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LIQUID LEVEL CONTROL OF AUTOMATIC POURING ROBOT BY TWO-DEGREES-OF-FREEDOM CONTROL

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Abstract: The purpose of this paper is to provide a method to hold the liquid in a spruc cup into the constant level and to suppress sloshing (liquid vibration). This paper uses tilting type automatic pouring robot. A two-degrees-of-freedom control system is used to control the liquid level. This paper presents a series of models representing each part of the pouring process. Through these models, feedforward input can be achieved. Also, to improve the control, two-degrees-of-freedom-control is applied. Liquid vibration inside a ladle after pouring is suppressed by a controller using the Hybrid Shape Approach. As a result, the liquid level in a spruc cap is held to around the setpoint, and sloshing is suppressed. The validity of the proposed control system is demonstrated through experiments.

Keywords: Level control; Modeling; Feedforward control; Disturbance; Vibration control

1. INTRODUCTION

The environment in a casting factory is very dirty and dangerous for workers. Especially, from the viewpoints of both hygiene and the risk of handling molten metal, foundry factory automation is inevitable. To enhance the quality of the product and the productivity of the factory, it is necessary to stabilize the pouring process. A high-speed pouring machine has been recently advanced. However, owing to the various problems of system and control, it cannot yet be used efficiently.

Control over pouring by using a tilting-type ladle in the factory has been generally employed by teaching and playback training. Teaching and playback training have some problems. If a ladle were inappropriately tilted backward after pouring, the molten metal will slosh. Molten metal often overflows out from the ladle due to excessive sloshing (liquid vibration), and dust, air bubbles and inclusions become trapped in the molten metal. Also, the liquid level in a spruc cup must remain constant regardless of disturbances. When the liquid level is lower than the reference level, inclusions such as slag, are caught inside a mold. When the liquid level is above the reference level, the molten metal often overflows from the spruc cup. Further, sloshing during the transfer of the ladle should also be suppressed and controlled. These matters are dangerous to workers and result in the waste of materials. For these reasons, both the productivity of the factory and the quality of the product are lower than could be. Thus, control of the liquid level in a spruc cup, and the suppression of sloshing during transfer or after backward tilting of a ladle, are prerequisite to further improving the production of sound casting products.

By real-time feedback of sloshing, sloshing suppression after the transfer of a ladle from a furnace to a mold (or from a mold to another mold) has been studied within the framework of H_∞ control (K.Yano and K.Terashima, 2001*a*). Also, without the feedback of sloshing in real-time, the sloshing suppression of three-dimensional ladle by using an automatic pouring robot with four-degrees-of-freedom has been reported by means of a Hybrid Shape Approach, which was proposed by K.Yano and Terashima, 2001*b*. It is difficult to measure sloshing in real-time in industrial processes involving molten metal; in this cases, and then the proposed sensor-less system on sloshing is useful(K.Yano and K.Terashima, 2001*b*). A study on sloshing suppression of a pouring machine exists for the case of backward tilting of a two-dimensional thin-type ladle (K.Terashima and K.Yano, 2001).

On the other hand, liquid level control in the mold has been reported for the continuous casting by H_∞ control(H.Kitada and K.Sasame, 1998). Also, the study regarding the control design and implementation (S.F.Graebe and G.Elsley, 1995) and model-based control of mold level under various model uncertainties (M.A.Barron and E.Melendez, 1998) have been studied in continuous casting. Studies on liquid level control in a sprue cup have not been reported for the batch process treated in this paper, despite its importance. The batch process is difficult to control because the process involves a change from a transient state to a steady state.

Therefore, this paper presents a method to hold the liquid in a sprue cup at a constant level, and to suppress the sloshing after backward tilting of a ladle for a three-dimensional fan-type ladle. For brevity, water is used as the target liquid in this paper, where the extension to molten metal is straightforward. A mathematical model of the series of pouring processes is built, and model parameters are identified. Based on the model, a two-degrees-of-freedom control system that combines feedforward control with feedback control is presented for liquid level control. To suppression of sloshing after backward tilting, the Hybrid Shape Approach is applied without direct feedback of sloshing.

