Proceedings in Manufacturing Systems

Proceedings in Manufacturing Systems, Volume13, Issue3, 2018, 133-140 ISSN 2067-9238

SINGLE POINT INCREMENTAL FORMING USING KUKA KR6-2 INDUSTRIAL ROBOT - A DYNAMIC APPROACH

Mihai CRENGANIŞ[1,*], Alexandru BÂRSAN[2], Sever-Gabriel RACZ[3], Monica Daniela IORDACHE[4]

[1)] Assistant Prof., PhD, Machine and Industrial Equipment Department, "Lucian Blaga" University of Sibiu, Romania
[2)]Assistant Prof., PhD Student, Machine and Industrial Equipment Department, "Lucian Blaga" University of Sibiu, Romania
[3)]Prof., PhD, Head of department, Machine and Industrial Equipment Department, "Lucian Blaga" University of Sibiu, Romania
[4)] Assoc. Prof., PhD, Manufacturing and Industrial Management Department, University from Pitesti, Romania

Abstract: *The single point incremental forming process (SPIF) of the metal sheets is a modern method of plastic deformation, with an enormous potential regarding the flexibility and personalization of the parts obtained by this process. SPIF of a sheet metal is a technologic manufacturing process where a sheet metal is formed into a desired part by a series of small incremental deformations. The main research objective is to determine the joint torques from the kinematic structure of the KUKA KR6-2 industrial robot during SPIF process. The dynamic model of the robot during SPIF processes is also presented. This study is necessary to determine if KUKA KR6-2 robot can be used for SPIF manufacturing processes of thin metal sheets without mechanical failure over time. To study and simulate the KUKAKR6-2 robot's dynamic behavior during the SPIF process, first the forces that appear during the process must be examined.*

Keywords: *Single point incremental forming, KUKA KR6-2, force analysis.*

1. INTRODUCTION

Industrial robots have found their place in a wide range of technological processes, replacing the human operator in performing auxiliary or basic operations. The most important applications are in the following areas: in mechanical machining processes Fig. 1, for the automatic supply of parts, tools or devices for CNC machines, or for drilling or grinding operations.

Another important application are the ones that follows: in automated assembly processes where the robot manipulates assembled parts or tools used for this purpose, in forging-pressing technologic processes, for the service of incinerators or presses and dies, in processes like spot welding or arc welding, where the robot manipulates the spot welding head or the electrode in arc welding, in casting processes, for manipulation of moulding frames, for cores mounting, for casting cleaning or for automatic feeding of pressure casting machines.

Nevertheless industrial robots have applicability in technological processes of superficial coatings, in which they handle painting guns or parts that are submerged in coating baths, pickling, etc., in technological heat treatment processes where they handle the parts when heated in furnaces or immersion in treatment baths, in carrying out the automatic control of the dimensions and shape of the parts and when loading and unloading the conveyors in stacking, transporting or storing operations.

In any case, in the realization of some applications one must ensure that the industrial robot does not appear as a foreign body in the process and its characteristics fully correspond to the characteristics of the technological process so as not to be influenced, by reaction, by the product object, the means of production or technologic process. The realization of industrial applications with robots requires a careful analysis of the variability of the environment or technological process to determine the degree of flexibility that the robot has to provide to the mechanics, the command and programming system, and the degree of flexibility of the peripheral interface elements.

The paper presents the steps taken to develop a dynamic model for the KUKA KR6 robot during single point incremental forming (SPIF) of metal sheets. This dynamic model of the KUKA KR6 robot is necessary to verify that the mechanical structure of this low payload industrial robot can withstand the forces in SPIF processes.

Fig.1. Industrial robot used in mechanical machining processes (milling, drilling, deburring).

*Corresponding author: Emil Cioran no. 4 Sibiu, Romania 550025,
Tel.: 0745311868,
E-mail addresses:*mihai.crenganis@ulbsibiu.ro*(M. Crenganis)

First the paper presents the SPIF process and highlights the forces that appear during this process.

Advantages and disadvantages of using the KUKA KR6 robot in this process are presented.

Then the paper describes a step for the development of the dynamic model of the robot that of creating a mathematical model for the inverse kinematics of the robot. The inverse kinematics is necessary to command and control the trajectory of the robot during the SPIF process. The dynamic model of the KUKA KR6 robot is created in MATLAB®-SimMechanics. After the dynamic model validation some specific trajectories are imposed and the forces that can appear during SPIF process are taken into consideration. After running the dynamic simulations, it was concluded that the KUKA KR6 robot can be used in single point incremental forming processes even if this is a small pay load robot

2. SINGLE POINT INCREMENTAL FORMING

In the last few years incremental sheet forming (ISF) process (SPIF) of thin metal sheets has attracted a continuous growing interest in the manufacturing of unique parts and rapid prototyping. This process has some unique advantages, such as process flexibility, low cost of tools and increased formability.

Single point Incremental forming of a sheet metal is a technologic manufacturing process where a sheet metal is formed into a desired part by a series of point to point small deformations. This process can also be applied to other materials, like polymers and composite not only to metal sheets. The process can be performed on different types of industrial machines like CNC machines and more recently industrial robots. In this manufacturing process, deformation is achieved using a numerically controlled punch or tool. This tool advances through a trajectory very well defined by the CNC program of a controlled machine or by the industrial robot program. The material is partially deformed only in the area that comes into contact with the punch, so the material is gradually deformed [1, 2]. A simplified view of SPIF process can be seen in Fig. 2.

