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Adaptive Mold Level Control in a Continuous Steel Slab Casting Process

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Surface quality of the steel slabs in a Continuous Casting (C.C.) process is mainly determined by the stability of the Mold Level Control (MLC). Excessive mold level fluctuations lead to an additional machine scarfing process which is applied to the slabs to avoid surface defects. A conventional Proportional-Integral-Derivative (PID) controller is not robust enough to deal with the disturbances caused by the hydraulic pressure hunting in a withdrawing system, submerged entry nozzle clogging, or unsteady bulging. Different types of mold level fluctuations can be observed online through the realization of Fast Fourier Transform (FFT) algorithms. An adaptive control logic was developed based on the calculations of the Accumulated Mold Level (Acc.ML) deviations and the results of mold level FFT, which enables choosing a phase-lead compensator, a phase-lag compensator, a sliding mode controller or a standing wave filter automatically in a MLC loop to restrain fluctuations. At China Steel (CSC), the value of Acc.ML deviations in a minute determines if a slab is going to be machined or not. Each of these control methods corresponds to a specific type of mold level fluctuation. Depending on the statistics, the phase-lead compensator is mostly triggered during the silicon steel casting, and the sliding mode controller is normally run in a peritectic steel casting. The phase-lag compensator lowers both the mold level fluctuating frequency and the Acc.ML deviations in most kinds of steel casting. A low-pass filter is adopted to eliminate the influence of the surface standing waves on the flow control actuator. These adaptive MLC methods were resident online in CSC #5 and #4 slab C.C. since 2011 and 2012 respectively, and also tested in #2 slab C.C. at Dragon Steel (DSC) in 2013. The stability is improved apparently after the accomplishment of the adaptive MLC in a continuous steel slab casting process.

Keywords: Mold level control, Continuous steel slab, Casting

1. INTRODUCTION

Surface quality of a C.C. steel slab is highly related to its MLC stability. The casting speed had to be slowed down while the mold level is fluctuating to avoid the generation of surface defects. A machine scarfing process had to be applied to the slab surface if the mold fluctuating level is higher than the threshold. The conventional PID controller is not able to deal with the disturbances caused by the unstable process variations. Lots of slabs had to be machined frequently after peritectic steel casting, which raises production costs. In the worse case scenario, even the blast furnace had to reduce its blasting air because of the retarded casting speed due to fluctuations of the mold levels.

H-infinity control theory was realized in a personal computer and applied to Kobe Steel #4 slab C.C. in 1995 to avoid the influence of bulging on MLC, and an improved testing result compared with the conventional PID controller was revealed(1). A robust controller was put into practical use in #6 slab C.C. of Fukuyama works in 1997, and the mold level fluctuations were reduced by about 60 percent of the conventional method(2). Sliding mode control theory was designed and evaluated in the MLC in POSCO #2 slab C.C. in 1997, and the mold level fluctuations were found to decrease within some of the experimental slabs at unchanged casting speeds(3). Siemens VAI designed a mold level controller with loop shaper principles based on H-infinity methods in Voest Alpine #3 slab C.C. in 2008 to suppress the fluctuations of the mold level(4).

2. SYSTEM DESCRIPTION

After a revamping in CSC #5 slab C.C in 2005, the pitch of the rollers for whole segments in the bow section were set the same in order to reduce the cost of spare parts. However, such an arrangement resulted in a serious superposition of wave fluctuation while bulging. The fluctuating level in peritectic steel casting was apparently enlarged. Many trials were done at different casting parameters but it was still not possible to reduce the amount of machining slabs. To make matters worse, the kernel MLC sequences at the Programmable Logic Controller (PLC) were not able to be accessed by users, because of it being locked by the manufacturer's passwords, which limited the possibility of advanced improvement.

An adaptive controller was designed and plugged into the MLC circuit in CSC #5 slab C.C. through an additional software switch in front of the PID controller, as shown in Fig.1. Both the mold level setting values (ML SV) and its present values (ML PV) were in parallel connected to the adaptive controller to generate control values (ML CV) sent to the PLC to try to improve the MLC stability. Another PID controller in the MLC circuit regulates the opening percentage of the sliding gate to control the molten iron flow rate from the tundish to the mold, which is composed of an analog circuit on an amplifier of a hydraulic servo-valve, so the control gains are not able to be adjusted online. The software switch also contains an exception handling function. When unexpected failures or process disturbances break into the system, the software switch will replace the input of the ML CV by the original ML PV to interrupt the adaptive control, and then it will monitor the conditions for reuse of the ML CV as the control input.