2. AUTOMATIC POURING ROBOT

The laboratory experimental apparatus used in this paper is shown in Fig. 1. The rotary direction of the Θ-axis is driven by an AC servomotor. The driving force of the AC servomotor can be amplified by reducing the gear ratio. The center of the ladle's rotation shaft is placed near the ladle's center of gravity. When the ladle is rotated around the center of gravity, the tip of the ladle nozzle (or mouth) moves in a circular trajectory. It is then difficult to pour the molten metal into a mold if the pouring mouth is moved by tilting. Then, the position of the tip of the ladle nozzle is controlled invariable during pouring, by means of a synchronous control of Y- and Z-axes for rotational motion around Θ-axis of a ladle.

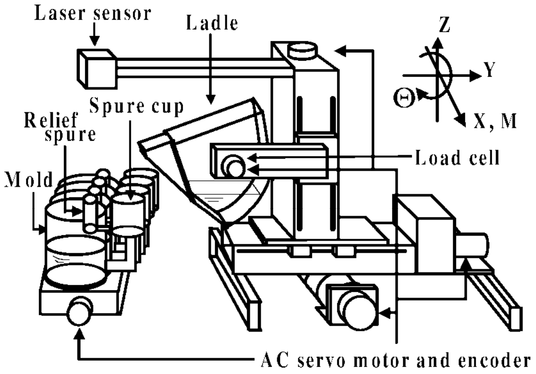


Fig. 1. Illustration of Automatic Pouring Robot

The rotation angle is measured by an encoder installed in AC servo motor. X-, Y-, Z- and M-axes are also driven by AC servo motors. But, the driving force of each of these motors is amplified through the ball and screw mechanism. Each axis can be independently moved.

The liquid level in a sprue cup is measured by a laser sensor above the relief sprue. This laser sensor measures the distance by triangulation. The liquid level is measured by using a relief sprue that has a float inside it.This float reflects the laser beam. The laser sensor used in this paper can measure liquid levels higher than 0.036[m] from the bottom of a cup (0[m]).

The measured value from the laser sensor and the encoder of each axis is inputted to a computer by A/D converter. A control input is sent to a motor driver via a D/A converter, driving the AC servomotor. The amount of sloshing in the ladle is measured by using an electric resistance-type sensor comprised of two stainless bars, where this sensor is not used for the purpose of feedback. A control instruction, a calculation of the control law and data processing are carried out in the DSP through the AD/DA converter and an up/down counter.

3. ANALYSIS OF THE POURING PROCESS

In this section, a modeling for the pouring process is carried out using water. The kinematic viscosity of the water(293[K]) and the molten metal(1673[K]) are 1.004×10^{-6}[m^2/s] and 0.970×10^{-6}[m^2/s], respectively. Therefor, the fulid behavior of the water is nearly equals to that

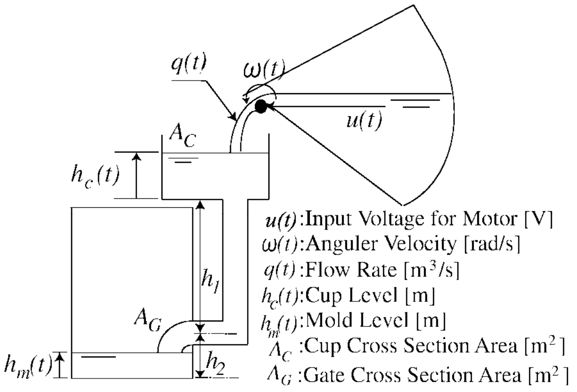


Fig. 2. A schematic diagram of poring model

of the molten metal. A schematic diagram of the pouring model is shown in Fig. 2, where h_1=0.165[m] and h_2=0.035[m].

Here, three models, from input voltage $u(t)$[V] for motor to the liquid level $h_c(t)$[m] in the sprue cup, are divided into three parts as follows.

(1) A model between input voltage of the AC servo motor $u(t)$ and the tilting angler velocity of a ladle $\omega(t)$: G_{0M};
(2) A model between the tilting angler velocity of the ladle $\omega(t)$ and the flow rate into the sprue cup $q(t)$: G_F;
(3) A model between the flow rate into the sprue cup $q(t)$ and the liquid level in the sprue cup $h_c(t)$: G_L.

G_{0M}, G_F and G_L are called, respectively, the motor model, flow rate model and level model.

