iC	
TCP robot velocity	Repeat count	TCP robot velocity	Repeat count
55.33 mm/s	30	55.33 mm/s	30
30.83 mm/s	30	22.83 mm/s	30

4 Evaluation of measurement

As mentioned in the previous chapters, the Renishaw Ballbar 20 software was used to record the measurement with Renishaw Ballbar measuring device. 21 different errors are identified from the test evaluation, but these are reported in relation to CNC machine tools. Some identified errors can be used to assess the industrial robot conditions, but others do not. A more detailed analysis of measured data can be realized by decomposing the recorded circular profile into individual harmonic components.

This method of analysis is used in engineering metrology, for example, when evaluating circularity. The recorded surface profile is replaced by a series of sinusoids whose frequencies are expressed by the number of undulation per revolution. These sinusoids are harmonic components of the surface profile. The distribution of harmonic components of the profile by frequency through amplitude and phase determination is performed by a method called Fast Fourier Transformation (FFT). Individual frequencies of harmonic components relate to errors in machine settings, vibrations, and the like. In the case of industrial robot measurements, analysis using the harmonics of the profile is used to assess the influence of the CNT parameter on the possible deformation of the circular path and to compare two methods of circular path creation.

Data analysis was performed in Microsoft Excel with the NumXL analytical add-in containing the Fourier transformation tool. The output from Ballbar 20 programme is a *.b5r file, which contains a lot of data about measurement as well as measured and evaluated data. However, for the purpose of analysis, only data recorded at one revolution of the Ballbar measuring device, without starting and ending part of the measured circle, are required. This data filtering was done in the ConverterTest program, previously created at the Department of Automation and Production Systems of the Faculty of Mechanical Engineering at the University of Žilina [17]. Outputs are two text files with required values for CW and CCW direction. Data thus prepared are then read into the Microsoft Excel environment and processed in the following way.

4.1 Assessment of the CNT parameter influence

The analysis carried out was the first considered the CNT parameter influence on the eventual deformation of the circular path created by the combination of two semi-circulars. Because, if deformations occur, a further comparison of two methods of circular path creation would be insignificant. A suitable method would be, in this case, a circular path created as a polygon consisting of 512 points.

The actual shape of the measured circle can be evaluated on the basis of the second harmonic component of the profile representing the ovality. Therefore, one way of identifying a possible circular path deformation is to compare the magnitude of the amplitude of the second harmonic component. The average amplitude values computed from thirty repeated measurements for the value of CNT100 with velocity v1 and CNT75 with velocity v2 (Table 3 and Table 4) are compared. These comparisons were made for both FANUC robots.

Table 3. Comparison of the average amplitude values of the second harmonic component of the profile for the LR Mate 200iD/7L robot

FANUC LR Mate 200iD/7L - the average amplitude value of the second harmonic component of the profile					
	CCW [mm]	CW [mm]		CCW [mm]	CW [mm]
CNT100	43.33	19.40	CNT75	39.95	21.18
v1 = 55.33mm/s	45.02	20.89	v2 = 22.83mm/s	41.30	24.10
$\Delta = CNT100 - v1 $	1.69	1.49	$\Delta = CNT75 - v2 $	1.35	2.92

Table 4. Comparison of the average amplitude values of the second harmonic component of the profile for the LR Mate 200iC robot

FANUC LR Mate 200iC - the average amplitude value of the second harmonic component of the profile					
	CCW [mm]	CW [mm]		CCW [mm]	CW [mm]
CNT100	172.25	209.38	CNT75	183.60	197.82
v1 = 55.33mm/s	167.56	200.70	v2 = 30.83mm/s	191.24	205.73
$\Delta = CNT100 - v1 $	4.69	8.68	$\Delta = CNT75 - v2 $	7.64	7.91

From the comparison in Table 3 and Table 4, small differences can be seen between individual average amplitude values of the second harmonic component profile. Based on this comparison, it can be said that when creating a circular path using two semi-circles, the CNT100 parameter does not deform the circular path thus created.

The eventual deformation of the circular profile can be evaluated in addition to the comparison of amplitudes of the second harmonic component profile also through the graphical representation of the actual circular path profile. For this purpose, in the Microsoft Excel environment, the first ten harmonic components of the profile were computed from measured values by the Fourier transformation. The amplitude of the first harmonic component was adjusted to zero since it represents eccentricity and is considered a measurement error. Subsequently, individual profile points are recalculated by the reverse composition of the profile using an inverse Fourier transformation. Polar charts created from these adjusted values are ultimately easier to compare.

In Figure 4 and Figure 5 it is possible to see polar graphs created by the above-mentioned method for both FANUC robot types. For illustration, only polar graphs for moving the robot's TCP in a clockwise direction with one value of the CNT parameter and its corresponding velocity are shown. By comparing two polar graphs for a particular robot type, only the minimum difference between displayed profiles can be observed. This raises the suspicion of a circular path deformation because if it occurs, it would appear on the displayed profile.

