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An Experimental Investigation of Hybrid Position/Force Control for Metal Spinning Process

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Abstract

This study proposes a new approach for controlling metal spinning process using force and position feedbacks. Problems which usually occur during common practices of spinning can be categorized as follows: sheet metal wrinkling, fractures and spring-back. In order to avoid the above mentioned defects optimized tool path strategies are required. Additionally, forming forces must be under control. In this paper, basic force control strategies which have been proposed for robotics applications and adopted for spinning processes, have been thoroughly reviewed. Classical control theories such as PID controllers are integrated with the reviewed force controller strategies. In order to investigate the efficiency of the proposed control method , a test rig is designed which is composed of a manual lathe ,a geared stepper motor, a linear encoder ,a 3-axis KISTLER dynamometer , a high speed motion control card and a high resolution 16-channel data acquisition card. A spinning roller and tool post is manufactured and mounted on the lathe. Further, a supervisory program has been developed in MATLAB software which can control the process in real time. The program can also analysis and record the data.

Keywords: Metal Spinning, Hybrid Control, Force control, Position control, Wall thickness

Introduction

Metal spinning typically involves the forming of asymmetric components over a rotating mandrel using rigid tools or rollers. Based on the common practices in industry, the method can be divided into two categories: manual or conventional spinning and power spinning, see [1] for further details. In the power spinning methods, a considerable amount of forces and thickness reduction can be take place. Shear spinning process is one of the power spinning methods which usually is applied for forming of conical and hemisphere or curved shapes. The most common application of shear spinning is for conical shapes. A schematic of the cone shear spinning process have been illustrated in Figure 1.

Since the process involves only localized deformation, much greater deformation of the material can be achieved with lower forming forces as compared with other similar processes such as deep drawing [2]. Metal spinning processes have been expand a new horizon in nowadays industries, since tendency to use minimum tool and equipment costs and also using lower forces. In addition, the automation of the process is of great importance to leading edge industries.

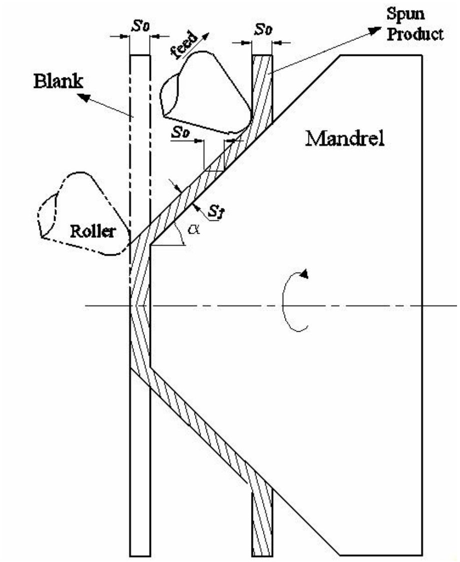

Fig1: Schematic of Shear spinning process

Unlike the metal cutting processes, in most cases a spun product with desired specifications cannot be achieved just by moving the roller along an accurate tool path. Due to the complex behavior of the material under spinning operation, it is essential to control the amount of forming forces.

There are a few force control algorithm reported in the open access literature, for example: Explicit Force Control [3, 4], Implicit Force Control [3, 4], Hybrid Position/Force Control [5], Reaction Compensation [6] and Impedance Control [7]. But these methods are usually applied to robotic applications such as assembling, welding, tracking and so on [8]. One of the pioneering reports about the importance of force control task on metal spinning processes is the research work by E.Quigley and J.Monaghan [9]. They reported that an NC spinning machine equipped with force measuring sensors will allow precise matching of roller passes. However, this research was limited to numerical simulation of the process.

H. Arai [8] proposed the force control of shear forming process. He used the Hybrid position/force control methodology and verified his control theory by conducting some of spinning experiments on aluminum blanks. D.Hanafi and J.Katupitiya [10, 11] implemented the on/off non-linear force controller for shear spinning. Their force controller acts similar to Reaction Compensation method. The presence of nonlinear terms in force controller, such as on/off, results in complicated controller.