3.1 *Motor model*

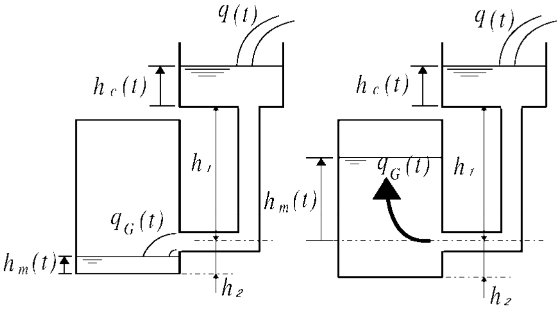
The relationship between the tilting angler velocity of the ladle and the input voltage to the motor is described in the following equation:

$$\frac{d\omega(t)}{dt} = -\frac{1}{T_{0m}}\omega(t) + \frac{K_{0m}}{T_{0m}}u(t) \qquad (1)$$

where ω[rad/s] is the tilting angler velocity, u[V] is the input voltage for Θ-axis, K_{0m}[rad/(sV)] is the gain of the motor, T_{0m}[s] is the time constant of the motor.

Further, the motor models of the X-, Y-, Z- and M-axes are described in the same form as in Eq. (1).

3.2 *Flow rate model*



(a) Drop Casting (b) Push Casting

Fig. 3. Level model of Case (a) and (b)

In this paper, a fan-type ladle is used for the pouring. Controlling the tip of the ladle nozzle invariably, the surface area of liquid in the ladle becomes constant while the ladle is tilted. Therefore, it can be considered that the pouring flow rate is constant when a ladle is rotated at a constant angler velocity. Hence, the flow rate model can be described by a first-order transfer function as follows.

$$\frac{dq(t)}{dt} = -\frac{1}{T_f}q(t) + \frac{K_f}{T_f}\omega(t) \qquad (2)$$

where K_f[m^3/rad] and T_f[s] are the gain and the time constant of the flow rate model.

3.3 *Liquid Level model*

The liquid level model is built separately for each of the two cases, as shown in Fig. 3, where (a) Drop Casting and (b) Push Casting.

When a fluid is poured into a mold, we neglect the dead time of the liquid dropping from the ladle to the sprue cup. So Drop and Push casting models are built by considering a mass balance, Bernoulli's theorem and continuous equation as follows.

Drop casting model

$$\frac{dh_c(t)}{dt} = -c\frac{A_G}{A_C}\sqrt{2g(h_c(t)+h_1)} + \frac{1}{A_C}q(t) \qquad (3)$$

Push casting model

$$\frac{dh_c(t)}{dt} = -c\frac{A_G}{A_C}\sqrt{2g(h_c(t)+h_1-h_m(t))} + \frac{1}{A_C}q(t) \qquad (4)$$

$$\frac{dh_m(t)}{dt} = c\frac{A_G}{A_M}\sqrt{2g(h_c(t)+h_1-h_m(t))} \qquad (5)$$

where c is the flow coefficient and g is gravitational acceleration.

The step responses of the two cases on level models are investigated by the simulation as follows.

- The level model is switched from the Drop casting model to the Push casting model by the flow state at the gate(Case 1);
- Only the Push casting model is adopted as the Level model(Case 2).

The responses in Case 1 and Case 2 were very similar to each other in the mold used in this paper. Therefore, by virtue of the brevity of its

Table 1. The parameters of models

Parameter	Symbol	Value
θ-motor gain	$K_{\theta m}$	0.427
θ-motor time constant	$T_{\theta m}$	0.0105
flow rate gain	K_f	1.48×10^{-3}
flow rate time constant	T_f	2.41
flow coefficient	c	0.852

analysis, we use the push casting model as the Level model in this study.

Table 1 shows the identification results of the parameters on the pouring models in this section.

4. FEEDFORWARD CONTROL OF LIQUID LEVEL

Feedforward control can achieve a high degree of accuracy when it is used in the appropriate situation. Systematic pouring operations that fill up a mold with molten metal and hold the liquid level constantly in a sprue cup are in high demanded. Since this pouring process is a batch process that handles the liquid from a transient state to a steady state, a system by feedback control alone is insufficient because of the time delay. In order to shorten the cycle time and maintain steady control (such as a constant level in a sprue cup), it is strongly required to have feedforward control in which the flow pattern is specified beforehand. We call an ideal outflow a pouring pattern. In the actual plant, pouring isn't carried out by a theoretically calculated outflow but by teaching and playback. In this section, we calculate the feedforward input that keeps the liquid level constant in a sprue cup. In this paper, the setpoint in a sprue cup is 0.06[m] for level control.