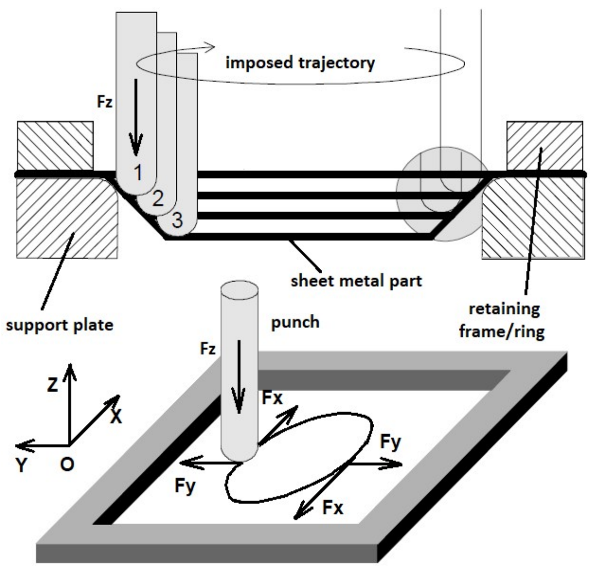

Fig.2. SPIF process representation.

The main features and advantages of the SPIF process are: the process does not require a mold in the classical sense, but only a fastening or clamping system for the metal sheet; the process is used as an alternative to conventional metal forming processes in the production of small series or prototypes metal parts;

The incremental forming process is relatively slow compared to conventional pressing and stamping processes but does not require expensive machining equipment; the manufacturing time of the parts depends on the length of the deformation trajectory necessary to achieve the desired profile, the speed of the active element with which the deformation is performed, and the available power of the equipment used; the deformation method has a high flexibility, with the same equipment being able to manufacture various configurations and sizes of parts; the levels of deformation obtained by this process are much higher than those obtained by conventional pressing processes, this making the process suitable for processing hard-deformable materials; [2−4]. In most cases, the sheet metal is incremental formed using a round tipped tool, with a diameter of 5 to 20 mm.

As disadvantages: the deformation being localized, some undeformed smooth areas remain onto the part, and in the deformed areas there is a considerable thinning of the thickness of the material. The deformation being asymmetrical, the states of stress and deformation in the material are uneven which leads to considerable elastic recoveries in the material, consequently the dimensional precision is lower than in the case of a conventional pressing process, and the methods for removing this inconvenience must be studied in future research [1].

Because single point incremental forming process (SPIF) process presents a great flexibility, different studies regarding the usage of industrial robots in this manufacturing process can be found. SPIF of the metal sheets is a modern method of plastic deformation, with an enormous potential regarding the flexibility and personalization of the parts obtained by this manufacturing process. Belchior et al. [2] used a Fanuc S420iF robot in their research to study forces during SPIF processes Fig. 3.

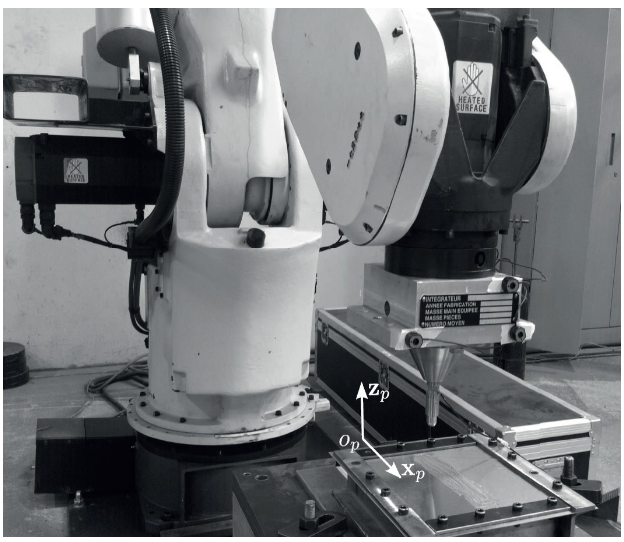

Fig. 3. SPIF process using an industrial robot.

Schäefer et al. [10] used at Fraunhofer Institute for Manufacturing Engineering and Automation an industrial robot in incremental forming by moving a hammer-punching instrument on a well-defined trajectory onto a thin metal sheet fixed in a rigid metal frame. The whole process was carried out without the use of a special mould plate to produce the desired three-dimensional piece. A three-dimensional metallic sheet of 300 × 300 mm was produced for the first time using this forming process. The punching frequency of the hammer instrument was about 100 hits / s. They conclude that forces during this process are relatively low compared to other forming processes. Therefore, an industrial robot with a medium pay-load can be used to move the percussion tool. Also, metal parts can be produced with cost-effective robotic system and without a major investment in the equipment. Production of sheet metal parts in small and medium businesses can benefit from this new technology.

Panti et al. presents in the paper [8] a two-sided incremental sheet forming (TSISF), which can be described as a kinematic ISF solution. He proposed a two sided forming concept with a C frame mounted on a FANUC S430iF industrial robot to create different shapes without releasing the metal sheet. The method presented by the tool path calculation showed that the eccentric mounting of the upper tool allows for an optimal contact position in the TSISF, however the eccentricity must be adjusted for the different pulling angles.

In all the studies presented so far, researchers describe the presence of forces on three directions during the incremental forming process, a vertical one *Fz* and two in the blank's plane *Fx*, *Fy*. Depending on the type of incremental forming process these three forces can vary from case to case depending on different process factors and parameters like: if a CNC machine is used or a robot, material type, sheet metal thickness, spindle speed, punch/tool diameter, incremental size, incremental depth size, metal part geometry or shape, punch trajectory. Blaga, presents in his work [1] various variants of deformation of thin metal sheets of DC04. He took into consideration different draw angles in the blank and different trajectories to obtain the truncated shape of the piece. The main objective of the study was to determine the optimal forming strategy by shifting the penetrating position of the punch and the path it follows to obtain a truncated cone through SPIF process, so that the strain distribution can be homogeneous and thickness reduction minimal. To carry out the tests, a DC04 steel sheet (SR EN 10130−2000) with a thickness of 0.7 mm was used.

The values of the forces on the horizontal direction *Fx*, *Fy*, in his research reached a maximum value of 414 N in the case of successive punch presses in the same area. In a spiral trajectory the maximum force value on the *Fx* and *Fy* directions is 391 N. In terms of *Fz* force, this reaches the maximum value of 1001 N.

