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Force-controlled Metal Spinning Machine Using Linear Motors

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***Abstract* - Metal spinning is a plastic forming process that forms a metal sheet by forcing the metal onto a rotating mandrel using a roller tool. A novel metal spinning machine was designed in which the roller is directly driven by linear motors. We aim to form non-axisymmetric products by controlling the pushing force of the roller so that the roller can quickly track the changing radius of the mandrel. Our experimental results show that the linear motors substantially improve response of the force control and non-axisymmetric products can be rapidly formed. Open-loop force control without a force sensor was also studied. It exhibited a comparable performance to closed-loop control with regard to the forming time.**

Index Terms - metal spinning, plastic forming, force control, linear motor

I. Introduction

Metal spinning [1][2] is a plastic forming process that forms a metal sheet by forcing the metal onto a rotating mandrel using a roller tool (**Fig. 1**) and is widely used for making round hollow metal products. This forming process is suitable for limited production lots of a wide variety of products and it is particularly effective in prototyping and product development, since it needs only one mandrel that costs much less than dies for metal stamping or deep drawing.

The forming roller usually moves very slowly while the mandrel and material swiftly rotate. Hence the products of metal spinning have been inherently limited to axisymmetric shapes that have circular cross sections around the rotation axis. Nonetheless, there is a potential demand for non-axisymmetric products formed by metal spinning which have e.g. elliptic, polygonal and eccentric cross sections. Metal spinning is expected to be used more widely if it can be used to produce a variety of non-axisymmetric products. Amano and Tamura [3] and Gao et al. [4] proposed spinning machines for elliptical cross section products. Shindo et al. [5] succeeded in metal spinning of pipes with eccentric or oblique axes. However, each method requires a specially designed spinning device for each shape.

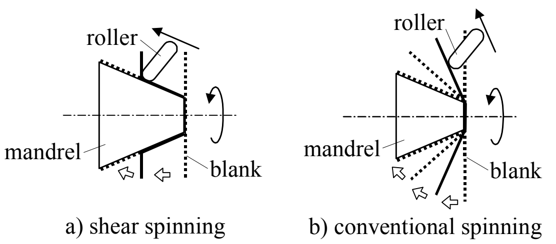

Fig. 1 Metal spinning.

In our previous study [6], we proposed a metal spinning process for non-axisymmentric products by controlling the pushing force of the forming roller in which hybrid position/force control is applied so that the roller follows contour of the non-axisymmetric mandrel while moving in the direction of the mandrel axis. We verified that a thin aluminum sheet could be formed into the same shape as the mandrel.

However, when a non-axisymmetric product is spun, the mandrel speed must be reduced and this leads to a long forming time. In this study, we developed a force-controlled metal spinning machine in which the forming roller is directly driven by linear motors. We aim to improve the response of the force control and significantly reduce the forming time. This paper describes the prototype machine and presents the results of our evaluation experiments.

The remainder of this paper is organized as follows. In Section II, we discuss problems in forming non-axisymmetric products using force control. The design of our prototype machine driven by linear motors is presented in Section III. Our experimental results using the prototype machine are reported in Section IV. In Section V, the feasibility of open-loop force control is investigated.

II. Forming Non-axisymmetric Products Using Force Control

As reported in [6], hybrid position/force control was applied for metal spinning of non-axisymmetric products. The pushing force of the forming roller is controlled and the material is forced onto the non-axisymmetric mandrel of a desired shape. The roller follows the contour of the mandrel to fit the material to the mandrel. This enables a non-axisymmentric product of the same shape as the mandrel to be fabricated.

This method does not need a specially designed mechanism to cope with each cross-sectional shape. Various non-axisymmetric shapes can be easily spun by replacing the mandrel. Since the shape of the product is determined by the shape of the actual mandrel, a large amount of 3-dimensional shape data are not required for control.