According to the results obtained in the current research, it has been shown that in order to achieve the uniform wall thickness on spun parts, the forming forces should be accurately controlled. Therefore, this paper proposes a hybrid position/force controller including PID controllers to overcome the non uniform thickness distribution problem on spun products.

Shear Spinning Mechanics

In shear spinning, the final wall thickness is achieved by controlling the gap between the roller and mandrel[1] [2]. Kalpakcioglu [12] proposed an ideal model to analyze the shear forming process. The sine law, which relates the blank wall thickness, S_0, and the finished work-piece wall thickness of the, S_f, is given by Equation 1. Where α is half the cone apex angle. When metal spinning is performed in accordance with sine law, the thickness of the component in the axial direction is the same as the thickness of the starting blank [1, 2].

$$s_f = s_0 \times \sin\alpha \tag{1}$$

Hybrid position/force Control and Control Law

In hybrid position/force control [5], all degrees of freedom are partitioned into two sets, the force controlled and the position controlled degrees of freedom. Each degree of freedom is controlled by either a force controller or a position controller and they are mutually exclusive. Two task frames are defined for the experiment: force sensor frame or "xyz" frame, and the work frame or "tn". The work frame is divided to two degrees of freedom (DOFs). For obtaining force and positional components in work frame, the corresponding components resulted from the sensor frame, have been projected using trigonometric relations. In the first DOF of Work frame, the roller feed along the path, V, is controlled to the desired constant value, V_d . Note that, the desired velocity is actually controlled by position controller. On the other hand, the other DOF of Work frame is responsible for controlling force component normal to the mandrel surface, F_n, so that this component is regulated to the constant value, F_{nd}.

DOFs of the hybrid controller, V_d *and* F_n are shown in Figure 2. The general control strategy of hybrid control is illustrated in Figure 3.

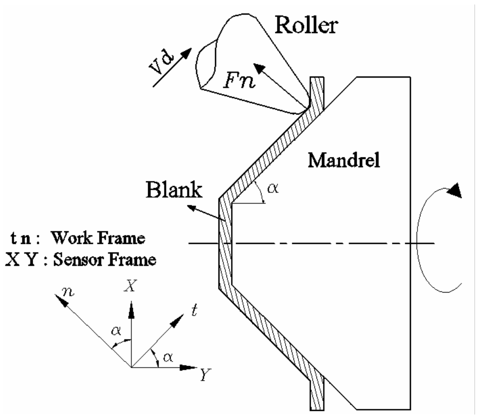

Figure 2: Degrees of freedom in shear spinning experiment

[1] Clearance

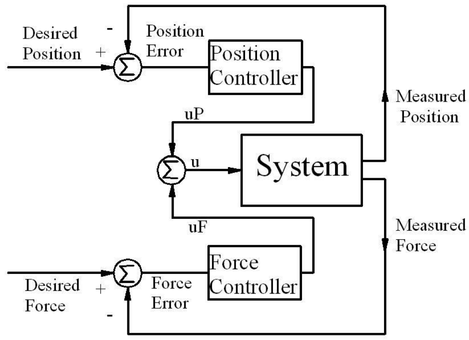

Figure 3: Hybrid Force / Position Control [5]

The proposed block diagram of PID controller is illustrated in Figure 4. The control law for hybrid force/position control is expressed by Equation 2. Note that because of noisy inherent of analog force signals, the derivative term is not used for the force controller [13].

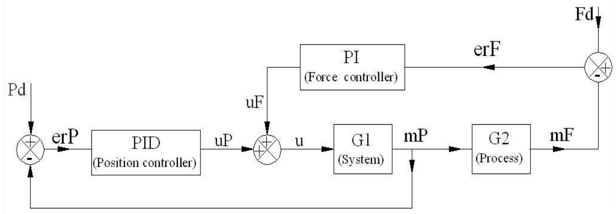

Figure 4: Proposed Hybrid Force / Position Control using PID controllers

$$u = uP + uF \tag{2}$$

$$uP = KpP \times erP + KiP \int erPdt + KdP \frac{derP}{dt}$$

$$uF = KpF \times erF + KiF \int erFdt$$

System Identification

In order to design reliable controller, the dynamic model of the system should be identified. The word "System" addresses all of the electronics and mechanical devices between the PC controller and the machine tool. During system identification experiments, input and output to the system are desired or commended position and actual or measured position, respectively. Figure 5 shows the schematics of system identification open loop experiments.

