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Automatic Restarting System for Continuous Caster with Utilizing Cooperated Predictive Control

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Abstract:

The automation of restarting an ongoing cast on a continuous caster of the common drive type calls for the pouring technology that allows the molten steel to rise to the same level in two or more molds at the same time. The high temperature of the molten steel made it difficult to continuously detect the molten steel level over a wide range. The characteristics of the continuous casting process were black box-like and changed so greatly that the automation of cast restart was difficult to achieve. The problem was solved by adding the method of correcting the process model with a small amount of discrete level information to the model-based predictive control.

1. Introduction

During pouring at a continuous caster, the operator's workload peaks at the start and restart of each cast. The start and restart of casting represent the tasks that must be automated with top priority. Steelmakers and steelworks have tackled and accomplished the automatic start and restart of casts on their continuous casters.

On a continuous caster of common drive construction two or more strands are simultaneously withdrawn with common rolls. The pouring of molten steel must be controlled so that the molten steel rises to the same level in the molds at the same time. This is like the No. 4 continuous caster at Nippon Steel's Kimitsu Works, hereinafter referred to as the Kimitsu No. 4 continuous caster. The pouring requirement hampered the automation of cast start and restart on continuous casters of the common drive type. The restart of a sequence cast of dissimilar steels calls for similar automatic control technology. The severity of the operating environment and the difficulty of continuously detecting the mold level made it impossible to achieve the automation of dissimilar-steel sequence-cast restart with conventional technology.

An automatic control method was developed for restarting an ongoing cast on a continuous caster of the common drive type, using only the discrete level information measured with a multiple-point level switch sensor. This article outlines the automatic control method, describes the idea behind its introduction, and presents the results of its test application at the Kimitsu No. 4 continuous caster.

2. Problems with Restart Automation

2.1 Cast start automation technology

In the continuous caster, molten steel refined in the previous process is poured from the ladle through the tundish into the mold. The molten steel starts solidifying at the surface in the mold and solidifies to the core as it is withdrawn in a continuous strand.

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When starting a cast the molten steel is poured into the mold with its bottom plugged with a dummy bar. When the molten steel rises to a high enough level in the mold, the strand is started to be withdrawn. The molten steel level in the mold is kept constant by matching the mold pouring rate with the strand withdrawal rate. Since keeping the mold level constant is the most important requirement to be met for product quality and operational stability, automation technology was implemented early for steady-state portions of casts. Automation is now accomplished using PID (proportional-integral-derivative) control or various modern control techniques. In recent years the automation of cast start has been implemented both on a trial basis and a production basis at many continuous casters from the perspective of reduction in the required number of operators.

Today's continuous casters can be divided into two main types: (1) the single-drive type to withdraw one strand with pairs of rolls and, (2) the common-drive type to simultaneously withdraw two or more strands with the same pairs of rolls. The former type is mostly used on large-section slab casters, while the latter is adopted on many small-section bloom and billet casters. This difference in the drive type has a great effect on the automation of casting start. When the molten steel is poured at the start of a cast with either drive type, it is important to control the mold level at and after the start of strand withdrawal. Mold level variations at the start of strand withdrawal exert adverse effects on quality and operation. When the strand is poorly cooled and insufficiently solidified in the mold, for example, a serious accident may occur. This is known as a breakout. The molten steel leaks through the thin solidified shell onto the machine. Thus becomes necessary to control the pouring of the molten steel.

The common-drive caster withdraws two or more strands at the same time and imposes the constraint that the molten steel must be poured into the molds so that it simultaneously rises to the same level in the molds as strands are simultaneously withdrawn. The single-drive type with fewer such constraints preceded the common-drive type in cast start automation technology. The start of casting was automated on the single-drive continuous casters of many steelmakers and steelworks. The following two control methods are key in these attempts:

(1) Open-loop control under which the molten steel is poured according to a predetermined pattern

(2) Closed-loop control under which the rising molten steel level is measured to control the pouring rate

The open-loop control method is used when the molten steel pouring rate do not appreciably vary in characteristics. The closed-loop control method measures the rising molten steel level on-line and incorporates the measured value into control to compensate for the variation of the pouring rate.

Recently, control measures with higher than ever accuracy were developed and applied to the automation of starting a cast on common-drive continuous casters. Nippon Steel implemented this cast start automation at the No. 3 continuous caster at the Muroran Works referred to as the Muroran No. 3 continuous caster.