Reduction of the forming time is a very important issue for practical application of this method. The forming time is represented as; (height of product) ÷ (roller feed for one turn of mandrel) ÷ (mandrel speed). When spinning non-axisymmetric products, the mandrel should be rotated at a much slower speed than when spinning axisymmetric products, and this results in a long forming time. Actually, it took 10 to 30 minutes in the forming experiments presented in [6], so the forming time must be significantly shortened.

The roller moves forward and backward to follow the contour of the mandrel while a non-axisymmetric product is being spun. However, if the mandrel speed is high, the roller cannot keep pace with the shape of the mandrel. The force feedback response oscillates due to actuator saturation, and surface of the product becomes rough, or the pushing force on the material is insufficient and the product separates from the mandrel.

On the other hand, a larger roller feed in the direction of the mandrel axis can be selected as the roller pushes the material with stronger force. However, using a pushing force that is too strong when spinning a non-axisymmetric product disturbs the rotation of the mandrel. The pushing force cannot be very strong when the mandrel motor does not have enough torque capability. Hence the roller feed should be small, but this also causes a long forming time.

III. Development of New Metal Spinning Machine

In Ref. [3], we proposed a control algorithm for reducing the forming time by adjusting the mandrel speed in response to the roller motion. However, this was just a temporary solution since such a problem should be intrinsically solved by the mechanical design of the metal spinning machine. In this section, the development of a metal spinning machine to form non-axisymmetric products rapidly is presented.

A. Selection of Actuators

We consider that the reasons for the long forming time mainly result from inadequate actuator capacity. The actuators of a metal spinning machine for non-axisymmetric spinning should satisfy the following requirements:

Actuators for the forming roller

- can provide large pushing force of the roller.
- can move at high speed and generate large acceleration.
- can achieve high-response force control while moving rapidly.
- have small friction and small effective inertia.
- have high back-drivability and little backlash.

Actuator for the mandrel

- has large enough torque capacity to rotate the mandrel, overcoming the pushing force of the roller.
- has little backlash and withstands sudden changes in external torque.

The setup in [6] used DC servo motors and ball-screws to drive the forming roller. Most conventional spinning machines on the market use hydraulic cylinders. On the other hand, considering the above actuator requirements, we now adopt linear motors as the linear actuators for the forming roller.

Linear motors can provide thrust force proportional to the running current, and the force can be directly applied to the objects without using transmission mechanisms such as ball-screws. The force control response can be improved since the mechanical characteristics of the transmission mechanisms do not have to be accounted for in the control loop. Even when the forming roller is abruptly pushed back by the mandrel, it does not cause any damage to the machine since there is no transmission mechanism. The friction is caused by only linear bearings and can be expected to be smaller than that of hydraulic cylinders or ball-screws. Linear motors can generate very high velocity and acceleration and can move much faster than other actuators. Consequently, if the forming roller of a metal spinning machine is driven by linear motors, the mandrel speed for spinning non-axisymmetric products can be significantly increased.

B. Design of Prototype Machine

We use iron-core-based brushless linear servo motors (NLA-1000NM, Nikki Denso Co.) for driving the forming roller. The motor consists of a moving coil with an iron core and a permanent magnet stator. This type of motor provides high thrust density, i.e. large force can be obtained using a relatively small motor. The mandrel is driven by an AC servo motor (SGMAH-04, Yaskawa Electric Co.) with a planetary gear. While spinning a non-axisymmetric shape, the external torque of the mandrel due to the roller force changes its direction intermittently. Hence a reduction gear with small backlash (< 3') is used (Harmonic Planetary®, Harmonic Drive Systems, Inc.). The rated torque of the motor is large enough so that it can overcome the roller force to rotate the mandrel. The actuators of the new metal spinning machine and those of the setup in [6] are compared in Table I.