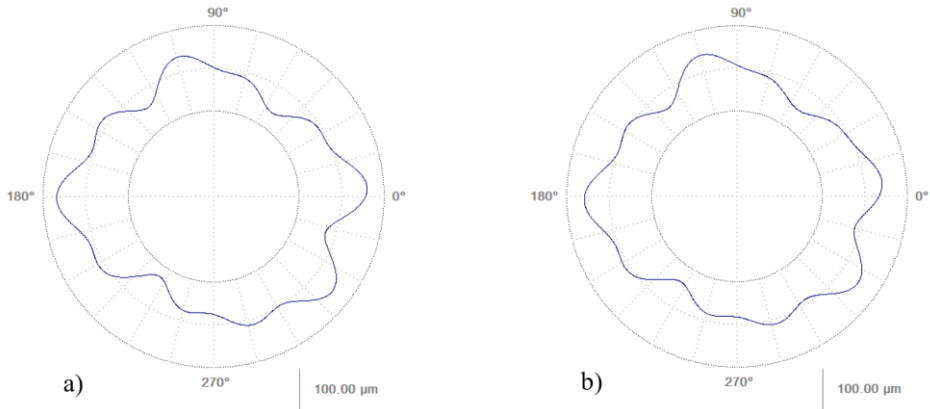


Fig. 4. Polar graphs: a) LR Mate 200iD/7L, CNT100, CW; b) LR Mate 200iD/7L, $v_1 = 55.33$ mm/s, CW

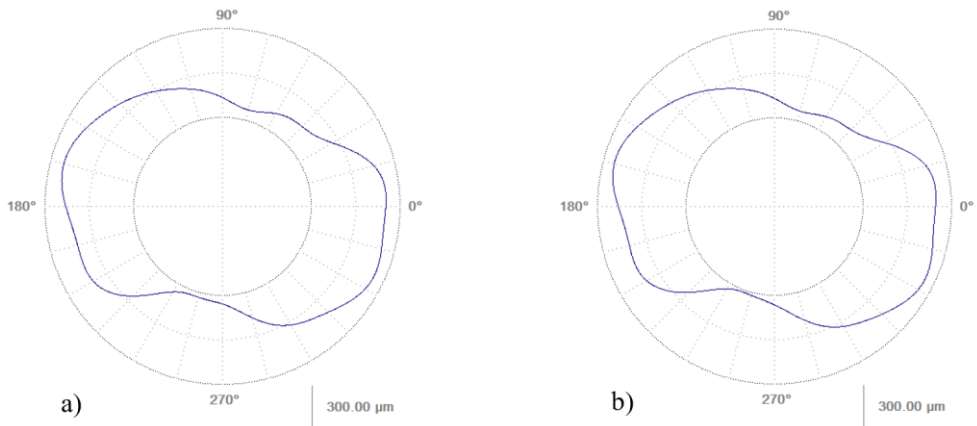


Fig. 5. Polar graphs: a) LR Mate 200iC, CNT100, CW; b) LR Mate 200iC, $v_1 = 55.33$ mm/s, CW

In polar graphs, it is possible to further observe a different profile shape when comparing both types of robots. More pronounced profile deformation for the LR Mate 200iC robot also represents higher average amplitude values in Table 4. This phenomenon is probably due to an inaccuracy in the calibration of the robot. Apart from the cause, this fact does not affect pronounced conclusions regarding the assessment of the CNT parameter influence on the circular path deformation.

4.2 Comparison of circular path creation methods

The aim of the next analysis was to compare two circle path methods to determine the most appropriate respectively the most accurate measurement method with the Renishaw Ballbar measuring device. In the case of the first method, the circular path was created using standard FANUC robot programming commands, such as a connecting of two semi-circles. The continuous transition between two parts of the circle is achieved using the CNT100 parameter. Its influence on the resulting circle shape is the subject of a previous analysis. The second method is based on the creation of a polygon representing the approximation of the desired circle as precisely as possible. For a continuous path, CNT parameters of 100 and 75 are used. Both methods were compared by calculating a relative error.

The relative error (8) is expressed as the share of the absolute error Δ and the true value of the measured value X_t . The relative error is expressed in percent and serves to determine the measurement accuracy, or it can be used to compare different measurement methods. If the calculated value is less than 1%, the measurement is considered to be accurate, the value up to 5% indicates laboratory accurate measurement. If the relative error value is greater than 5%, the measurement is labelled as inaccurate.

$$\delta_{(X)} = \frac{\Delta}{X_t} \cdot 100\% \tag{8}$$

The measured value for the calculation of the relative error was the amplitude value of the second harmonic component of the profile. Based on the decomposition of the recorded profile using the FFT (Fig. 6) it is evident that the second harmonic component of the profile representing the ovality is dominant. At the same time, the second harmonic component of the profile carries the information about circularity and squareness error that can be used to evaluate conditions of industrial robots.