2.2 Necessity for development of cast restart automation technology

The Kimitsu No. 4 continuous caster is schematically illustrated in **Fig. 1**. The stoppers installed in the tundish are moved up and down to control the tundish pouring rate. The molten steel is poured through the immersion nozzle into the mold. Each stopper is connected to and operated by an electrohydraulic stepping cylinder. The largest characteristic of the Kimitsu No. 4 continuous caster is that it is a slab/bloom combination casting machine of the common drive type. When blooms are cast in two strands, they are simultaneously withdrawn from the two molds. The Kimitsu No. 4 continuous caster can apply the cast start automation technology of the Muroran No. 3 continuous caster. The same technology cannot be applied to the cast restart automation technology at the Kimitsu continuous caster due to the following constraints:

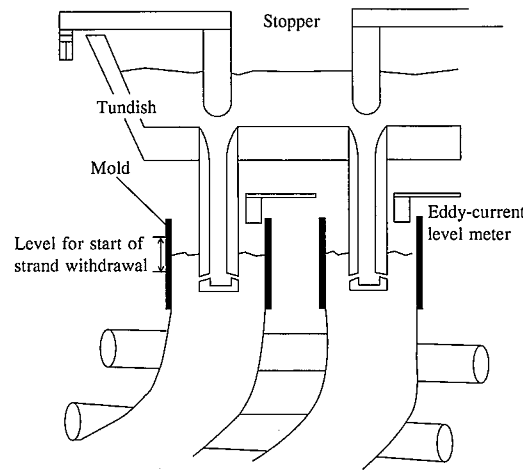

Fig. 1 Schematic of Kimitsu No. 4 continuous caster

- Large variation in pouring rate
- Difficulty of detecting molten steel level in molds

The term "restart" refers to the resumption of the casting operation after the stop of mold pouring and strand withdrawal during a sequence cast of dissimilar steels or a tundish change. As soon as the ongoing cast is restarted, the molten steel level is so low that the strand cannot be withdrawn. As is the case with a cast start, the molten steel is poured into the mold, and when the mold level rises high enough, the withdrawal of the strand is started. The actual procedure does not differ from that followed when starting a cast.

Fig. 2 shows the relationship between the stopper position and the molten steel pouring rate, or the pouring rate characteristic at the restart of casts. The pouring rate varied more than observed at the start of casts. This is probably because the stopper and immersion nozzle refractories are conditioned clean when a cast is started, but are already altered physically due to wear or skulling when

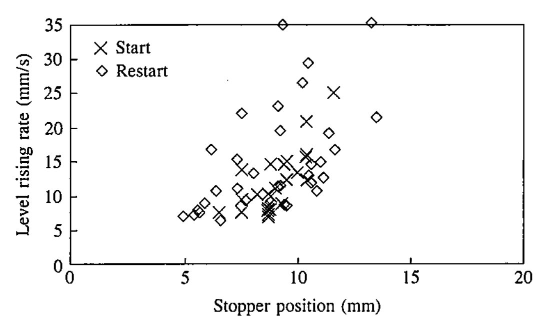

Fig. 2 Variation in pouring rate characteristic

an ongoing cast is restarted. This variation in the pouring rate characteristic makes it difficult to pattern the controller action.

The measurement of the molten steel level itself is constrained at the restart of the ongoing cast. The molten steel level detector used in casting start control is of either the gamma ray or thermocouple type. The gamma ray type had to be abandoned because it required a costly and extensive modification of the existing mechanical equipment. The thermocouple type detects the molten steel level in the mold according to the temperature distribution measured with the thermocouples embedded in the mold. Thermocouples were already installed in the molds of the Kimitsu No. 4 continuous caster and presented no equipment problems. Investigations showed that thermocouples used for the start of casting cannot be used for the restart of casting.

Thermocouple-measured temperature rises at the start and restart of casts are shown in **Figs. 3**(a) and **3**(b), respectively. The thermocouples are sequentially numbered in increasing order from the lowest. At the start of casting, the thermocouples sequentially rise in the measured temperature in increasing order. At the restart of casting, the thermocouples are markedly delayed in response as compared with the start of casting, and the sequence in which the thermocouples rise in the measured temperature is reversed. This is probably because at the restart of casting the mold copper plates are already hot and are slow in the rate of temperature rise and because heat transfer is made uneven by the buildup of solidified mold powder on the mold wall. This is called a slag rim or rope. At the Muroran No. 3 continuous caster, the mold is cleaned at the restart of casting to remove foreign matter deposits, accelerate the temperature drop of the mold copper plates, and create the same conditions as observed at the start of casting. For these reasons the same level detection method employed at the start of casting is adopted at the restart of casting at the Muroran No. 3 continuous caster. The Kimitsu No. 4 continuous caster cannot allow the same mold cleaning time as the Muroran No. 3 continuous caster from the standpoint of productivity and cannot use thermocouples as its mold level sensing elements.