Petek used in [12] a computer numerical controlled machine to perform the forces analysis during single point incremental sheet metal forming. The paper presents results regarding the influence of the wall angle, rotation of the punch, vertical step size, tool diameter and lubrication on the magnitude of forming forces during the manufacturing process. The forming forces were measured using specially designed force measuring system which was connected to the milling machine. The deformations and forces analyses were researched on DC05 steel of 1 mm in thickness. The experiments were carried out with the wall angles of 40°, 50°, 55°, 60°, 65°, 70°, 71°, 75° and 90°, respectively on truncated cone geometry.

The value of *Fz* force started from 1000N when using a 10 mm diameter punch and 1mm forming depth for some parts and reached the maximum value of 1750 N for a 16 mm diameter punch and 3 mm depth increment. Pohlak created in [9] a model for incremental sheet forming process through finite element analysis (FEA) but also measured the process forces with a piezoelectric load cell. He concluded that in SPIF the final thickness of the wall depends directly on wall draft angle. If this angle is approaching 0°, the strain state is above forming limit curve and material will break [9]. Forces determined by FEM reached the maximum value of 300 N for *Fz* and 130 N for *Fx*, *Fy*. The forces recorded from the measurements reached the same values as for the finite element analysis.

Belchior et al. [2] used a Fanuc S420iF robot in their research to study forces during SPIF processes. Also, they created a FEA model to evaluate the tool center point forces during the forming stage. These forces were then defined as an input data of the elastic robot model to predict and correct the tool path deviations. The material used in the research was 5086 H111 aluminum alloy. The part consists in a frustum cone with 45° wall angle and a 200 × 200 × 1 mm^3 metal sheet. The depth of the frustum cone was 40mm. They used a hemispherical punch forming tool with a diameter of 15 mm. To minimize friction, grease was used between the sheet and the tool. The trajectory consists in successive circular tool paths at constant 1 mm feed rate. The Fz measured forces were about 800–1200 N when using the industrial robot. Kyung Hee Koh et al. performed some analysis of forming forces in SPIF process producing a cone frustum from 1050 aluminum sheet metal of 0.8 mm thickness. The forming tool has a 6 mm diameter ball type. The step distance was 0.5 mm/path. The measured *Fz* force has a maximum of about 500 N, *Fx*, *Fy* registered a value of about 300 N each. Jeswiet [7] measured the forces during SPIF process when forming cones and truncated pyramids from 3003–0 aluminum alloy with 1.2 mm thickness. He adopted three draw angles 30°, 45° and 60°. For this work a cantilever type of sensor was specially designed using strain gauge Wheatstone bridges. The maximum normal forces measured was 289 N for 30°, 445 N for 45° and 596 N for 60°.

Other research like Arens [11] and Bagudanch, reached grater values for the forces during PSIF process. When using a greater tool diameter of 20 mm the measured *Fz* forces were of about 3581 N. A table-type dynamometer Kistler 9257B was used for measurement. The blanks had a dimension of 150 × 150 mm × mm. The geometry used in this work was a conical frustum truncated, the initial drawing angle 20º and the generated radius of 40 mm. The material used was stainless steel AISI 304 with a sheet thickness of 0.8 mm. The parameters varied during the experiments were the tool diameter (6, 10 and 20 mm), the step down (0.2 and 0.5 mm) and the spindle speed (free and 1000 rpm). The feed rate used for all tests was set to 3000 mm/min. Houghton TD-52 lubricant for metal forming applications was used.

To conclude, it is necessary and of a great importance to know the magnitude of these forces when trying to determine if the equipment available is capable of incremental forming of metal sheets. A preliminary step to the incremental forming of different blanks is creating the model of the process and the finite element analysis. Often this modeling procedure is quite laborious and time consuming. Also, the characteristics of the material must be known like: strength coefficient [MPa], strain hardening exponent, material anisotropy, Young's modulus of elasticity [MPa], density [kg/m3], Poisson's ratio, initial specimen thickness, to fully and correctly model the FEM analysis.

3 KUKA KR6-2 INVERSE KINEMATICS

This paragraph describes the steps taken into account to develop the inverse kinematics for the 6 degrees of freedom (DOF) KUKA industrial robot. A simplified view of KUKA KR6-2 is presented in Fig. 4.

Before one can study the dynamics of a robot in different manufacturing processes the laws of motion or movement should be known. As mentioned before KUKA KR6-2 robot is a small pay load industrial robot and developing the inverse kinematics for this structure is a preliminary step to the dynamic simulation of single point incremental forming using this industrial robot.

In Fig. 5, the kinematic scheme of KUKA KR6-2 robot is presented. Based on this scheme all the kinematics and the dynamics of the robot is developed. One can notice that the robot has in its structure the following types of joint movements: $A1$ − Rz, rotation around the OZ axis; A2 − Ry, rotation around the OY axis; $A3$ − Ry, rotation around the OY axis; $A4$ − Rx, rotation around the OX axis; $A5$ − Ry, rotation around the OY axis; $A6$ − Rx, rotation around the OX axis.

If one attaches to each element "i", (i = 0…6) of the structure, one fixed coordinate system k_i (O_i, x_i, y_i, z_i), then the homogeneous transfer matrices A_i which characterize the relative movements between each element of the mechanic structure can be expressed. If one knows the relative parameters θ_i, (i = 1 …6) and the homogeneous transfer matrix form between two elements or the homogeneous transfer matrix between the coordinate systems attached to each element, the total transfer matrix between the system k_6 (O_6, x_6, y_6, z_6) and system k_0 (O_0, x_0, y_0, z_0) can be determined.

$$H_{06} = A_1 \cdot A_2 \cdot A_3 \cdot A_4 \cdot A_5 \cdot A_6 \cdot A_7 \cdot A_8 \cdot A_9 \cdot A_{10} \cdot A_{11} \cdot A_{12} \tag{1}$$

$$\begin{gathered} A_1 = Rz\,(\theta_1),\ A_2 = Tx\,(L1),\ A_3 = Tz\,(L2), \\ A_4 = Ry\,(\theta_2),\ A_5 = Tz\,(L3),\ A_6 = Ry\,(\theta_3), \\ A_7 = Tz\,(-L4),\ A_8 = Tx\,(L5),\ A_9 = Rx\,(\theta_4), \\ A_{10} = Ry\,(\theta_5),\ A_{11} = Rx\,(\theta_6),\ A_{12} = Tx\,(L_6). \end{gathered} \tag{2}$$

where: $L1$ = 260 mm; $L2$ = 675 mm, $L3$ = 680 mm; $L4$ = 35 mm; $L5$ = 670 mm; $L6$ = 115 mm.