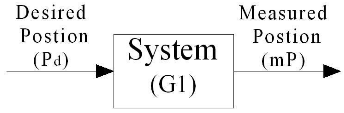

Figure 5: System identification input and output

Since the input of system during force control operation is a ramp signal integrated with the force effort oscillations, thus a set of ramp signals modulated with sine waves with the frequencies of 0_5 Hz have been applied to system that is shown in Figure 6. The open loop experiment results have been loaded to Mathwork System Identification Toolbox of MATLAB software which is based on Ljung's system identification theory [14]. The agreement between the identified model and the actual output is extremely close, 99.18% for X-axis.

Equation 3 shows the indentified transfer function of system(Figure 6).

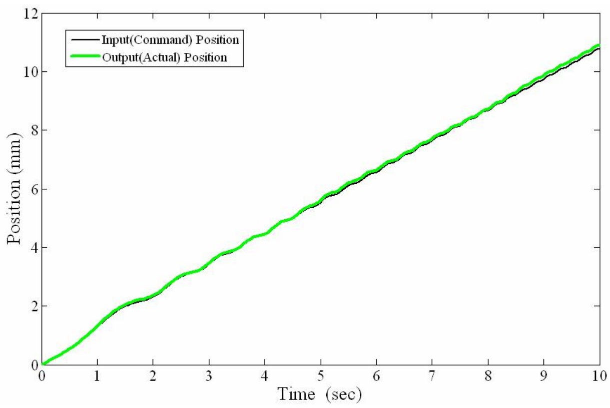

Figure 6: System identification of X axis

$$G_1(s)=\frac{1.01s^2+99.52s+3982}{s^3+0.1173s^2+3948s+0.02563}$$	(3)

In order to identify the dynamic model of forming process G_2, the forming force profile should be calculated by complicated numerical calculations during the process. But this approach is highly complex real time control problems. Thus, the process is modeled with linear constant stiffness for sake of simplicity, see [10]. An experiment has been done for measuring the stiffness of tool post in X and Y directions by moving the tool post in above mentioned directions, with incremental steps toward rigid mandrel. By recording the machine position and force components, relationship between the displacement and force in X and Y directions can be derived. The experimentally obtained stiffness value for tool post in machine axis directions is according to Equation 4. .

$$K_x = 4941 N/mm \qquad (4)$$
$$K_y = 4143 N/mm$$

Test rig and Experimental setup

To implement the metal spinning process, a roller tool, tool post and a mandrel has been manufactured, see Figure 5. In order to investigate the efficiency of the proposed control method, a test rig is designed which is composed of following equipments: A TN50BR[2] manual lathe equipped with a planetary gear (reduction rate: 1/5) and a stepper motor for linear motion of the *x* axis. A linear encoder with the 5µm resolution was used to measure the positional feedback of the machine tool table. For receiving the output pulses from encoder and also for sending motion pulses into motor, a high speed Advantech PCI-1240 motion card has been used. A Kistler 9255b 3-axis dynamometer is used for measuring force feedbacks for control system. The A5070 amplifier is integrated to amplify the acquired force signals via dynamometer. For purpose of analyzing sampled data via dynamometer on computer, output analog signals from dynamometer and amplifier should be digitized. This task was done by Advantech PCI-1711 high resolution 16-channel data acquisition card. A microswitch has been mounted on longitudinal axis for starting the operation. Figure 8 shows the above mentioned experimental setup. Also, schematic diagram of the experimental setup is shown in Figure 9.

