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Transfer and Sloshing Control of Molten Metal Using a Ladle with 6-Degrees-of-Freedom Robot Arm in Die Cast Process

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In the die casting process, it is necessary to shorten the transfer time for avoiding the temperature drop of the molten metal. It is often used to draw the molten metal from furnace into a ladle using a multi-joint robot arm with 6 degrees-of-freedom and also transfer it to a plunger of a die cast machine. Productivity of die casting is decided by cycle time. Therefore, if transfer time is shortened and casting cycle time is reduced, the casting productivity can be progressed. Hence, speedup of the molten metal transfer is highly demanded. However, if the transfer speed is increased, sloshing (liquid vibration) is generated, and the quality and the safety deteriorates, because contamination and effusion are occurred. In addition, the waiting time until damping sloshing prolongs and the productivity is decreased because of the residual vibrations. The speedup of the molten metal transfer system with sloshing suppression by means of the robot arm is highly demanded for improvement of the safety and productivity. In this paper, we give a trajectory planning control of transferring a ladle using robot arm, and also presents the sloshing control of aluminum alloy molten in the ladle. First, sloshing model in a ladle is built. Secondly, we apply an input shaping control to suppress the sloshing while transferring a ladle with high speed. Finally, the effectiveness of the proposed approach in this paper is demonstrated through simulation and experiments.

1. Introduction

In the die casting process, it is necessary to shorten the transfer time for avoiding the temperature drop of the molten metal. It is often used to draw the molten metal from furnace into a ladle using a multi-joint robot arm with 6 degrees-of-freedom and also transfer it to a plunger of a die cast machine.

Productivity of die casting is decided by cycle time. Therefore, if transfer time is shortened and casting cycle time is reduced, the casting productivity can be progressed. Hence, speedup of the molten metal transfer is highly demanded.

However, if the transfer speed is increased, sloshing is generated, and the quality and the safety deteriorates, because contamination and effusion occur. In addition, the waiting time until damping sloshing prolongs and the productivity is decreased because of the residual vibrations. The speedup of the molten metal transfer system with sloshing suppression by means of the robot arm is highly demanded for improvement of the safety and productivity.

Various approaches has been used by researchers to tackle sloshing suppression problem. Feedback control of closed loop approach uses sensor measurements for feedback to generate input in a closed loop. Solutions using this approach presents good and relatively robust control ability against disturbances. Examples include generalized PI control [2], and H_∞ feedback control system [3]. However, in the die casting process, it is difficult to do accurate sensing of liquid level in a real time manner.

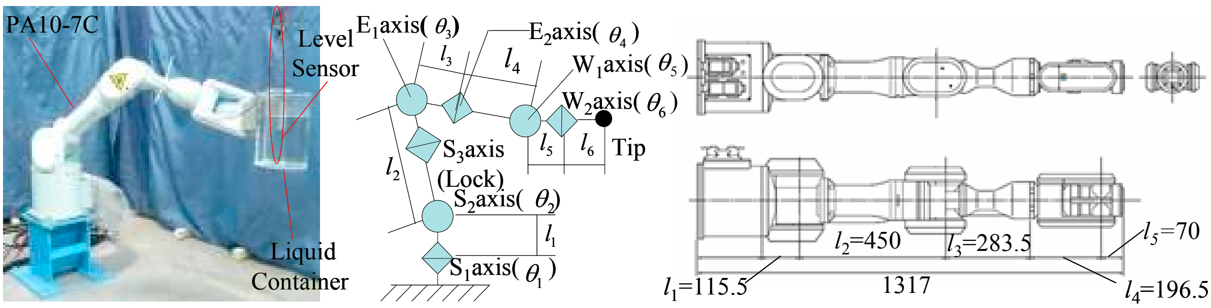
On the other hand, feedforward approach [5-8] does not require sensor measurement feedback, yet can provide good performance assuming that natural frequency and damping factor of the system are known beforehand.

If the sloshing phenomena is mathematically modeled, the faster transfer control with sloshing suppression can be expected based on the process model. If sloshing phenomena can be modeled by a series of second order transfer function comprised of mass, spring, and damper, input shaping approach developed by Singer and Seering [1] is one of most practical control approach. In input

shaping approach, residual vibration is completely suppressed for the vibration systems including higher model oscillation, and the fastest control input in case of using only the same sign of control input can be obtained.
This research explores the use of input shaping technique to suppress sloshing on transfer of liquid container using 7 degree-of-freedom robot arm. Section 2 presents the liquid transfer system construction. Section 3 explains in detail modeling of the system, while simulation and experiment result is presented and discussed in Section 4.