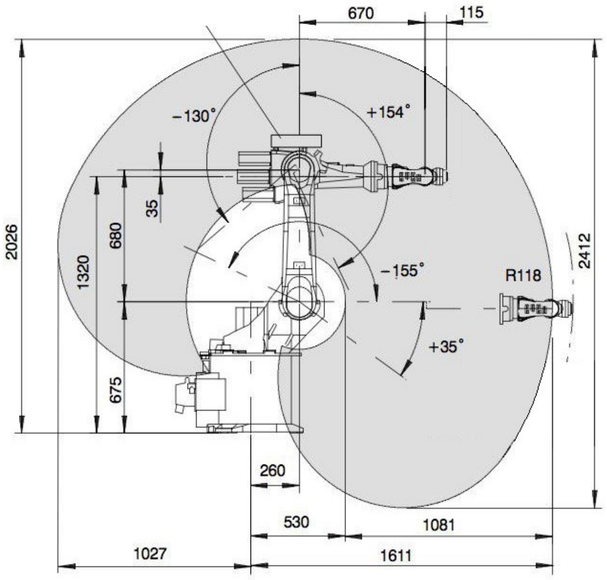

Fig. 4. KUKA KR6-2 industrial robot schematic.

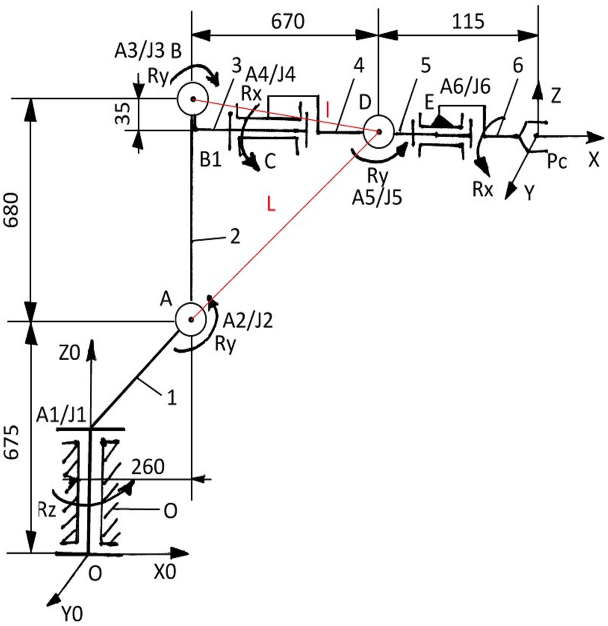

Fig. 5. KUKA KR6-2 kinematic scheme.

To resolve the inverse kinematics problem, one need to start from the fact that the position and the orientation of the end effector x, y, z, ϕx, ϕy, ϕz in reference to the fixed coordinate system are known then one needs to determine the relative positions between robot's elements, in this case θ_i, (i = 1 …6). Therefore, it must be determined the relative parameters θ_i between elements which represent the rotation in all the kinematic joints of the industrial KUKA robot. The steps for solving the inverse kinematic problem are: The transfer matrix which characterize the end effector position and orientation in reference to a fixed coordinate system k_0 (O_0, x_0, y_0, z_0) has to be created, based on the absolute parameter`s x, y, z, ϕx, ϕy, ϕz of the end effector or the tool.

$$H_{06} = T_x \cdot T_y \cdot T_z \cdot R_{\varphi x} \cdot R_{\varphi y} \cdot R_{\varphi z}. \tag{3}$$

Another step is to determine the position of $J5$ kinematic joint (position of D). Based on D position, θ_5 is computed like follows.

$$H_D = H_{06} \cdot A_{12} - 1, \quad (4)$$

were:

$$x_D = H_D(1,4);$$
$$y_D = H_D(2,4); \quad (5)$$
$$z_D = H_D(3,4).$$

If D is known, by projecting its position onto XOY plane the first joint movement θ_1 is determined:

$$\theta_1 = \arctan\frac{Y_D}{X_D}. \quad (6)$$

Because θ_1 angle is determined it is simple to compute the position of $J2$ joint (position of A).

$$H_A = A_1 \cdot A_2 \cdot A_3. \quad (7)$$

If position of A and D are known, using a geometric/trigonometric approach one can compute the θ_3 joint movement. To determine θ_3 one also need to use the generalised cosine formula in ABD and $B1BD$ triangles. The distance from point B to D is:

$$l = \sqrt{L4^2 + L5^2}. \quad (8)$$

The distance from point A to D is:

$$L = \sqrt{(X_D - X_A)^2 + (Y_D - Y_A)^2 + (Z_D - Z_A)^2}. \quad (9)$$

The θ_3 joint movement is computed using the equation:

$$\theta_3 = \pm(\alpha - \beta), \quad (10)$$

where:

$$\alpha = \arccos\frac{(L^2 - {l_3}^2 - l^2)}{(-2 \cdot l_3 \cdot l)} \quad (11)$$

is the angle between $L3$ and l and:

$$\beta = \arctan\frac{l_5}{l_4} \quad (12)$$

is the angle between $L4$ and l .