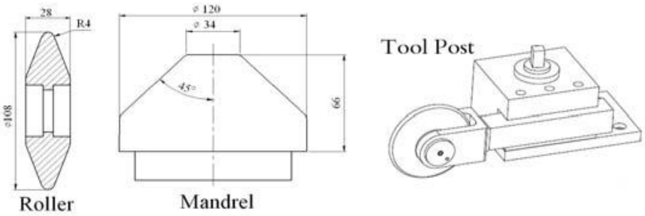

Figure 7: Spinning tooling used for experiments

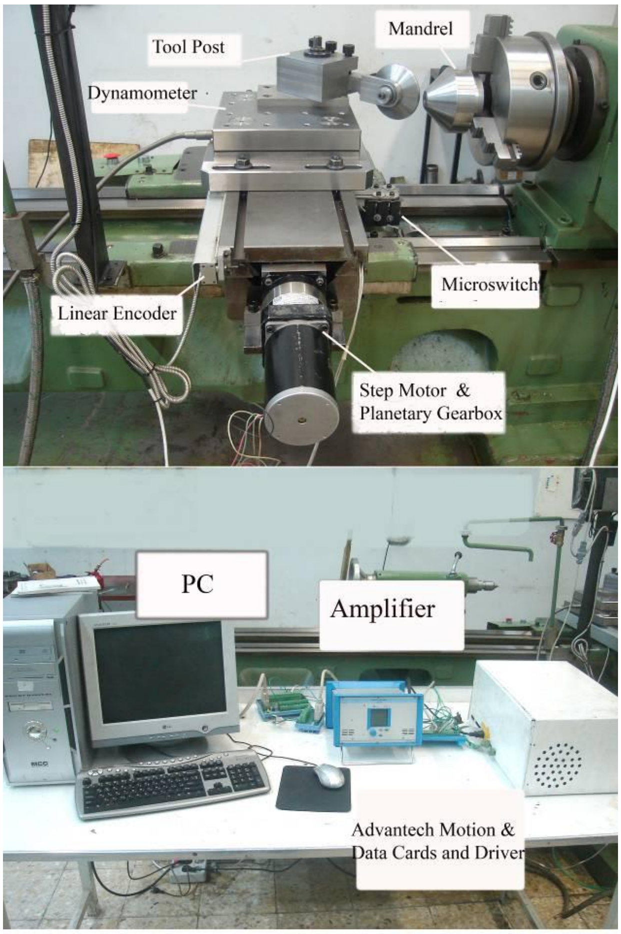

Figure 8: Experimental test rig

Further, a supervisory program has been developed in MATLAB® software which can control the process in real time. The program can also analysis and record the data. Graphical user interface[3] of this program have been illustrates in Figure10.

The blanks used for spinning experiments are made of annealed aluminum alloy Al-1050 with the size of $160\times160\times1$mm (1mm thickness). The surface of the roller and blank was lubricated with liquid lubricant (SAE 68).