2. System Construction

The liquid transfer system concerned uses 7 degree-of-freedom Mitsubishi PA10-7C robot arm. Weighing only 40 (kg), its longest arm reach is 1 (m), and can carry up to 10 (kg) of load on its arm tip. A cylindrical container, 150 (mm) in diameter and 250 (mm) in height, is mounted on the robot arm tip. Electric-resistance level sensor is attached to the container, placed on one side of the cylinder to measure height of liquid over time. It works by detecting changes in the resistance between two electrodes. Height fluctuation detected represents magnitude of sloshing. Fig. 1(a) shows picture of the robot arm holding the container with level sensor attached.



(a) Overall view (b) Axis placement of robot arm (c) Robot link dimension

Fig.1 Complete setup of the liquid transfer system

3. Modeling and Control Design

3.1 Robot Arm

Axis placement of the robot arm and robot arm link dimension are shown in Fig. 1(b),(c). One of the arm joints, the S_3 joint, is locked so that practically only six joints are actively used because redundancy of arms is not necessary for the present purpose in this paper, but required in next step to avoid obstacles. The active joints are S_1, S_2, E_1, E_2, W_1, and W_2. Thus six axes are assigned, one on each active joint.

Inverse kinematics is used to translate tip position to each joint angle. Rotation matrix and translation matrix for each axis i is defined by:

$$\left.\begin{array}{l} R_{xi} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_i & -\sin\theta_i \\ 0 & \sin\theta_i & \cos\theta_i \end{bmatrix} \\ R_{yi} = \begin{bmatrix} \cos\theta_i & 0 & \sin\theta_i \\ 0 & 1 & 0 \\ -\sin\theta_i & 0 & \cos\theta_i \end{bmatrix} \\ R_{xi} = \begin{bmatrix} \cos\theta_i & -\sin\theta_i & 0 \\ \sin\theta_i & \cos\theta_i & 0 \\ 0 & 0 & 1 \end{bmatrix} \end{array}\right\} \tag{1}$$

$$\left.\begin{aligned} L_{xi} &= [l_i \quad 0 \quad 0]^T \\ L_{yi} &= [0 \quad l_i \quad 0]^T \\ L_{zi} &= [0 \quad 0 \quad l_i]^T \end{aligned}\right\} \tag{2}$$

Relation between position (x, y, z) and orientation (φ, θ, ψ) of the arm tip and joint angles is as follows:

$$[x \quad y \quad z]^T = R_{Z1}(L_{Z1} + R_{y2}(L_{z2} + R_{y3}(L_{z3} + R_{z4}(L_{z4} + R_{y5}(L_{z5} + R_{z6}L_{z6}))))) \tag{3}$$

$$\left.\begin{aligned} \phi &= \tan^{-1}(T_{23} / T_{13}) \\ \theta &= \cos^{-1}(T_{33}) \\ \varphi &= \tan(T_{32} / T_{31}) \end{aligned}\right\} \tag{4}$$

, where matrix T is product of all rotation matrices:

$$\begin{bmatrix} T_{11} & T_{12} & T_{13} \\ T_{21} & T_{22} & T_{23} \\ T_{31} & T_{32} & T_{33} \end{bmatrix} = R_{Z1}R_{y2}R_{y3}R_{z4}R_{y5}R_{z6} \tag{5}$$

We use vector $\boldsymbol{P}$ to denote position and orientation of robot arm tip and $\boldsymbol{\theta}$ for joint angles:

$$P = [x \quad y \quad z \quad \phi \quad \theta \quad \varphi]^T, \theta = [\theta_1 \quad \theta_2 \quad \theta_3 \quad \theta_4 \quad \theta_5 \quad \theta_6]^T$$

Values of joint angles decide position and orientation of the robot arm tip. Relation between P and θ is as follows:

$$P(t) = f\{\theta(t)\} \tag{6}$$

$$\dot{P}(t) = J\{\theta(t)\}\dot{\theta}(t) \tag{7}$$

, where $\boldsymbol{J}$ is the 6×6 Jacobian matrix. Thus derivative of $\boldsymbol{\theta}$ can be calculated from derivative of $\boldsymbol{P}$, provided that $\boldsymbol{J}$ is invertible:

$$\dot{\theta}(t) = J^{-1}\{\theta(t)\}\dot{P}(t) \tag{8}$$

3.2 Sloshing Model

Sloshing inside open container can be well represented by equivalent mechanical models, either a pendulum model or spring-mass model. One approach is by using simple pendulum model [6], where one pendulum represents one sloshing mode. Damper is added to the pendulum model to represent viscosity and friction of liquid with container walls. Considering only fundamental sloshing mode, which is dominant in container transfer, and neglecting other subsequent minor modes, the pendulum model as shown in Fig. 2 can adequately represent the dynamics of sloshing in lateral direction. In this model, planar liquid surface is perpendicular to the pendulum, which swings as container accelerates (or decelerates) by α, forming angle θ between planar liquid surface and horizontal line. Coefficient c represents dampin.