Once the angles θ_1 and θ_3 have been computed, the angle θ_2 can be determined. This is possible by using the solve function in Matlab, which will solve a system of two equations with two unknowns, namely $\sin\theta_2$ and $\cos\theta_2$. The two equations of the mathematical system are extracted from the equality:

$$H_D = A_1 \cdot A_2 \cdot A_3 \cdot A_4 \cdot A_5 \cdot A_6 \cdot A_7 \cdot A_8, \quad (13)$$

where H_D express the position of D also determined by (4). In the above system of equation only $\sin\theta_2$ and $\cos\theta_2$ are unknown. After solving the system using "solve" function from Matlab we obtained numerical values for $\sin(\theta_2)$ and $\cos(\theta_2)$.

$\sin(\theta_2)$= (l2 - z1)/(c3*l5 - l4*s3) + ((c3*l4 - l3 + l5*s3)*(l2*l3 - l3*z1 - c3*l5*(c3^2*l4^2 + c3^2*l5^2 - 2*c3*l3*l4 - l2^2 + 2*l2*z1 + l3^2 - 2*l3*l5*s3 + l4^2*s3^2 + l5^2*s3^2 - z1^2)^(1/2) + l4*s3*(c3^2*l4^2 + c3^2*l5^2 - 2*c3*l3*l4 - l2^2 + 2*l2*z1 + l3^2 - 2*l3*l5*s3 + l4^2*s3^2 + l5^2*s3^2 - z1^2)^(1/2) - c3*l2*l4 + c3*l4*z1 - l2*l5*s3 + l5*s3*z1))/((c3*l5 - l4*s3)*(c3^2*l4^2 + c3^2*l5^2 - 2*c3*l3*l4 + l3^2 - 2*l3*l5*s3 + l4^2*s3^2 + l5^2*s3^2));

$\cos(\theta_2)$ = -(l2*l3 - l3*z1 - c3*l5*(c3^2*l4^2 + c3^2*l5^2 - 2*c3*l3*l4 - l2^2 + 2*l2*z1 + l3^2 - 2*l3*l5*s3 + l4^2*s3^2 + l5^2*s3^2 - z1^2)^(1/2) + l4*s3*(c3^2*l4^2 + c3^2*l5^2 - 2*c3*l3*l4 - l2^2 + 2*l2*z1 + l3^2 - 2*l3*l5*s3 + l4^2*s3^2 + l5^2*s3^2 - z1^2)^(1/2) - c3*l2*l4 + c3*l4*z1 - l2*l5*s3 + l5*s3*z1)/(c3^2*l4^2 + c3^2*l5^2 - 2*c3*l3*l4 + l3^2 - 2*l3*l5*s3 + l4^2*s3^2 + l5^2*s3^2),

where:
$c1 = \cos(\theta_1)$; $s1 = \sin(\theta_1)$; $s3 = \sin(\theta_3)$; $c3 = \cos(\theta_3)$;
$l1$, $l2$, $l3$, $l4$, $l5$, $l6$ are the lengths of the robot kinematic elements; $x1, y1, z1$ is the position of D.

$$\theta_2 = \arctan\frac{\sin(\theta_2)}{\cos(\theta_2)}. \quad (14)$$

The last step for the inverse kinematics mathematical model development is to determine the θ_4, θ_5, θ_6 joint movements.

From (1) and (13) one can note the expression:

$$H_{06} = H_D \cdot A_9 \cdot A_{10} \cdot A_{11} \cdot A_{12}. \quad (15)$$

From the above system of equations only A_9, A_{10}, A_{11}, are unknown so the below notation can be made :

$$H = A_9 \cdot A_{10} \cdot A_{11}, \quad (16)$$

$$H = H_D^{-1} \cdot H_{06} \cdot H_{12}^{-1}. \quad (17)$$

obtained by multiplying the matrix $H_{06}$to the left and to the right with H_D^{-1}, H_{12}^{-1}.

As an observation, the H matrix expresses only the orientation of the end effector of the robot. Because of this by referring to Euler angles to describe the orientation of a rigid body with respect to a fixed coordinate system results the following equations:

$$\theta_5 = \arccos(H(1,1)),$$
$$\theta_6 = \arctan\frac{H(1,2)}{H(1,3)}, \quad (18)$$
$$\theta_4 = -\arctan\frac{H(2,1)}{H(3,1)}.$$

To validate the mathematical model of the inverse kinematics one can use the direct kinematic model which is very simple to be determined. Knowing all θ_i relative joint movements it results that all Ai matrix are known. It results from (1) that $H06$ matrix is known. $H06$ will be noted:

$$H_{06} = \begin{pmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{pmatrix}. \quad (19)$$

The direct kinematics states that knowing all the relative movements from the kinematic joint one can determine the absolute position and orientation of the robot expressed to the $k0$ reference base frame. From homogeneous transfer matrix definition results the position of the tool center point:

$$\begin{cases} X = a_{14} \\ Y = a_{24}\,. \\ Z = a_{34} \end{cases} \quad (20)$$

Using the Euler angles formulation one can obtain the absolute orientation of the end effector:

$$\begin{cases} \varphi_x = -\arctan2(a_{23}, a_{33}) \\ \varphi_y = \arcsin(a_{13}) \quad . \\ \varphi_z = -\arctan2(a_{12}, a_{11}) \end{cases} \quad (21)$$

4 KUKA KR6-2 INVERSE DYNAMICS IN SPIF PROCESSES

The entire dynamic model of the KUKA KR6-2 robot is necessary to validate if this type of robot can be used in Center of Metal Forming for single point incremental forming (SPIF).

The entire dynamic model of the KUKA robot used in PSIF process is modelled in MATLAB®/Simulink SimMechanics. To create the dynamic model of the KUKA robot a tri-dimensional model was preliminary modelled in SolidWorks. SolidWorks was used to develop CAD model of KUKA KR6-2 robot parts and its assembly because it is quite difficult to model complicated 3D parts directly in SimMechanics environment. The SolidWorks virtual model is presented in Fig. 5.