Fig. 2 is an outline of the prototype machine. The forming roller is driven by an xy-table composed of two linear servo motors crossing perpendicularly. The roller is slanted at 45 deg relative to the y-axis. A 6-axis force sensor is attached to the roller holder. The x-axis and the mandrel axis (θ-axis) are set in parallel. When a non-axisymmetric product is spun, only the y-axis is force-controlled. Then the y-axis solely moves back and forth following the mandrel, and the effective inertia is smaller than when both x- and y- axes move.

TABLE I
Specification of Actuators

	New machine	Setup of Ref.[6]
Actuator for roller	linear servo motor	servo motor + ball screw
Continuous force	1000 N	580 N
Peak speed	3.0 m/s	0.17 m/s
Actuator for mandrel	servo motor + planetary gear	servo motor + planetary gear
Continuous torque	14 Nm	3.9 Nm
Rated speed	270 rpm	250 rpm

IV. Evaluation Experiments

A. Parameter Identification

Fig. 3 shows a photo of the prototype machine. First, the dynamics parameters of each axis, i.e., coulomb friction, viscous friction and inertia, are identified by providing constant velocity commands and constant acceleration commands. The parameters of each axis are listed in Table II.

The coulomb frictions of the *x*- and *y*-axes are unexpectedly large. The permanent magnet of the stator attracts the iron core of the moving coil with huge force (about 12000 N). This causes large friction at the linear bearing in the guide mechanism. The selection of the motor type might need to be reconsidered in this respect. Nevertheless, the maximum thrust force 3000 N at the state of no external force leads to acceleration of 6.9 G, and the capability to track a non-axisymmetric mandrel will be sufficient.

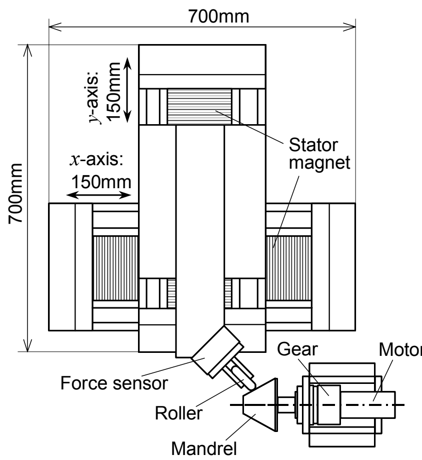

Fig. 2 Linear motor driven metal spinning machine.

TABLE II
DYNAMICS PARAMETERS OF EACH AXIS

	x-axis	*y*-axis	θ-axis
Coulomb friction	100 N	97 N	1.0 Nm
Viscous friction	153 Ns/m	153 Ns/m	0.07 Nms/rad
Inertia	116 kg	43 kg	0.013 kgm^2

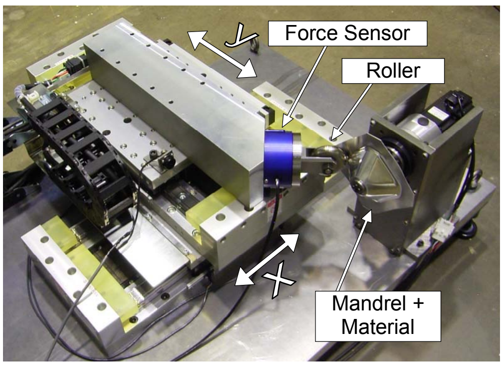

Fig. 3 Photo of linear motor driven metal spinning machine.

B. Control Law

Among the various techniques in the metal spinning process, here we assume shear spinning, in which the roller is moved along the surface of the mandrel and the metal sheet is squeezed onto the mandrel (Fig. 1 a)). During this process, projection of the roller velocity onto the mandrel axis, V_X, is controlled to the desired constant value, V_{Xd}. The force component of the roller normal to the mandrel axis, F_y, is controlled so that the component normal to the mandrel surface, F_n, is regulated to the constant value, F_{nd} (**Fig. 4**). Even when the roller follows the non-axisymmetric shape of the mandrel, the trajectory of the roller is maintained on the same plane as the flange and this prevents wrinkles at the flange.