[2]Manufactured by Tabriz machine tool manufacturer company

[3] GUI

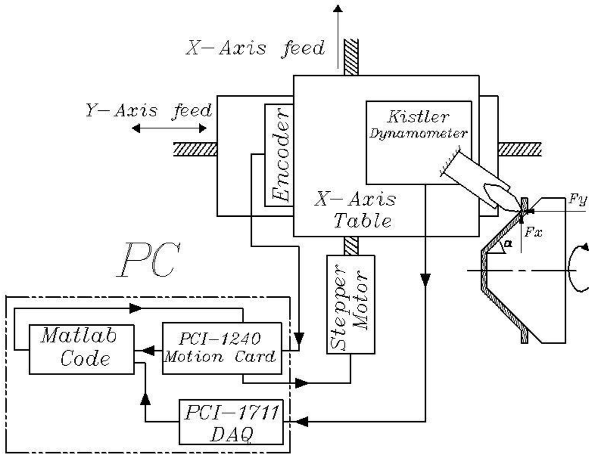

Figure 9: Signal routing and schematic of experimental setup

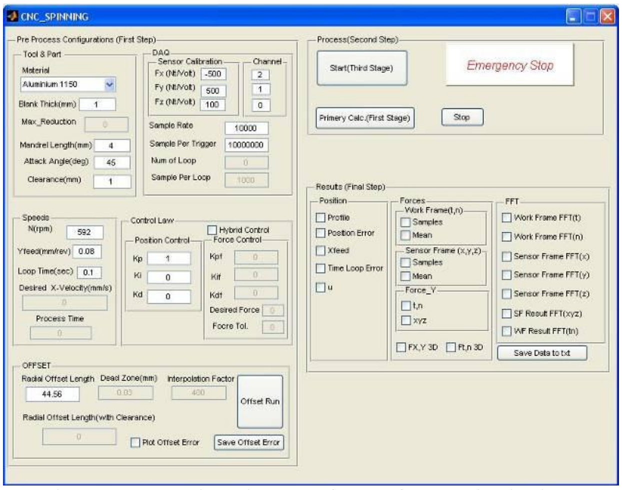

Figure 10: Developed GUI software for metal spinning experiments

Results and Discussion

1- Force Time History

A set of experiments has been done to know how the forming forces act in cone shear forming. During experiments, the roller tool path is controlled by a simple PD position controller. The feed rate (V_d) and spindle rotational speed (N) during the experiments is 1.04 mm/sec and 560 rev/min, respectively. The Clearance, has been adjusted to C=0.7mm according to sin law(C=S_f =1×sin45°=0.7mm). Force history of shear spinning experiments under abovementioned conditions is shown in Figure10 which illustrates the normal force on mandrel surface F_n is higher than feeding force F_t. This is because of the F_n component is responsible for reduction of the blank thickness in normal direction. There are an overshoot in the starting stage of force history plot. That is due to the forming the radial corner of mandrel in the primary steps of process and also it is due to the first contact between roller and rotating blank.

Comparing shape of obtained force history data with the previous experimental works [8, 15], it has been observed that the obtained force time history is in accordance with those reported for the same material and conditions.

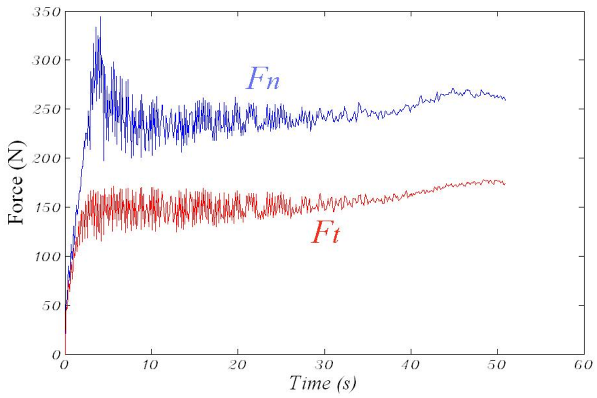

Figure 10: Force signals acquired during position control experiment

2- *FFT* [4] *Analyze of Force Signals*

For illustrating the noises effects on acquired force signals, Discrete Fourier Transform has been performed on the force signals which sampled during forming operation. The discrete Fourier transform analyse, help to identify the probable electrical or mechanical defects existing in test rig. So with getting insight to the noise sources, it is possible to reduce noise effects on force signal measurements.

The spectrum resulting from sampling rate at 1 kHz is shown in Figure 11.

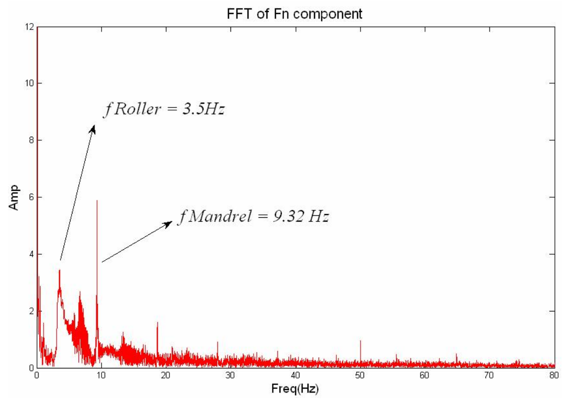

Figure 11: Discrete Fourier transform of "*Fn*" force signals

It has two frequency peaks, one around 9.32Hz, and another slightly above 3.5 Hz. It is clear that the f_{Spindle}= 9.32Hz component corresponds to the machine's spindle rotational speed N=560rev/min. The other component shown with $f_{\text{Roller}} =$ 3.5Hz corresponds to the roller tool' rotational speed. But the roller frequency component is not constant due to de variable rotational speed of it during stroke of operation. According to the geometrical specifications roller and mandrel and speed conditions of experiment, frequency component of roller was varied between around 3Hz to 10Hz. Equation 5 represents the growth of roller's rotational frequency component during forming experiment.