This 3D model is a very important step because all SolidWorks® robotic arm features, element dimensions, coordinate systems, vector relationships between elements, mass, center of mass and volume, gravity forces, and inertia modules will be imported into SimMechanics®.

The SimMechanics virtual model is presented in Fig. 6.

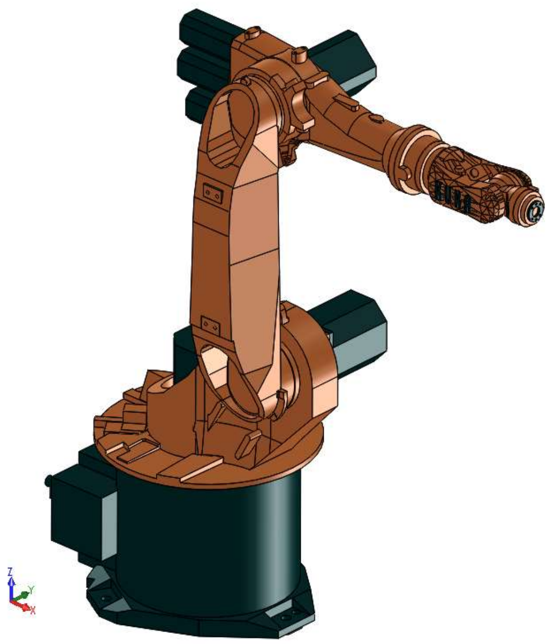

Fig. 5. Tri-dimensional SolidWorks model of KUKA Kr6-2.

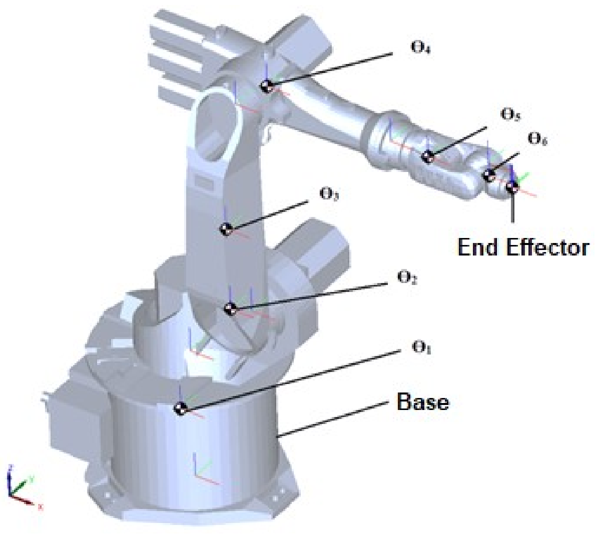

Fig. 6. SimMechanics model of KUKA Kr6.

In SimMechanics inverse dynamics starts with given motions as functions of time provided by above presented inverse kinematics equations and differentiates them twice to yield the forces and torques needed to produce the given motions. The model contains all the kinematic elements of the KUKA robot and all the revolute joint between the structure elements. At the revolute joints blocks in MATLAB SimMechanics joint sensors that can sense the computed torque in Nm were attached. Also from forces analysis during SPIF process we have concluded that the forces that must act at the end effector to validate the usage of KUKA KR6-2 in incremental forming are as follows: *Fz* = 500 – 1000 N; *Fx*, *Fy* = 300 – 500 N; We have choosen *Fz* = 1000 N, *Fx*, *Fy* have a sine wave form for an imposed circular trajectory of the tool. *Fx*max = *Fy*max = 500 N.

The most important KUKA KR6-2 characteristics are presented in Fig 7. The max joint torquesare shown.

In Figs. 8 and 9 the dynamic model block from SimMechanics is presented.

The variation of joint torques are presented in Fig. 10.

Type	**KR 6-2**			
Rated payload	**6 kg**			
Maximum total load	**36 kg**			
Number of axes	**6**			
Axis data	**Joint speed with rated payload**	**Nominal motor speed**	Gear ratio	Maximum torque Dynamic/ static
	6 kg			
Axis 1 (A1)	**156°/s - 26rpm**	4100 rpm	157.69:1	5.8 / 18.9Nm
Axis 2 (A2)	**156°/s - 26rpm**	4100 rpm	157.69:1	5.8 / 18.9 Nm
Axis 3 (A3)	**156°/s - 26rpm**	3000 rpm	115.38:1	4.7 / 9.6 Nm
Axis 4 (A4)	**343°/s - 57rpm**	6000 rpm	105.26:1	0.8 / 4.5 Nm
Axis 5 (A5)	**362°/s - 60rpm**	6000 rpm	100:1	0.8 / 4.5 Nm
Axis 6 (A6)	**659°/s - 110rpm**	6000 rpm	54.54:1	0.8 / 4.5 Nm

Fig. 7 KUKA KR6-2 PMSM motor technical data.

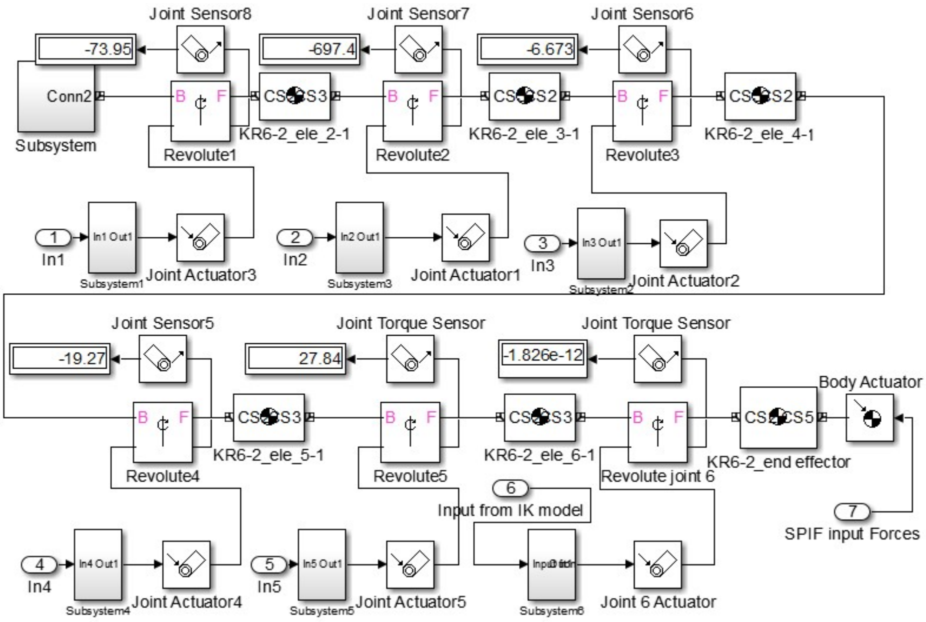

Fig. 8. SimMechanics model block of KUKA KR6 Dynamics.