As the mandrel axis and the *x*-axis are parallel in this prototype, independent control laws can be implemented for the *x*- and *y*-axes. Position control law using traditional PD feedback is applied for the *x*-axis;

$$f_x = m_x\{k_{vx}(V_{xd} - \dot{x}) + k_{px}(V_{xd}t - x)\} \qquad (1)$$

where, f_x is the thrust of the *x*-axis motor, m_x is the inertia of the *x*-axis, and k_{px} and k_{vx} are feedback gains.

Impedance control law based on a virtual internal model [4] is used for the *y*-axis. First, the force F_{yd} in the *y*-direction is calculated so that the normal force to the mandrel surface becomes F_{nd}.

$$F_{yd} = (F_{nd} - F_x \sin\alpha)/\cos\alpha \qquad (2)$$

α is a representative half-cone angle of the mandrel. F_x in the *x*-direction can be measured by the force sensor. A virtual impedance comprising inertia M_y and viscous friction B_y is defined. The desired acceleration $\dot{V}_{yd}$ and desired velocity V_{yd} of the *y*-axis are calculated as;

$$\begin{cases} \dot{V}_{yd} = (F_y - F_{yd} - B_y V_{yd})/M_y \\ V_{yd} = \int \dot{V}_{yd}\, dt \end{cases} \qquad (3)$$

Then V_{yd} and $\dot{V}_{yd}$ are substituted into the following velocity control law.

$$f_y = m_y\{\dot{V}_{yd} + k_{vy}(V_{yd} - \dot{y})\} \qquad (4)$$

f_y is the thrust of the *y*-axis motor, m_y is the actual inertia of the *y*-axis, and k_{vy} is a feedback gain. The effect of the coulomb friction can be suppressed by the high-gain velocity feedback. This control law realizes a state as if the desired force F_{yd} was being applied through the virtual impedance M_y and B_y .

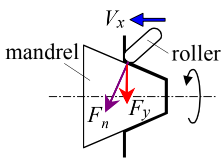

Fig. 4 Force control of roller.

In this application, the forming roller should rigidly contact the material and constantly apply a large force at the contact point, while moving with high velocity and acceleration. This is a very harsh situation for force control. Moreover, the force control should be absolutely stable in any situation since vibration caused by the controller immediately deteriorates the quality of the products. Consequently, we experimentally evaluated the force control law, and adjusted the control parameters by trial and error. An eccentric circular plate cam (110 mm diameter, 10 mm eccentricity, stainless steel) is attached to the θ-axis instead of the mandrel. The spinning process is simulated by forcing the roller onto the cam with the force control while rotating the θ-axis.

It is preferable to make the impedance parameters, M_y and B_y, as small as possible in order to speed up the force control response. However, vibration occurred when the inertia parameter M_y was smaller than the actual inertia of the y-axis (43 kg). Hence M_y is set at 55 kg to include a safety margin. On the other hand, changes of the viscous friction B_y did not have any critical influence. B_y is set at 150 Ns/m, which is nearly equal to the actual viscous friction.

C. Forming experiments

Forming experiments were conducted using the same two types of non-axisymmetric mandrels as in [6] (**Fig. 5**). Mandrel #1 was fabricated from a stainless steel cone with a 45 deg half angle, and with the side surface partly machined into flat planes. The cross section normal to the mandrel axis is composed of circular arcs and straight lines. Mandrel #2 is a carbon steel cone with a 30 deg half-angle, which was slanted 10 deg, and the top and bottom were cut horizontally. The mandrel axis is eccentric and the cross section normal to the axis is elliptic. The maximum angle between the side surface and the mandrel axis is 40 deg, and the minimum angle is 20 deg. The blank is a round disc of pure aluminum (1100-H24) with a 150 mm diameter and 1.0 mm thickness. The diameter of the forming roller is 70 mm. The edge is rounded to a 9.5 mm radius. The roller is made from alloy tool steel (AISI D2).