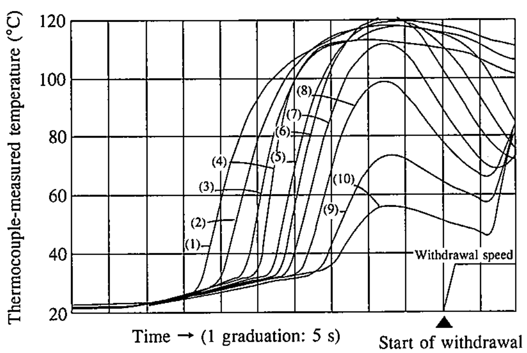

Fig. 3(a) Thermocouple-measured temperature at start of cast

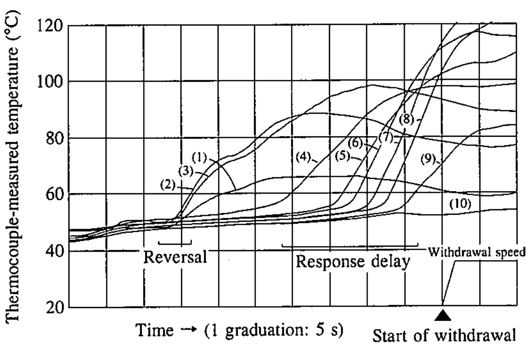

Fig. 3(b) Thermocouple-measured temperature at restart of cast

The application of other types of level meters was studied, but no appropriate ones were found. The following reasons may be cited:

- Durability in poor environment (as represented by high temperature, splashing, waving, and dust generation)
- Equipment constraint (small sensor required)
- Measuring range (about 100 to 500 mm)

Specifically, the eddy-current level meter that is often used for steady-state level control is narrow in the measuring range and is unable to measure the level range required for the control purpose. The laser and ultrasonic level meters cannot measure the molten steel level that rises with wave formation. The contact level meter cannot withstand the temperature of the molten steel.

As a result, it was unavoidable to adopt a low-cost disposable multiple-point level switch sensor. It is advantageous in that it is simple, trouble free, rapid in response and accurate. Its main disadvantage is that the level of information obtained is limited.

This shortcoming of the multiple-point level switch sensor created the need for developing a new control method that can control the pouring rate with a limited amount of level information.

3. New Control Method

For the reasons described previously, it became necessary to develop a new control method that enables two or more molds to achieve the same molten steel level at the same time by using only the level information detected at several points with a level switch sensor in the continuous casting process whose parameters change moment by moment.

3.1 Point of development

To accomplish the automatic restarting of an ongoing cast on a common-drive continuous caster, the following control specification (4) with respect to the following control constraints (1) to (3) is necessary:

(1) In a system where the pouring rate characteristic is unstable,

(2) Based on the limited, discrete level information obtained with a multiple-point level switch sensor,

(3) Control the manipulated variable (stopper position at the Kimitsu No. 4 continuous caster); and

(4) Minimize the difference between the molds in the time for the molten steel to reach the level at which strand withdrawal can be started.

The quantity of level switches can be increased to improve control accuracy. In reality two to six level switches are used by such reasons as small mold cross-sectional area.

Under this severe environment for measurement and control, it was necessary to control the pouring of molten steel from one tundish into two or more molds and to coordinate the rise in the molten steel level between the molds.

3.2 Description of the new control method

Step 1: Model-based predictive control

The new control method, based on the current information, reduces the deviation within a given time limit and agrees with the concept of the model-based predictive control. Thus the decision was made to adopt the model-based predictive control as the new control method.

Generally in model-based predictive control, the predictive value $\hat{y}(k+n)$ $(i = 1,\cdots, n_1)$ with respect to the future output of the plant when the input $u(k+i)$ $(i = 1,\cdots, n_2)$ is added after the current time k is calculated using the model, and the manipulated variable $u(k+i)$ $(i = 1,\cdots, n_2)$ is determined to minimize the performance index represented by Eq. (1).

$$J=\sum_{i=1}^{n_1} q_i \cdot (y_{sp}(k+i)-\hat{y}(k+i))^2+\sum_{i=1}^{n_2} r_i \cdot \Delta u^2(k+i) \quad \cdots\cdots(1)$$

where $y_{sp}(k)$ is the output set point (desired value) at the time k.