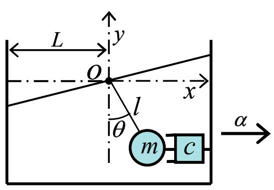


Fig.2 Pendulum model of one-mode sloshing

By considering moment balance around fulcrum of the pendulum, dynamic of the model can be described by the following equation:

$$J\frac{d^2\theta}{dt^2} = -c\frac{d(l\theta)}{dt}l \cdot \cos^2\theta - mgl \cdot \sin\theta + mg\alpha \cdot \cos\theta \tag{9}$$

, where J ($= ml^2$) is moment of inertia. The liquid level h on the side wall equals $L \cdot \tan\theta$. Considering only small value of θ, linear approximation of the above non-linear model is as follows:

$$\ddot{\theta} = -\frac{c}{m}\dot{\theta} - \frac{g}{l} + \frac{\alpha}{l} \tag{10}$$

$$h = L\alpha \tag{11}$$

Transfer function between liquid level h and lateral acceleration α is thus described by the following equation:

$$\frac{h(s)}{\alpha(s)} = \frac{L/l}{s^2 + cs/m + g/l} \tag{12}$$

Comparing above equation to second-order damped linear oscillator with natural frequency ω_n and damping ratio ζ gives:

$$\omega_n = \sqrt{g/l} \tag{13}$$

$$\varsigma = \frac{c}{2m}\sqrt{\frac{l}{g}} \tag{14}$$

, where m is mass of liquid, and equivalent pendulum length l (m) and coefficient of viscosity c (Ns/m) are identified by agreement of simulation and experiments as shown in next chapter.

3.3 Input Shaping Control

An uncoupled, linear, vibratory system of any order can be specified as a cascaded set of second-order poles with the decaying sinusoidal response:

$$y(t) = \left[A\frac{\omega_0}{\sqrt{1-\varsigma^2}} \exp(-\varsigma\omega_0(t-t_0)) \cdot \sin(\omega_0\sqrt{1-\varsigma^2}(t-t_0)) \right] \tag{15}$$

, where A is amplitude of the impulse, ω_0 is the undamped natural frequency of the plant, ζ is the damping ratio of the plant, t is time, and t_0 is time of the impulse input [1].

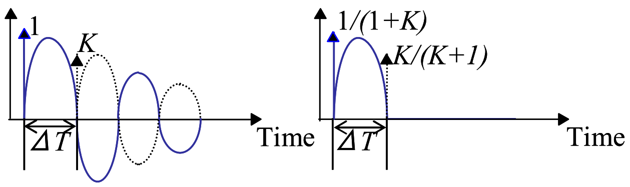


Fig.3 .Principle of input shaping

We obtain the magnitude K and time ΔT of second impulse as follows:

$$K = \exp\left(-\frac{\varsigma\pi}{\sqrt{1-\varsigma^2}}\right) \tag{16}$$

$$\Delta T = \frac{\pi}{\omega_0\sqrt{1-\varsigma^2}} \tag{17}$$

Adjustment should be made so that the sum of the two impulses equals 1 (thus the command does not go beyond maximum value), giving $1/_{1+K}$ as first impulse magnitude and $K/_{1+K}$ as the second impulse magnitude.

4. Simulation and Experiment

In this paper, only straight path transfer is focused from start point to end point. Liquid transfer on curved path induces nonlinear phenomena such as centrifugal force, Coriolis force, etc., and it is difficult to exactly suppress sloshing in curve transfer by only input shaping method. Therefore, curve transfer with sloshing suppression using robot arm is not considered in this experiment, but will be reported in near future.

For this experiment, robot arm has to move the container on a straight path from start point (700, -500, 250) to end point (700, 500, 250). Height and mass of liquid inside container is 170 (mm) and 3 (kg), respectfully. Maximum acceleration and velocity is 2 (m/s^2) and 0.5 (m/s), respectfully.

Theoretical value of undamped natural frequency ω_n for fundamental mode of sloshing inside circular cylindrical container is defined as follows [4]:

$$\omega_n = \sqrt{1.841 \frac{g}{L} \tanh\left(1.841 \frac{h_s}{L}\right)} \tag{18}$$

, where h_s is the height of liquid from bottom of the container. For our system, theoretical natural frequency equals 15.506 (rad/s) = 2.469 (Hz). From this value and (12), we obtain equivalent pendulum length (l) of 0.0408 (m). Value of damping ratio ζ was estimated from experiment, and coefficient of viscosity c can be calculated from (13), found to be equal 1.02 (Ns/m). Table I lists all parameter values of our system.