Fig. 6 shows finished products using Mandrel #1 and #2. As the motor to drive the mandrel has sufficient torque capacity, larger products can be spun compared with the process in [6]. The mandrel can continue to rotate even when the radius of the product is large and large external torque due to the pushing force of the roller is applied. In the Ref. [6] setup, the mandrel stopped rotating because of inadequate torque capacity when the desired roller force F_{nd} was larger than 450 N for Mandrel #1. However, the mandrel torque of the new machine is less than 35% of the maximum torque even when the desired roller force F_{nd} is 850 N.

Fig. 7 shows cross section profiles of the product surface measured by a laser displacement sensor. The products are formed into non-axisymmetric shapes along the mandrels. The distance between the outer surface of the product and the mandrel is less than 0.88 mm for Mandrel #1, and less than 1.27 mm for Mandrel #2. Considering the wall thickness of the products, the springback is relatively small and the products tightly fit the mandrels.

We performed a series of forming tests using Mandrel #2 varying the desired pushing force of the roller F_{nd} and the mandrel speed (**Fig. 8**). The roller feed in the x-direction for one turn of the mandrel was 0.4 mm/rev. "O" means that the product was formed successfully. "Δ" means the product deviated from the mandrel near the bottom and the shape was distorted. "×" means that the roller repetitively collided with the mandrel through the material and the control program finally stopped the forming process as it detected excessive force impulses. We found that the mandrel speed can be increased as the pushing force became larger.

Fig. 9 shows the measured pushing force F_n for mandrel speeds of 240 rpm and 180 rpm, when the desired pushing force F_{nd} is 1000 N. As the forming roller rapidly moves back and forth, the actual pushing force F_n greatly changes due to the inertia. The amplitude of the force variation becomes larger as the mandrel rotates faster. Nonetheless, the averaged force is 1017 N and 1021 N, respectively, and almost equal to the desired force. As the upper limit of the pushing force that can result in successful forming has a wide range, the products were satisfactorily formed for both cases.

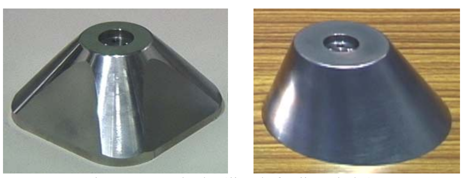

Fig. 5 Mandrels (#1: left, #2: right).

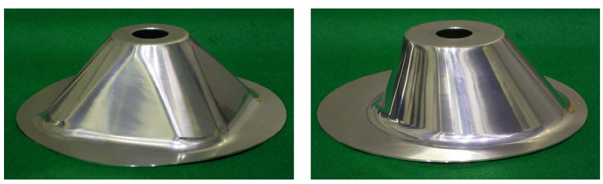

Fig. 6 Non-axisymmetric products (#1: left, #2: right).

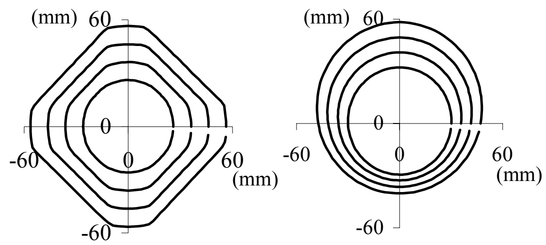

Fig. 7 Shape of products (#1: left, #2: right).

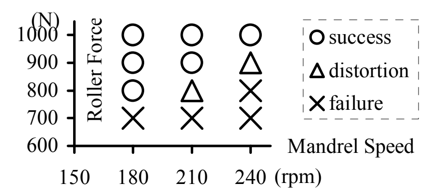

Fig. 8 Effect of pushing force vs. mandrel speed.