The difference between the plant output y(k) and the model output $\hat{y}(k)$ is also fed back so that the offset does not remain, as shown in **Fig. 4**.

Step 2: Modified model-based predictive control

The design of a control system must allow for the magnitude of the prediction error. Generally, the following factors are included in the prediction error:

- Immeasurable disturbance
- Modeling error
- Noise

Of these factors the modeling error has the greatest impact when model-based predictive control is applied to the restart control of the continuous caster.

The restart of casting is performed in a system with such a process variation that the pouring rate characteristic changes moment by moment. The effect of the modeling error is so large that the effects of the other factors can be ignored. Usually, model-based predictive control is not applied to a process with such a variation as to cause a large modeling error, because it leads to the incorporation of an unstable control factor.

To apply it to a greatly varying process, model-based predictive control is transformed to a modified model-based predictive control method that makes up for its shortcoming as shown in **Fig. 5**. A mechanism to correct the model itself with past inputs and outputs is incorporated to reduce the modeling error.

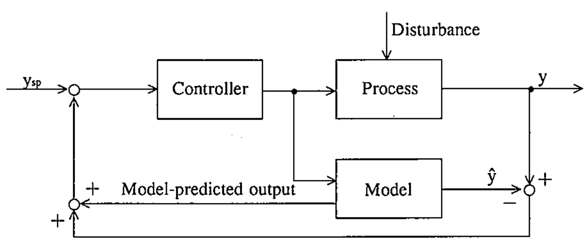

Fig. 4 Model-based predictive control

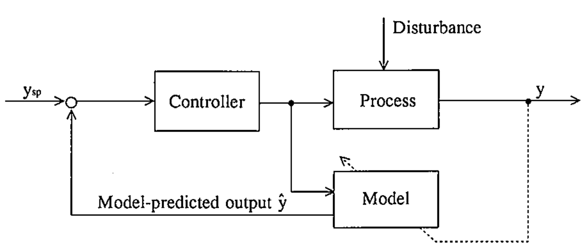

Fig. 5 Modified model-based predictive control

Step 3: Performance index

The number of detection points with level switches is 6 at the most. In the constraint, to limit to a few seconds the difference between the molds in the time to reach the molten steel level (100 to 120 mm below the mold top) at which strand withdrawal can be started cannot be done. The control accuracy is still not high enough, even if the modified model-based predictive control method described in Step 2 is used. Next, attention was focused on the performance index.

The performance index is determined to place the control point on the minimization of the difference between the molds in the time to reach at the final level. Using the δ function for the weighting function in the performance index of Eq. (1),

$$q_i = \delta(i - n_0 + k) \quad \cdots\cdots(2)$$

$$r_i = r(= \text{const.}) \quad \cdots\cdots(3)$$

Equation (1) can be rewritten as follows:

$$J=(y_{sp}(n_0)-\hat{y}(n_0))^2+r \cdot \sum_{i=1}^{n_2} \Delta u^2(k+i) \quad \cdots\cdots(4)$$

where n_0 satisfies the following equation:

$$y_{sp}(n_0) = \text{withdrawal level} \quad \cdots\cdots(5)$$

The δ function is used in Eq. (2) to ignore the deviation in the rising process and to evaluate only the difference in the final level. Since the change in the manipulated variable tends to promote the plant variation, the second term of Eq. (4) is left.

Step 4: Set point

The provision of the set point was ingeniously devised. The fact that there are less constraints on the molten steel pouring time at the restart of casting than at the start of casting was put to effective use. When the ongoing cast is restarted, the molten steel level often varies at the start of pouring, and there is no need to have the same set point $y_{sp}(k)$ for each restart. Since it suffices to determine $y_{sp}(n_0)$ as the only set point as described in the preceding section, it was decided to minimize only the difference in the arrival time between the molds. That is, the molten steel is poured into a given mold according to a predetermined stopper position pattern, and the control input is added for the other molds on the basis of Eq. (4) by referring to the rise in the molten steel level of the first mold (see **Fig. 6**). The features of this new control method may be summarized as follows:

(1) Control equations transformed from those of model-based predictive control

(2) On-line model modification

(3) Evaluation of only difference in final level

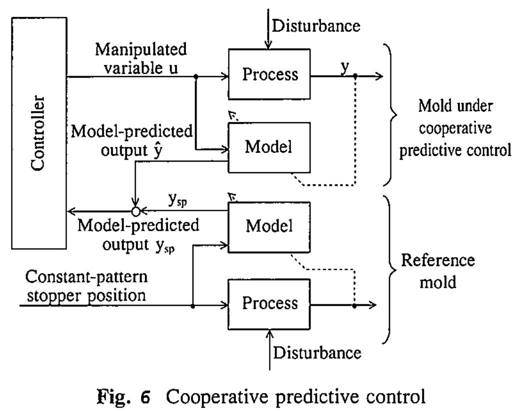

Fig. 6 Cooperative predictive control

(4) Control of pouring rate into other molds by reference to rise in molten steel level of one mold

This control method emphasizes the compatibility of one mold with the other mold or molds in the rise of the molten steel level and is thus called cooperative predictive control.

4. New System and Its Evaluation

4.1 Equipment outline and control flow

To put the above-mentioned control method to actual use, the system shown in **Fig. 7** was installed and tested at the Kimitsu No. 4 continuous caster.

The flow of the control sequence is shown in **Fig. 8** and described below.

Flow

(1) The pouring of the molten steel into the molds is started in response to the increase in the tundish weight.

(2) The molten steel is poured into all molds according to the same stopper position pattern.

(3) The mold level detected first with the level switches is taken as reference value.

(4) The molten steel continues to be poured into the reference mold according to a predetermined pattern.

(5) The molten steel continues to be poured into the other molds under cooperative predictive control.

(6) A strand withdraw command is issued after the detection of the condition that all molds have reached the same withdrawal start level.

(7) The stopper position is controlled to suit the withdrawal rate.

(8) Cooperative predictive control is switched to steady-state level control (constant-value control).

4.2 Results of on-line test

The change with time in the molten steel level of two molds under cooperative predictive control is shown in **Fig. 9**. The molten steel level detected with the level switch sensor in each mold is shown. Although the molten steel level is measured at only four points per mold, it is clear that the two molds converge to the same molten steel level with elapse of time.

The molten steel level measured with the eddy-current level meter also changed smoothly without the operator's manual intervention in steady-state level control.