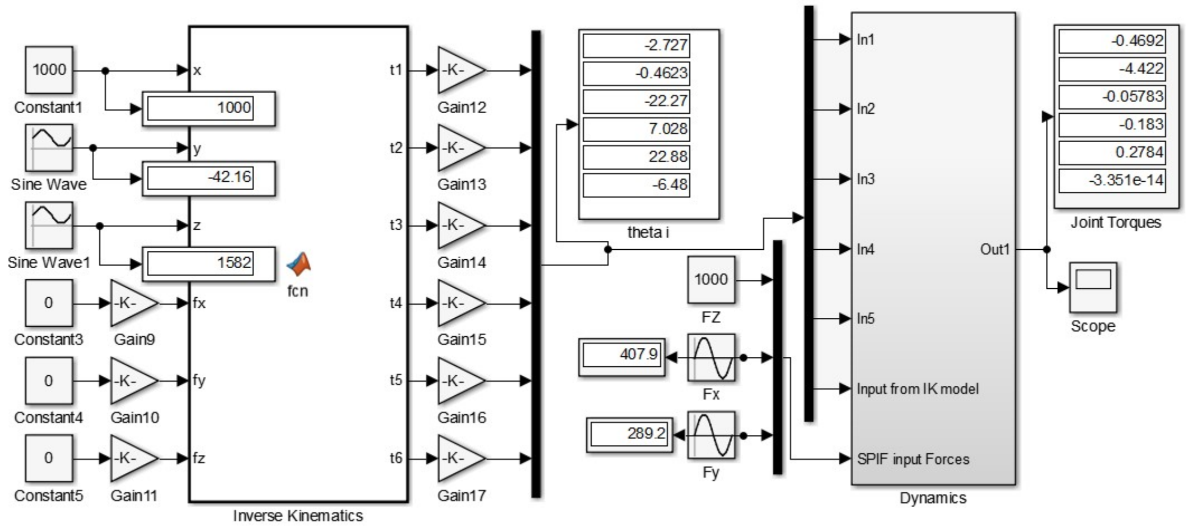

Fig. 9. Dynamic model results during simulations.

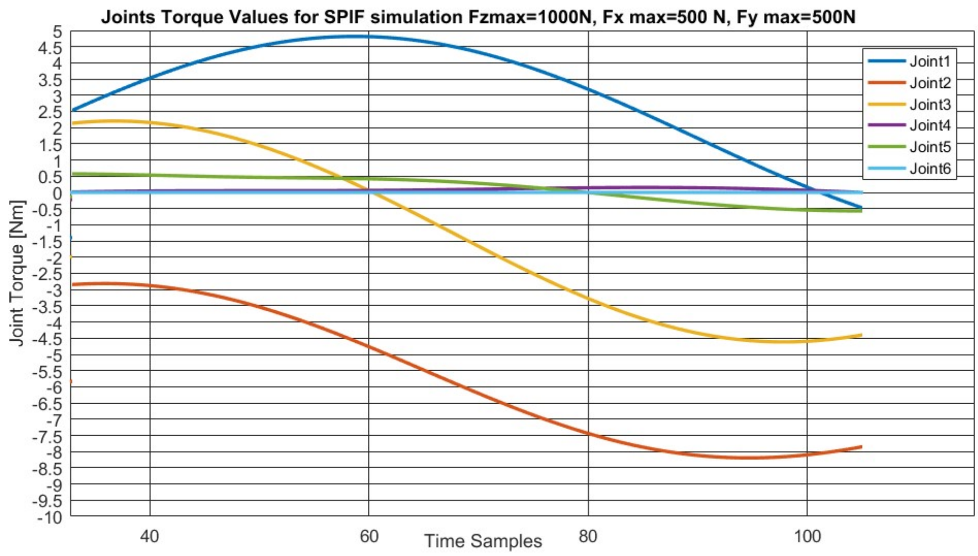

Fig. 10. Torque joint variation in a simulated SPIF process.