An ideal pouring pattern has three parts. First, in the Rising Part, the liquid level in a sprue cup must be raised to the setpoint as quickly as possible. Second, the liquid level must be held constant in the sprue cup in the Drop and Push Casting Part. Finally, in the Cutting Part of the pouring pattern, backward tilting after pouring must be carried out quickly. A general pouring pattern is shown in Fig. 4. Now, by the theoretical analysis, feedforward input is decided for three parts.

4.1 *Rising Part*

The Rising Part is decided as shown in Fig. 5, where H_{C0} is a setpoint and Q_e is the equilibrium flow rate in the setpoint.

The input voltage of the Rising Part is calculated by a combination of two sine waves. The amplitude and the period of these waves are decided by the following consideration.

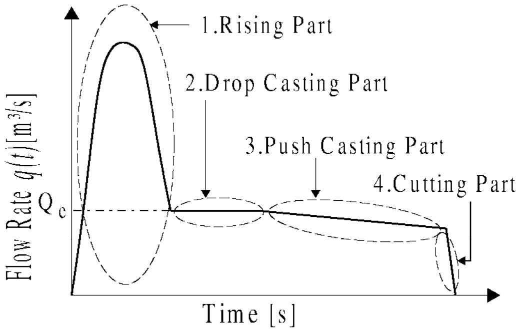


Fig. 4. General pouring pattern

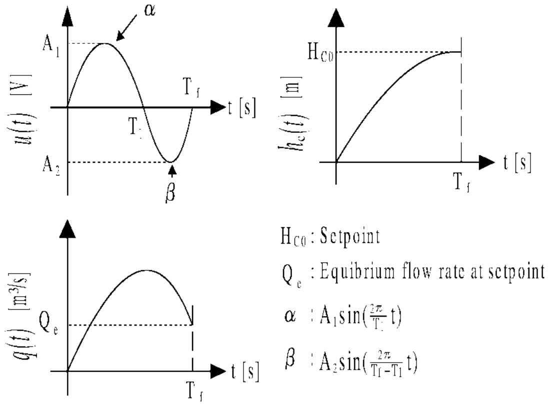


Fig. 5. Feedforward input in Rising Part

(1) Flow rate is Q_e in T_f;
(2) Liquid level is H_{C0} in T_f;
(3) Liquid level must not be over H_{C0} in the rising period.

From these, each factor of the two sine waves in Fig. 5 is A_1, A_2, T_1 and T_2. These parameters are decided by simulation using Eq.(1), Eq.(2), Eq.(4) and Eq.(5). As a result, each parameter becomes A_1=0.344[V], A_2=-0.0649[V], T_1=1.5[s] and T_2=1.4[s].

4.2 *Equilibrium Part*

The input voltage of the equilibrium part is decided by Eq.(1), Eq.(2) and Eq.(4). From Eq.(1), Eq.(2) and Eq.(4), Input $u_e(t)$, which holds the setpoint, becomes as follows.

$$u_e(t) = \frac{cA_G\sqrt{2g(H_{C0} + h_1 - h_m(t))}}{K_f K_{\theta m}} \tag{6}$$

where A_G is cross-sectional area of mold's gate and H_{C0} is setpoint.

4.3 *Cutting Part*

The input voltage of the Cutting Part to stop the pouring of liquid is not considered in the sense of feedforward control. This is because the cutting of liquid by backward tilting of a ladle is done by a feedback controller using the Hybrid Shape Approach (K.Yano and K.Terashima, 2001*b*). Hybrid Shape Approach considers both time and frequency domain. There are some control specifications such as settling time, overshoot, restriction