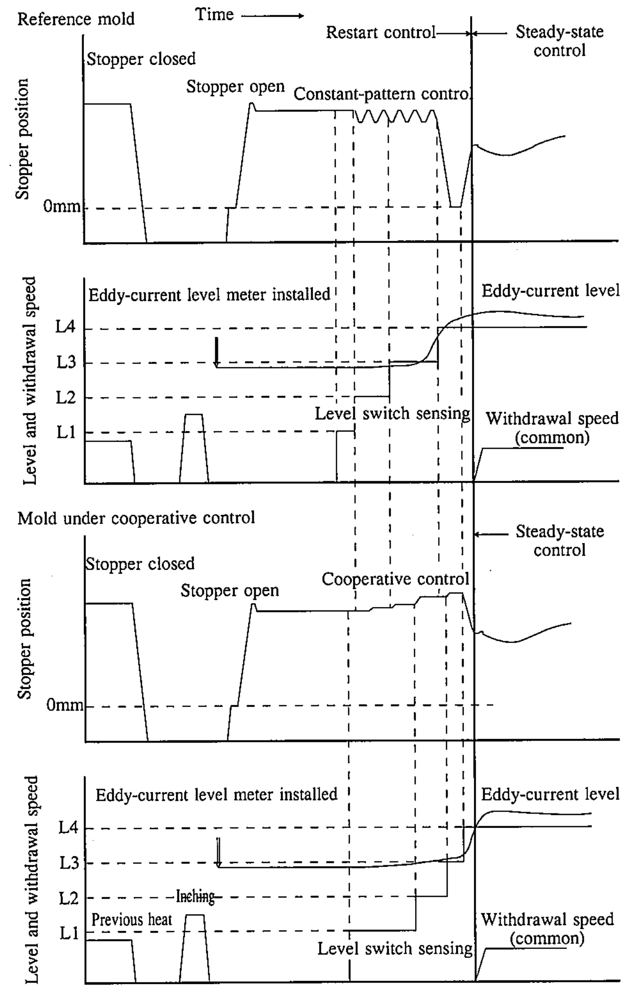

Fig. 8 Automatic restart control flow

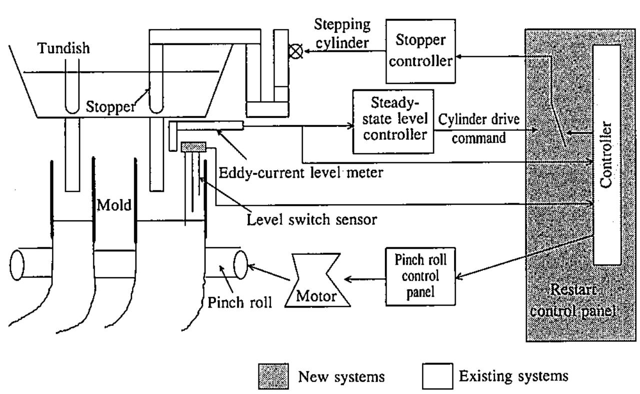

Fig. 7 System configuration

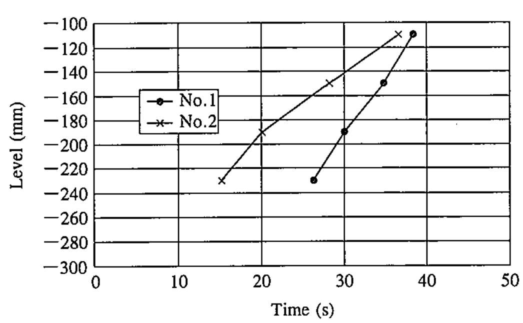

Fig. 9 Rise in level during control

4.3 Evaluation and discussion

The cooperative predictive control method reported here was actually tested for a total of 12 casts and compared with the following two additional control methods which were also tested.

(1) Open-control method (or pattern control method) whereby the molten steel is poured according to a predetermined stopper position pattern.

(2) Modified model-based predictive control method whereby the same level switches and set points as those of the cooperative predictive control method are used (steps 1 to 3 in 3.2)

These two control methods were tested in addition to the cooperative predictive control method. The cooperative predictive control method and the control method (2) above used the same four level switches at intervals of 40 mm.

The molten steel pouring time and the difference in the arrival time between the molds are shown in **Table 1**. When attention is focused on the pouring time alone, the variation in the pouring time is reduced the most by the modified model-based predictive control method (2) and is greater with the cooperative predictive control method in which the set point varies each cast. When the difference between the molds in the time to reach the strand withdrawal start level is examined, the mean and variability are less under modified model-based predictive control than under pattern control, but these two control methods are greater in the mean and variability than the cooperative predictive control method. Given the objective of control, the cooperative predictive control method has clearly the highest control accuracy.

The arrival time differences are shown in histogram form in **Fig. 10**. As evident from **Fig. 10**, the cooperative predictive control method has markedly reduced the arrival time difference between the two molds and materially improved the control accuracy.

Table 1 Comparison of control accuracy

	Level rise time (s)		Arrival time difference (s)	
	Mean	Standard deviation	Mean	Standard deviation
Cooperative predictive control	27.3	9.7	3.1	1.9
Pattern control (1)	28.9	12.1	10.7	5.1
Modified model-based predictive control (2)	28.6	6.0	4.6	4.1

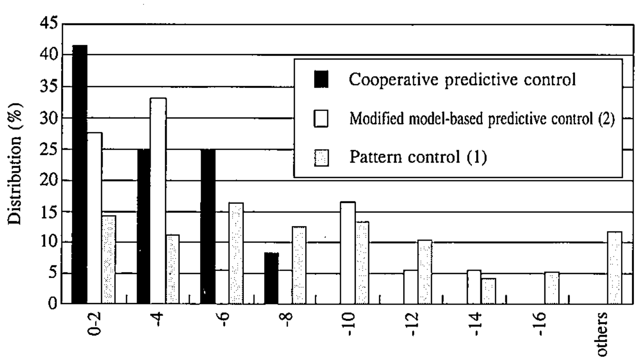

Fig. 10 Comparison of control accuracy (histogram)

5. Conclusions

A new control method has been proposed as the technology of automatically restarting the casting of molten steel on a continuous caster.

Under the situation where controlled variable information is discrete and limited and where plant characteristics vary and are difficult to control, the new control method was devised by incorporating the characteristics of the continuous caster plant into the control scheme by transforming model-based predictive control. The new control method was on-line tested at the Kimitsu No. 4 continuous caster to verify its control accuracy. Good results were obtained.

The new control method is now being applied to the actual casting operation of the Kimitsu No. 4 continuous caster and is expected to advance as one measure for achieving cost reduction and operational stability.

References

1) Tsuneki, A. et al.: CAMP-ISIJ. 9(5), 933(1996)
2) Shah, Dumont: IEEE CAC Tutorial Workshop on Model-Based Predictive Control. September 1993