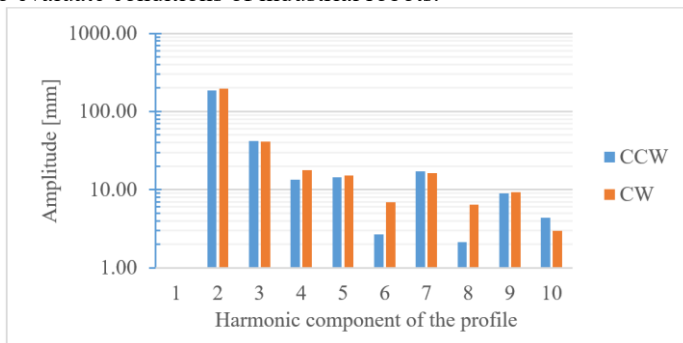


Fig. 6. FFT analysis – LR Mate 200iC, CNT75

In Table 5 and Table 6 are presented calculated relative error values for both circular path creation methods and both FANUC robots. It can be seen from results that only in the case of the LR Mate 200iC industrial robot and the approximated circle with the CNT75 parameter value, the relative error becomes more than 1%. In all other cases, the calculated value is below 1%, so the measurement can be evaluated as accurate. With regard to the comparison of the measurement accuracy of two used circular path creation methods, more accurately the measurement is based on the circular path created by connecting two semi-circles. However, the difference between relative error values for both methods is minimal. On this basis, it is possible to conclude the final conclusion on mutual equality, respectively the same accuracy of both methods.

Table 5. Calculated relative error values for the LR Mate 200iD/7L robot

FANUC LR Mate 200iD/7L – the relative error $\delta_{(A2)}$					
	CCW [%]	CW [%]		CCW [%]	CW [%]
CNT100	0.41	0.44	CNT75	0.52	0.69
v1 = 55.33 mm/s	0.38	0.40	v2 = 22.83 mm/s	0.95	0.53

Table 6. Calculated relative error values for the LR Mate 200iC robot

FANUC LR Mate 200iC – the relative error $\delta_{(A2)}$					
	CCW [%]	CW [%]		CCW [%]	CW [%]
CNT100	0.86	0.42	CNT75	1.32	0.52

v1 = 55.33 mm/s	0.65	0.32	v2 = 30.83 mm/s	0.90	0.99
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5 Conclusion

Two methods of circular path creation are compared on the basis of experimental measurements. The aim of the comparison is to determine the most advanced way of creating the circle needed for measurement with the Renishaw Ballbar QC20-W measuring device. In the FANUC robots programming environment, a circular path can be created using a connection of two semi-circles using standard programming commands. The CNT100 parameter is used to ensure continuous movement between two semi-circles. However, in connection with the use of the CNT parameter, a possible deformation of the circular path is suspected. Therefore, in order to solve the problem with two semi-circles, a method based on the formation of an n-polygon was proposed. The generated polygon for experimental purposes is composed of 512 points and represents the most accurate approximation of the desired circle.

Individual measurements were made on two FANUC robots, namely LR Mate 200iD/7L and LR Mate 200iC. Four series of measurements were performed on each industrial robot. Two series of measurements were made with an approximate circle, with a CNT parameter of 100 and 75 being used for a continuous transition between individual segments connecting polygon vertices. For the other two series of measurements, the circular path was created by connecting two semi-circles. In this case, measurements were made at two velocity values so that the selected velocity value is as close as possible to that of the approximate circle.

The analysis of measured data was realized by decomposing the recorded circular profile into individual harmonic components. The first was evaluated the effect of the CNT100 parameter on the deformation of the circular path created by connecting two semi-circles. The analysis performed for this purpose was based on the comparison of average values of the second harmonic component of the profile for each series of measurements. As a result, there are small differences between average values of both methods, which give rise to a suspicion of deformation. This conclusion is confirmed by the comparison of polar graphs illustrating the profile of the circular path.

The purpose of the next analysis was to determine the most appropriate, respectively the most accurate method of circular path creation. Both methods were compared based on the calculation of a relative error. The measured value in the calculation is the amplitude value of the second harmonic component of the profile. By comparing calculated relative error values, a more accurate method is to create a circular path using two semi-circles. However, the difference between relative error values for both methods is minimal. Therefore, it is possible to both circle path creation methods identified as equivalent.

Based on experiment results, it is possible to conclude about benefits of both presented methods. Creating a circular path using two semi-circles is a simpler and faster way to prepare a control program. It is not necessary to realize a relatively complex calculation of polygon vertices coordinates and consequently to generate a robot control program. Most likely, this method will also be used for further experiments with Renishaw Ballbar measurement device on industrial robots. At the same time, however, it should be noted that the method utilizing the n-polygon finds application in specific cases requiring greater control in the creation of the circular path.

This work was supported by the Slovak Research and Development Agency under the contract No. APVV-16-0283

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