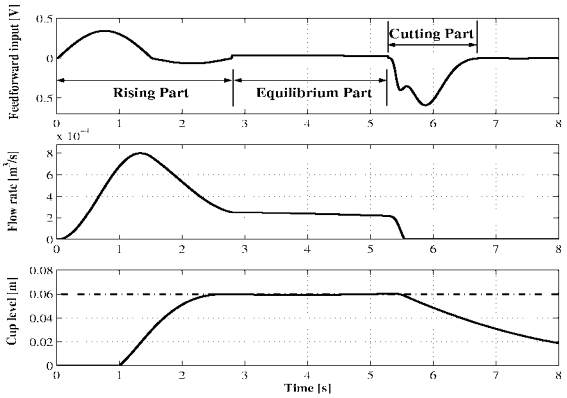


Fig. 6. Simulation results of feedforward control

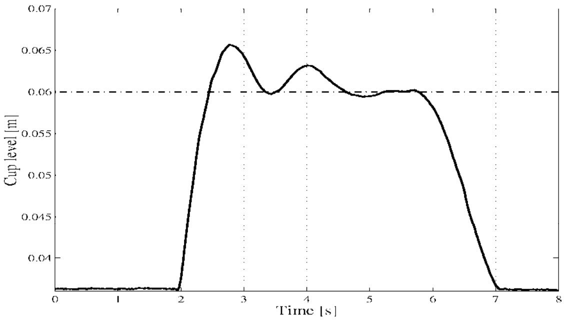


Fig. 7. Experimental results of feedforward control

of control input's magnitude and sloshing suppression. This controller consists of proportional control gain, a notch filter and a lowpass filter. So, this controller suppresses sloshing (liquid vibration) after backward tilting of ladle.

4.4 *Validity of the pouring model*

In this section, the pouring model is verified by using feedforward input. Feedforward input is constituted by a series of control inputs obtained in each pouring part. Simulation results of feedforward control are shown in Fig. 6. In Fig. 6, the upper graph shows feedforward input for the motor of the Θ-axis, the middle one shows the flow rate by which liquid flows out of a ladle and the lower one shows the liquid level in a sprue cup. The feedforward input in Fig. 6 keeps the liquid level around the setpoint of 0.06[m].

Experiments are carried out by using this feedforward input. Experimental results are shown in Fig. 7. A liquid level below 0.036 [m] in a sprue cup could not have been measured in this experiment, owing to the problem of sensor allocation. In this experiment, the liquid level is stable, dose not vibrate in the sprue cup, although the liquid level is a little vibrated in the relief sprue as shown in Fig. 7. Because the relief sprue is attached at the front of the ladle. therefore the water from the ladle flow directly into the relief sprue. The results of Fig. 7 is the consequence of above mention.

The liquid level is held around the setpoint similar to that in Fig. 6. This result implies that the pouring model from input voltage to liquid level, as proposed in this paper, can well explain the actual pouring process.

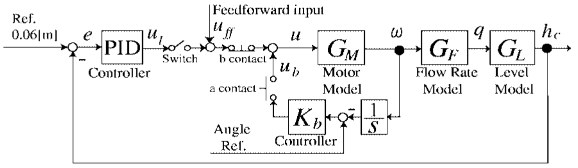


Fig. 8. Block diagram of pouring process control system

5. LIQUID LEVEL AND SLOSHING SUPPRESSION CONTROL

If feedforward control is adopted in an appropriate situation, such as no disturbance to the pouring process, it is able to hold the liquid level to around the setpoint. However, when a disturbance is added to the pouring process and model uncertainty exists, feedforward control cannot hold the liquid level to around the setpoint. Therefore, feedback on the liquid level is necessary. For this, we propose two-degrees-of-freedom control for the liquid level control. A PID controller is used for feedback control. Gain of the PID controller is decided by simulation of two-degrees-of-freedom control. As a result, the proportional, differential and integral gains become 5, 0.5 and 3. A block diagram of two-degrees-of-freedom control and the sloshing suppression control system is shown in Fig. 8. The switch is turned on when the liquid level is over the setpoint of 0.06[m]. Namely, Feedback control is started. Level control is carried out by two-degrees-of-freedom control while pouring. The inner loop in Fig. 8 is the sloshing suppression control system. Sloshing control system is carried out during only backward tilting of the ladle after pouring, where K_b is a controller that conducts the sloshing suppression, and then the a-contact is turned on. It implies that the b-contact is switched off.

In this paper, the pouring for molds is carried out twice. Movement of the automatic pouring robot when pouring into molds is carried out in five steps as follows.

