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Tilting Motion Control of Automatic Pouring Ladle with Weir for Liquid Vibration Suppression

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This paper presents analysis results of molten metal vibration for the teapot ladle of an automatic pouring system and proposes suppression control during ladle tilting. First, by means of CFD simulations, we analyzed responses of molten metal behavior using the teapot ladle. In this analysis, trapezoidal shape input was designed as back tilting velocity and applied to simulations. As a result, molten metal in a teapot ladle showed not only sloshing but also flow oscillation beneath the weir. Secondly, it was assumed that two vibrations were equivalent to a second-order lag system. Characteristic parameters were identified from residual vibrations and control input was designed based on its process parameters using the Input Shaping control approach. The effectiveness of the proposed suppression control input was evaluated by comparison with the non-controlled case using CFD simulations. The results provide valuable information that can be used to reduce casting defects caused by the pouring process.

Keywords: *automatic pouring system, teapot ladle, filling accuracy, liquid vibration control, Input Shaping control*

1. Introduction

Tilting-type automatic pouring systems are automation equipment developed to enhance safety in factories and improve yields of cast products [1]. One solution is to drive ladle quickly during transferring or pouring in casting processes, e.g., transferring the ladle from a melting furnace to molds and tilting during pouring of molten metal. It is important to suppress sloshing, i.e., surface vibration in the liquid container.

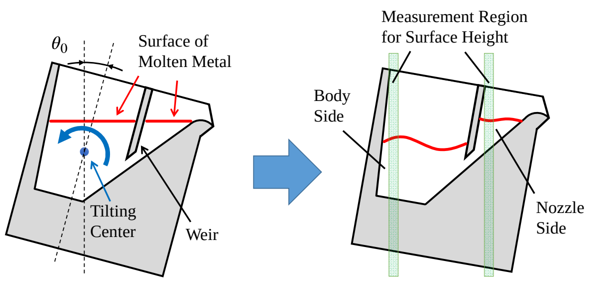
The literature includes many achievements concerning analysis or sloshing suppression [2]-[4]. Of course, sloshing suppression control approaches are also applied for the pouring process of casting. Some achievements have been applied to back-tilting motion for cutting off pouring [5]. The cut off process has a deep relationship with the accuracy of filling volume into molds, and faster cutting is important to shorten a cycle time [6].

Previous studies, however, show suppression control approaches for a ladle with a simple shape. Therefore, those approaches have not yet been applied to a teapot ladle; there is a weir inside the ladle, which separates body and nozzle sides [7]. To our knowledge, there are no proposals of suppression control of liquid vibration using a liquid container with a weir in the literature. However, this problem is deeply related to filling accuracy of molten metal in a mold. Therefore, this paper presents vibration analysis of molten metal for a teapot ladle and design of the suppression control input for back-tilting motion.

2. Liquid vibration suppression for teapot ladle

The teapot ladle shown in Fig. 1 was assumed as the target of vibration suppression control. It is an example of the teapot ladles used in the tilting-type automatic pouring process. The ladle is constructed of two parts, namely, a cylindrical body part and a thin part extending from the body to the nozzle.

Behavior of molten metal in the ladle was simulated using computational fluid dynamics (CFD) analysis. In this work, the CFD application used was FLOW-3D ® (Flow Science Inc.) [8]. Casting iron was chosen as the target molten metal.



(a) Before tilting (b) After tilting

Fig. 1 Simulation condition for teapot ladle

2.1 Analysis result by trapezoidal input

At first, backward tilting motion for cut-off pouring was simulated using the reference input; the ladle was tilted to a target angle from an initial posture θ_0. In this paper, θ_0 was 15 deg. Before backward tilting, as shown in Fig. 1(a), the ladle was filled with molten metal without any flow outside the ladle. The reference input of backward tilting was assumed as a trapezoidal pattern. In this work, the reference input was assumed as follows: maximum velocity -4deg/s, maximum acceleration ±11.05 deg/s^2, and target tilting angle -5 deg.

Residual vibration of the liquid surface was measured at points close to the wall of the ladle, as shown in Fig. 1(b). FFT analysis of residual vibration revealed that vibration responses had two peak frequencies: 1.15 Hz and 0.34 Hz. 1.15 Hz vibration was first order-mode sloshing. It was mainly induced in the surface of the body side. 0.34 Hz vibration was flow oscillation of molten metal beneath the weir between body and nozzle sides, similar to a U-tube manometer. It was shown that backward tilting motion of the ladle induced not only sloshing but also volume moving vibration when teapot ladle was used.

2.2 Vibration Suppression by Input Shaping control

The Input Shaping approach is one of the vibration suppression controls; amplitudes and phases of multiple inputs are designed and superposed so that all residual vibrations eliminate one another [9]. Shaped input is dependent on natural frequency and damping ratio of vibration response. In this work, in which the Input Shaping approach was used, shaped input was applied to suppress the two vibration modes referred to in the previous subsection.

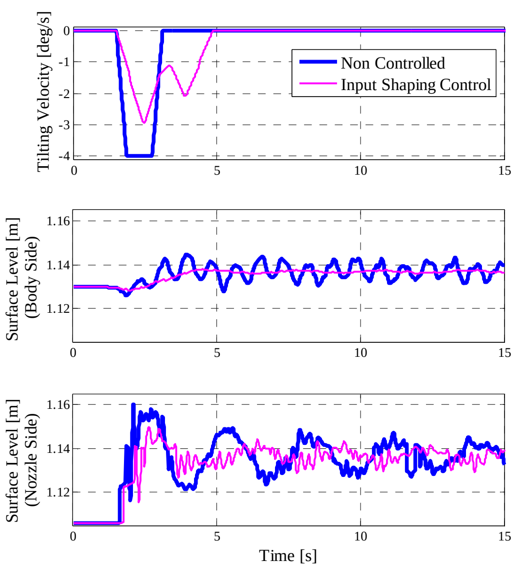


Fig. 2 Comparison result of residual vibrations

The controlled response and the non-controlled one are compared in Fig. 2. This figure compares inputs and their responses between the non-controlled response and the proposed one. The thick blue plot shows the result of the non-controlled response, and the thin magenta plot shows the result of the proposed approach. The proposed velocity input achieved good suppression control for the two vibration modes.

3. Conclusion

This paper presented CFD analysis results for backward tilting motion using a teapot ladle; cut-off pouring induced not only sloshing but also flow oscillation similar to a U-tube manometer. In addition, we applied Input Shaping control to suppress two vibration modes. The proposed control effectivity suppressed the amplitude of residual vibration.

In the next phase of this work, we will endeavor to completely suppress liquid vibrations and to clarify the relativities of a center position of a ladle tilting. Finally, we intend to verify the effectiveness of the proposed approach by experiments using actual pouring systems with molten metal.

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