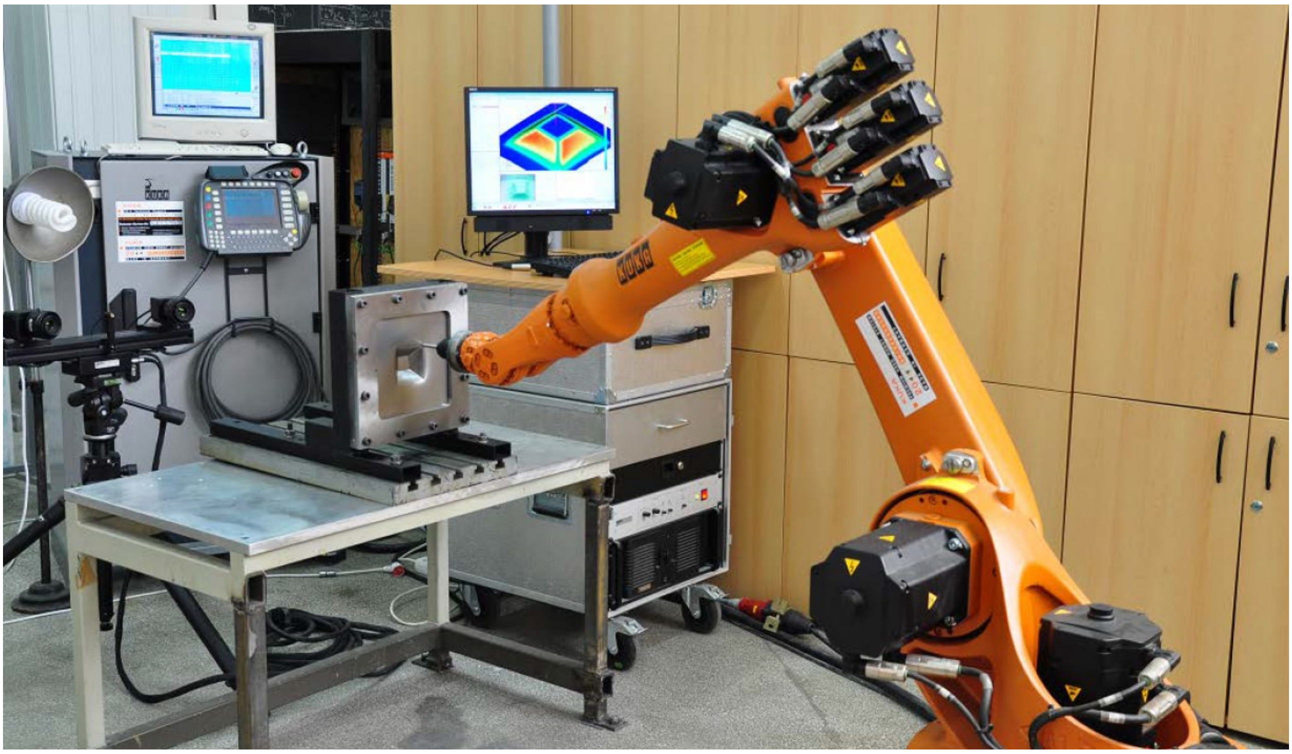

Fig.11. The KUKA KR6-2 robot used for SPIF processes in the Center of Metal Forming Sibiu.

5 CONCLUSIONS

After running the simulations, we concluded that the kinematic equations and the developed dynamic model were correct and were validated during the virtual forming processes.

This dynamic model of the KUKA KR6 robot was necessary to verify that the mechanical structure of this low payload industrial robot can withstand the forces in SPIF processes.

The simulations were carried out for the following values of the forces during the SPIF process: Fz = 1000 N, Fx, Fy have a sine wave form for an imposed circular trajectory of the tool. Fxmax = Fymax=500 N. The maximum resistant torques measured in the kinematic joint were: $T1$ = 4.82 Nm; $T2$ = −8.2 Nm; $T3$ = −4.62 Nm; $T4$ =0.2 Nm; $T5$ = 0.58 Nm; $T6 \approx 0$ Nm;

Comparing the measured results from SPIF virtual simulations and the technical data provided by the above Fig. 7 we have concluded that the KUKA KR6-2 industrial robot can be used in SPIF processes without getting a mechanical failure in the robot's structure.

ACKNOWLEDGEMENT: This work was supported by a grant of the Romanian Ministry of Research and Innovation, CCCDI – UEFISCDI, project number PN-III-P1-1.2-PCCDI-2017-0446/82PCCDI/201, within PNCDI III”.

REFERENCES

[1] A. Blaga, *Contributions regarding single point incremental forming of thin metal sheets,* PhD Thessis, Sibiu 2011.

[2] J. Belchior, D. Guines, L. Leotoing, E. Ragneau. *Force prediction for correction of robot tool path in single point incremental forming*. ESAFORM, 2013, Trans Tech Publications, 554-557, pp.1282-1289, 2013.

[3] R.E. Breaz, O. Bologa,V. Oleksik, G. Racz, *Computer Simulation for the Study of CNC Feed Drives Dynamic Behavior and Accuracy*, The IEEE Region 8 EUROCON 2007, International Conference on “Computer as a tool” Warsaw University of Technology, Warsaw, Poland, September 9-12, pp. 2229-2233, 2007.

[4] R.E. Breaz, O. Bologa, S.G. Racz, *Selecting industrial robots for milling applications using AHP*, 5th International Conference On Information Technology And Quantitative Management, ITQM 2017, New Delhi, India, December 08-10, 2017, Volume 122, pp. 346-353, 2017.

[5] J.R. Duflou, Y. Tunçkol, A. Szekeres, P. Vanherck,*Experimental study on force measurements for single point incremental forming*, J Mater Process Technol 189(1–3):65–72(2007).

[6] Iseki, H., Kato, K., Kumon, H. Ozaki, K., *Flexible and Incremental Sheet Metal Bulging Using a Few Spherical Rollers*, TR. JSME, 59(565-C), 2849-2854.

[7] J. Jeswiet, F. Micari, Hirt G, Bramley A, Duflou J, Allwood J. *Asymmetric single point incremental forming of sheet metal.* CIRP Ann-Manuf Technol2005; 54:623–49.

[8] I. Paniti, *A novel, single-robot based two sided incremental sheet forming system*, ISR 2014 München.

[9] M. Pohlak, J. Majak, and R. Küttner, *Incremental sheet forming process modelling – plimitation analysis,*Journal of Achievements in Materials and Manufacturing Engineering, vol. 22, no. 2, pp. 67–70, 2007.

[10] T. Schaefer, R. Schraft,*Incremental Sheet Metal Forming with industrial robots,* Fraunhofer Institute Manufacturing Engineering and Automation, Stuttgart, 2004.

[11] R. Aerens & P. Eyckens & A. Van Bael & J. R. Duflou, *Force prediction for single point incremental forming*,Int J Adv Manuf Technol, 2009.

[12] A. Petek, K. Kuzman, J. Kopac, *Forces and deformations analysis of incremental sheet metal forming,* CAM3S, 11^{th}, International Scientific Conference on temporary achievements inmechanics, manufacturing and materials science.