Table 1 Parameter values

Parameter	**Value**	**Unit**
Equivalent pendulum length, l	0.0408	(m)
Coefficient of viscosity, c	1.02	(Ns/m)
Mass of liquid, m	3.0	(kg)
Nominal level, h	0.17	(m)
Radius, L	0.075	(m)
Gravity Acceleration, g	9.8	(m/s^2)

By using those parameter values, input shaper is constructed, with K equals 0.966 and time between two impulses ΔT equals 0.21 (s). Fig. 4 shows the shaped acceleration profile as compared to the unshaped one. The shaped acceleration profile takes slightly longer time because of the input shaping delay.

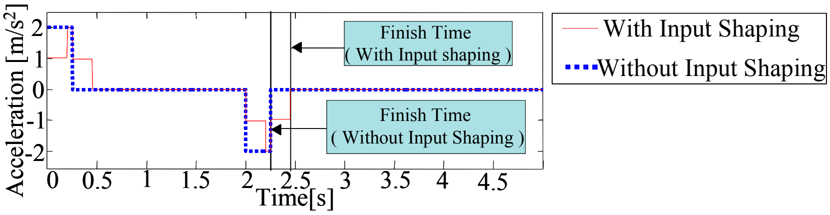
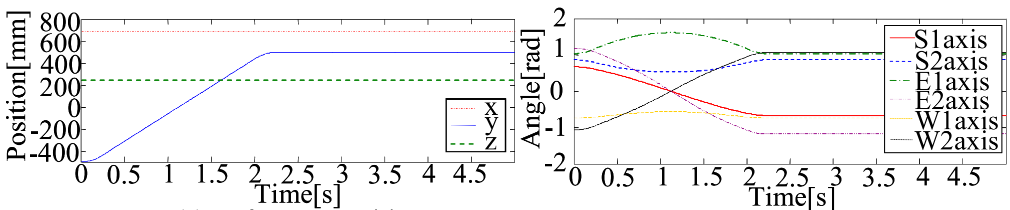


Fig.4 Acceleration and deceleration profile

Container position trajectory, shown in Fig. 5(a) is then generated from the acceleration profile. Inverse kinematics procedure translates the position trajectory to robot joint angles trajectory as shown in Fig. 5(b). Those joint angles are then used as command to move the robot arm.

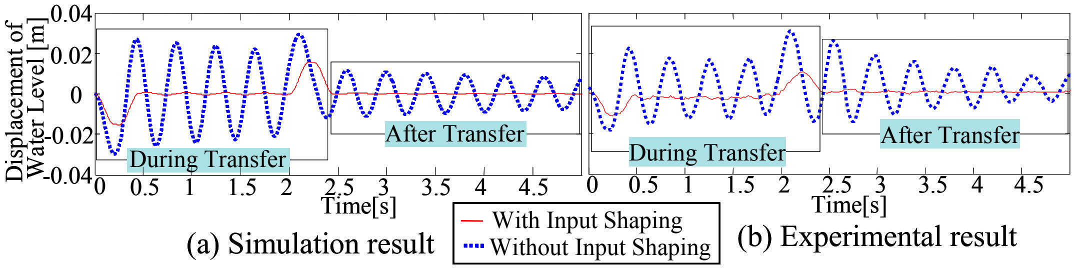


(a) Reference Position (b) Angle to Each Axis

Fig.5 Shaped position reference and axis angle reference

Using the axis angle reference, simulation is conducted. The result is shown in Fig.6. Without shaping, liquid surface oscillates relatively highly. Small damping of the liquid causes the sloshing stays during transfer and even long after transfer. Effect of shaping is apparent, in that water level displacement occurs only when container accelerates and decelerates, quite effectively suppressing sloshing of the liquid transfer system considered.

Experiment is conducted by supplying axis angle reference to the PA10 robot motion controller. Fig. 10 shows the experiment result, showing high confirmation with the simulation result. It is easily seen that sloshing is much lower when input shaping is performed, both during and after transfer. However, it should be noted that transfer time required by input shaping approach (2.46 second) is slightly longer than that without input shaping (2.25 second).



(a) Simulation result (b) Experimental result

Fig.6 Result

5. Conclusion

In this paper, sloshing suppression by input shaping principle on liquid transfer using robot arm has been achieved. This initial work on sloshing control for this kind of system looks promising, as already shown in this paper. Future work is directed to address robustness issue, as well as transfer on curved path to exploit the flexibility, such as obstacle avoidance, offered by many-degrees-of-freedom robot arm with redundancy.

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