Next, the actual pushing force F_n is compared in **Fig. 10** when the desired force F_{nd} is 1000 N and 800 N. The mandrel speed is 210 rpm. When F_{nd} is 800 N, which results in failure of the forming, F_n abruptly jumps once a turn. F_n decreases nearly to 600 N just before the jump. Here the forming roller is pushed back by the material and deviates from the mandrel due to inadequate pushing force. The peak of the pushing force occurs when the forming roller, while it is separated from the mandrel, contacts the mandrel again. When the mandrel speed is too high or the desired pushing force F_{nd} is too small, the separation between the roller and the mandrel becomes large, and this causes a strong impact force at the contact. If F_{nd} is enough large, the roller does not separate from the mandrel in spite of the variation of F_n. When F_{nd} = 1000 N in Fig. 10, the abrupt change of the pushing force disappears. F_n varies continuously and the forming is properly achieved.

In the forming tests using various forming parameters, we have confirmed that the upper limit of the mandrel speed is 60 rpm for Mandrel #1 and 240 rpm for Mandrel #2. Up to these speeds, the roller can keep pace with the mandrel and the forming succeeds. With Mandrel #1, the pushing force abruptly changes at the boundaries between the curved surface and the planar surface, and the mandrel speed cannot be very high.

Using the setup in [6], the mandrel speed was limited to about 15 rpm for Mandrel #1 and 30 rpm for Mandrel #2. With the new prototype machine, their speeds can be increased up to four times and eight times, respectively. Moreover, the roller feed can be larger as the new machine can provide large pushing force. When the roller feed is 0.4 mm/rev, a product 30 mm high can be formed within 75 sec (Mandrel #1) and 19 sec (Mandrel #2). Our metal spinning machine using linear motors has achieved significant reduction of the forming time for non-axisymmetric products.

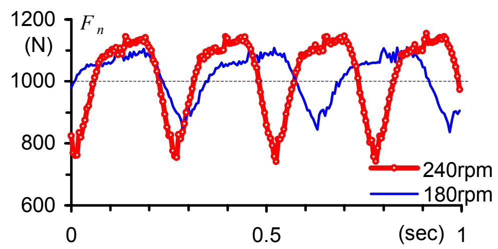

Fig. 9 Pushing force of roller.

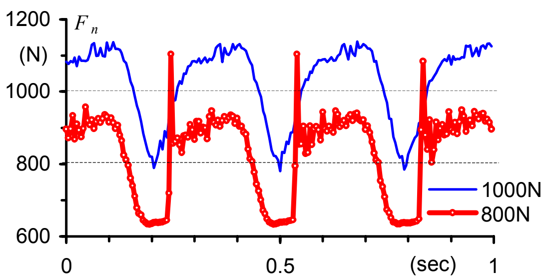

Fig. 10 Pushing force of roller.

V. Open-Loop Force Control

We have used a 6-axis force sensor at the roller holder for closed-loop control of the pushing force. However, from the viewpoint of practical applications, a force sensor is generally expensive, too fragile to withstand overload or impact, and requires a complicated controller. Therefore, it would be very useful if the pushing force could be controlled without using the force sensor. As our prototype machine is driven by linear motors, the motor thrust is directly transmitted to the roller. We expect that the pushing force can be easily controlled by the motor current. In this section, we investigate whether open-loop control of the pushing force is applicable to form non-axisymmetric products.

When using open-loop control, it is difficult to control the force component F_n normal to the mandrel surface since the force components in the x- and y-directions cannot be precisely measured (Fig. 4). Instead, the pushing force F_y in the radial direction is controlled using the motor thrust f_y. The most simple control law;

$$f_y = F_{yd} \tag{5}$$

is applied, where F_{yd} is the desired value of F_y. On the other hand, position control of Eq. (1) based on PD feedback is used for the x-axis:

$$f_x = m_x\{k_{vx}(V_{xd} - \dot{x}) + k_{px}(V_{xd}t - x)\}$$

As F_n and F_y have different directions, it is necessary to learn how to determine the desired force F_{yd}. For this purpose, F_n and F_y, which have already been measured in the forming experiments using closed-loop force control, are compared. The averaged values of F_n and F_y are plotted in **Fig. 11**, when the forming was successful using Mandrel #2. The roller feed was 0.4 mm/rev. These data include various mandrel speeds from 120 rpm to 240 rpm. The plots are aligned straight irrespective of the mandrel speed. Hence the averaged values of the pushing force F_y in the radial direction and the normal force F_n are linearly related if the roller feed is constant.