$$R_R \times \omega_R = R_M \times \omega_M \tag{5}$$

[4] Discrete Fourier transform computed with a fast Fourier transform algorithm

The eccentricity of roller and mandrel is adjusted on 0.01mm to achieve minimum force oscillations during measuring force signals. Moreover the roller and mandrel surfaces should have satisfactory smoothness. In this experiments surface roughness of roller and mandrel are 0.4µm and 0.25µm, respectively. Also all the electronic devises is connected to a common earth, and all the wires is shielded. It can be concluded that during force control spinning a proper anti aliasing lowpass filter should be apply for force measurements.

3- Thickness Distribution on spun part

The spun part produced in beforehand mentioned experiments, has been illustrated in Figure 12.

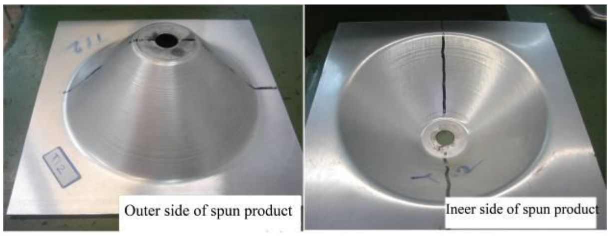

Figure 12: Produced Spun Part

It is shown that the surface smoothness of inner side is better than outer side, due to higher surface smoothness of mandrel relative to roller. Furthermore, the roller tool oscillations due the controller efforts can decrease the blank's outer surface smoothness.

The distribution of thickness along the spun product in metal spinning experiments is measured by a ReniShaw digitizer with 0.01mm resolution. One of the results for thickness distribution on spun part is shown in Figure 13. It is clear that during position control shear spinning, the final thickness was not uniform except that the final portion of part. Considering to final portions in Figure 10 and Figure 13, it is clear that increasing normal force in final steps of forming, the final thickness of spun part tends to obey the sine law. The normal force in this region is about 270N. This value of force signals can be a desired normal force for the desired condition of shear spinning operation.

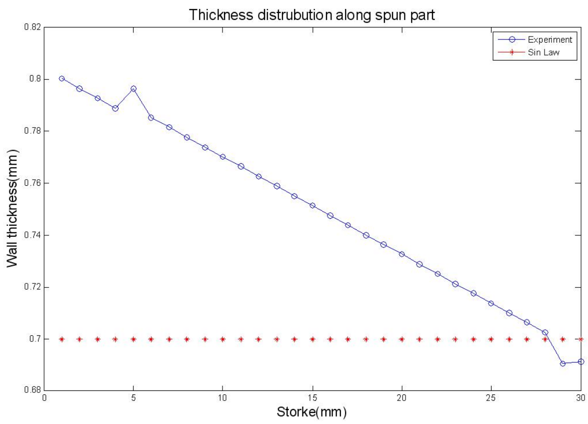

Figure 13: Thickness distribution on spun part in compare with sin law

Conclusions

This Research presented a method to integrate force and position sensors to a conventional manual spinning operation. More importantly, it discusses about the implementation of a force controller to control forming forces of shear spinning in order to achieve uniform thickness on spun parts. An experimental setup has been designed to implement the shear spinning operation and verify the proposed idea. The dynamic model of test rig is estimated experimentally. Several shear spinning operations have been performed to record the force time history and thickness distribution in position control spinning. Furthermore the effects of mechanical and electronical noises in sensor assisted shear spinning have been discussed. It was concluded that in the sensor assisted metal spinning operations, the eccentricity of tooling equipments and noise effects of electronic wires and devices should be minimize as possible.