- 1st step : The ladle is transferred from the origin to first mold;
- 2nd step : The first pouring(pouring for first mold);
- 3rd step : The second mold is transferred to be poured at the place of ladle;
- 4th step : The second pouring(pouring for second mold);
- 5th step : The ladle is transferred to the origin.

The controller from the Hybrid Shape Approach is used for each transfer process of the ladle, as

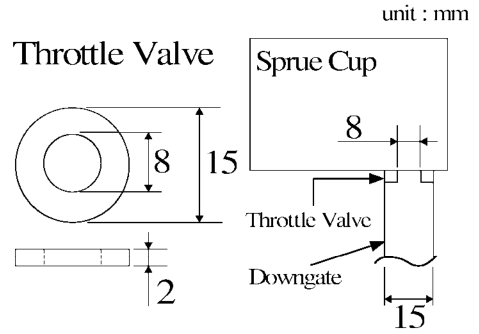


Fig. 9. Throttle valve as disturbance

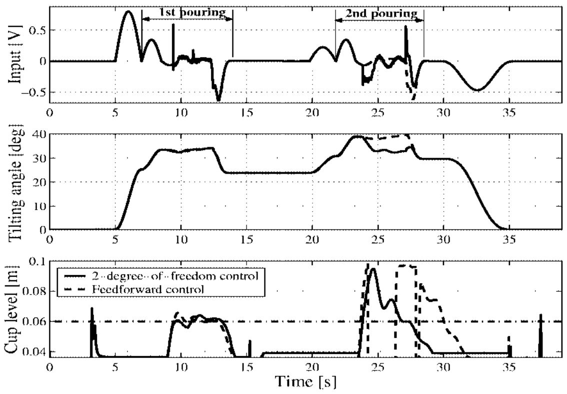


Fig. 10. Liquid level in a sprue cup

well as for the mold and the cutting of the liquid to suppress sloshing.

A throttle valve is used as a disturbance to the pouring process. Because the choke of slag for the downgate is assumed to occur in the actual plant, a throttle valve is shown in Fig. 9. This throttle valve is installed in the second mold.

The experimental results are shown in Fig. 10.The solid line is two-degrees-of-freedom control and the dashed line is feedforward control.

In Fig. 10, In the first pouring, accuracy in maintaining control of the liquid level dose not differ so much between two-degrees-of-freedom control and feedforward control.

In the second pouring, a laser sensor unmeasures the liquid level when liquid is poured into the second mold by feedforward control. This fact means that liquid has overflowed from the sprue cup because of a disturbance. However, overflow is avoided by a large backward-tilting input by feedback control in the case of two-degrees-of-freedom control. Here, the liquid level is approached near the setpoint.

Sloshing after the first pouring is shown in Fig. 11. The solid line is sloshing after backward tilting in the Hybrid Shape Approach. The dashed line is after backward tilting by proportional control. The settling time of backward tilting by the Hybrid Shape Approach and by proportional control is given to be the same. Sloshing by the Hybrid Shape Approach is suppressed better than it is by proportional control.

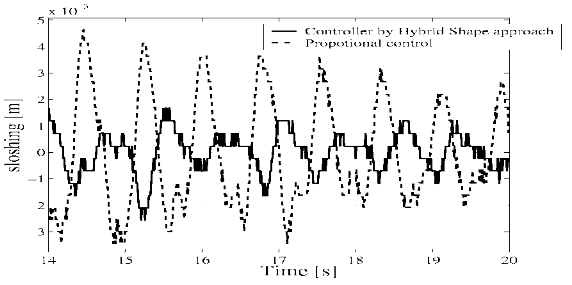


Fig. 11. Sloshing after backward tilting

6. CONCLUSION

This paper presented a means of controlling the liquid level and of sloshing suppression using an automatic pouring robot. The model was built for the pouring process. The validity of the model was demonstrated via experiments. Feedforward control inputs for the pouring process were obtained based on the model, and the liquid level in a sprue cup was held to around the setpoint. The effectiveness of the proposed two-degrees-of-freedom control was distinctly confirmed in the case of a disturbance. Sloshing after backward tilting was suppressed by using the Hybrid Shape Approach. Through this research, a basis was established to make a reliable automatic pouring robot system in the future.

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