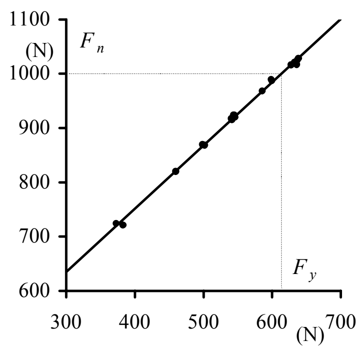

Fig. 11 Relationship between F_n and F_y.

From Fig. 11, F_y should be about 600 N if F_n is 1000 N, which led to good forming results in the previous section. Thus we conducted forming tests setting the desired pushing force F_{yd} to be 600 N and the roller feed to be 0.4mm/rev. We repeated the test while gradually increasing the mandrel speed, and confirmed that the roller could track the mandrel and the product was successfully formed at mandrel speeds up to 240 rpm.

Fig. 12 shows a graph of F_y when the mandrel speed is 240 rpm. F_y varies considerably due to the inertia and friction force. However, abrupt changes of the pushing force, as in Fig. 10, are not observed. Actually, the roller does not deviate from the mandrel and continuously pushes the material onto the mandrel. The average of F_y is 637 N and the average of F_n is 1026 N. The desired pushing force is approximately achieved.

We also tested open-loop force control using Mandrel #1, and confirmed that the mandrel speed can be increased up to 60 rpm (desired pushing force: F_{yd} = 600 N, roller feed: 0.4 mm/rev). These results demonstrate that, with regard to the limit of the mandrel speed for both Mandrel #1 and #2, the simple open-loop control of Eq. (5) has performance comparable to closed-loop control using a force sensor.

In this application, pushing force that can result in successful forming has a wide range, and the force control does not need to be very precise. Rather than force accuracy, it is more important that the roller quickly follows the change of the mandrel radius and maintains contact with sufficient pushing force. Vibration caused by the controller must be absolutely avoided, and the force control should always be stable. Thus the parameter settings for closed-loop control should inevitably be conservative. For the above reasons, open-loop control provides performance similar to closed-loop control.

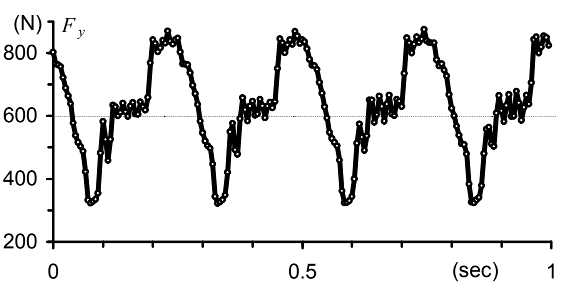

Fig. 12 Pushing force of roller.

Taking other factors also into consideration, such as the cost and endurance of the force sensor and the complexity of the controller, we can conclude that open-loop control is practically superior to closed-loop control in this case. To improve the response of open-loop force control further, modification of the hardware, e.g. reducing the weight of the y-axis and eliminating friction at the linear bearing, would be effective.

VI. Conclusions

We developed a novel metal spinning machine in which linear motors directly drive the forming roller, with the aim of high-speed forming of non-axisymmetric shapes. We experimentally confirmed that the roller could follow the mandrel and non-axisymmetric products could be successfully formed, even when the mandrel was rotated much faster than that in the setup which was driven by ball screws. The forming time of the non-axisymmetric products was significantly reduced. We also investigated the application of open-loop force control without the force sensor. Open-loop control exhibited forming time performance comparable to closed-loop control.

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