The results of experiments shows that for achieving a uniform thickness distribution on shear spinning process, the positional control of roller tool path is not sufficient. For overcoming this problem a hybrid position/force controller have been proposed.

List of Symbols

C	Clearance
er_F	Force error
er_P	Position error
f	Frequency
F_d	Desired force
F_n	Normal force
F_{nd}	Normal desired force
F_t	Feeding force
G_1	System transfer function
G_2	Process transfer function
K_{dP}	Derivative gain of position controller
K_{iF}	Integral gain of force controller
K_{iP}	Integral gain of Position controller
K_{pF}	Proportional gain of force controller
K_{pP}	Proportional gain of position controller
Pd	Desired position
R_M	Radius of Mandrel
R_R	Radius of Roller
$S0$	Blank initial thickness
Sf	Final thickness of spun part
u_F	Force controller effort
u_P	Position controller effort
V	Velocity
V_d	Desired Velocity

Greek symbols

α	Half apex angle of mandrel cone
ω_M	Rotational speed of mandrel

ω_R Rotational speed of roller

References

[1] B.P. Bewlay, D.U. Furre, 2006, "ASM Handbook , Metalworking: Sheet Forming",Vol.14B, No. 05120,pp. 367-375, Materials Park, Ohio 44073, USA

[2] C.C.Wong, T.A.Dean, J. Lin, 2003. "A review of spinning shear forming and flow forming processes", International Journal of Machine Tools & Manufacture, Vol. 43, june, pp. 1419-1435.

[3] R.Volpe, P.Khosla, 1993. "A Theorical and Experimental Investigation of Explicit Force Control Strategies for Manipulators", IEEE Transaction on Automatic Control, Vol. 38, No. 11, November, pp.1634-1650.

[4] R.Volpe, 1990. "Real and Artificial Forces in the Control of Manipulators: Theory and Experiments". Ph.D. Thesis, Carnegie Mellon University, Pitssburg,September.

[5] M.Raibert , J.Craig, 1981. "Hybrid Position/Force Control of Manipulators", ASME Journal of Dynamic Systems, Measurement and Control, Vol. 103, No. 2, pp126-133 , June.

[6] H. G. Tanner and K. J. Kyriyakopoulos, 2001 . “Position and force control by reaction compensation,” in *IEEE International Conference on Robotics and Automation*, Seoul, Korea, May, pp. 3926–3931.

[7] N. Hogan, 1985. “Impedance control: An approach to manipulations, parts iiii,” *ASME Journal of Dynamic Systems, Measurement, and Control*, vol. 107, pp. 1–24.

[8] H. Arai, 2003. “Robotic Metal Spinning - Shear Spinning Using Force Feedback Control”, IEEE Int. Conf. on Robotics and Automation (ICRA2003), pp. 3977-3983

[9] E.Quigley, 2000. J.Monaghan, "Metal forming: an analysis of spinning processes", Journal of Materials Processing Technology,Vol. 103, pp. 114–119

[10] D.Hanafi, J.Katupitiya, 2006. "Very Low Compliance Force Control On a CNC Lathe Machine", Proceedings of the 2006 IEEE International Conference on Robotics and Automation, May , pp. 4002-4006

[11] D.Hanafi, 2007. "Automated Metal Spinning:Visual Tracking and Force Control Methodologies ", Ph.D. Thesis, University of New South Walse, Australia.

[12] S. Kalpakcioglu, 1961. “On the mechanics of shear spinning”, Transactions of the ASME, Journal of Engineering for Industry 83 (1961) , pp.125–130.

[13] K.Ogata, 1970. "Modern Control Egineering", PrenticHall, Upper Saddle River, NJ.

[14] Ljung, L. 1999. “*System Identification: Theory for the User*”, Second edition. PTR Prentice Hall, Upper Saddle River, NJ.

[15] M. Hayama et al., 1965"Experimental Study of Shear Spinning," Bulletin of Japan Society of Mechanical Engineers, Vol. 8, No. 31, pp. 453-460.