The adaptive controller was realized in a RISC-based processor and composed of a phase-lead compensator, a phase-lag compensator, a sliding-mode controller and a standing wave filter. A MLC decision logic was also developed and shown in Fig.2 to determine which compensator mode should be activated. It was induced from the online FFT results of the ML PV and

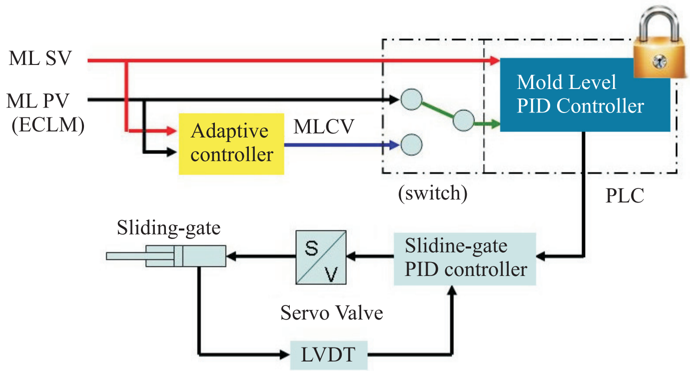

Fig.1. Adaptive mold level control diagram.

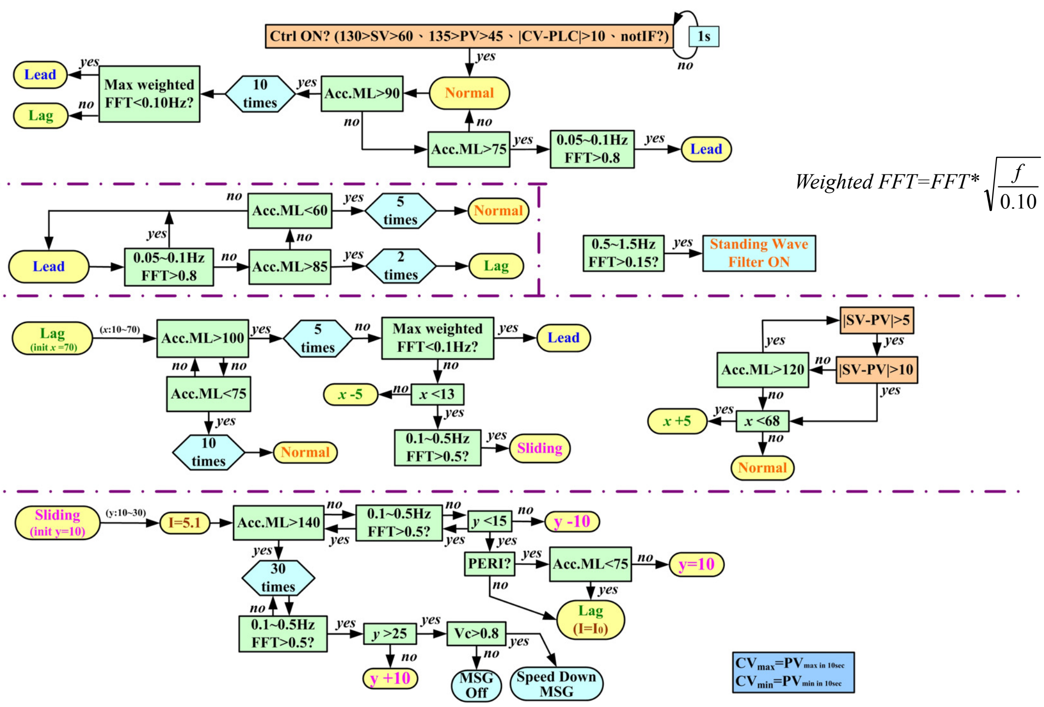

Fig.2. MLC compensator decision logic.

the calculation of the Acc.ML. The effects of the casting speed, casting steel grade, mold width setting, hydraulic pressure hunting or unsteady bulging on the MLC will be observed in a real-time FFT plot. Both the intensity of the lag compensator and the sliding mode controller can be adjusted online through the algorithm shown in Fig.2. The standing wave filter is turned on independently while the FFT amplitude between some specified frequencies was detected. The adaptive controller is resident in the MLC circuit and works fully automatically without any advanced assistance from the operators.

The Human Machine Interface (HMI) of the adaptive controller is shown in Fig.3. The upper window in Fig.3 shows the casting information and the control status in real time. The next window in Figure 3 shows the online mold level chart in the past five minutes and its FFT plot in the last minute. Some control buttons as shown in the bottom of HMI were used at testing stage during the system development. These buttons were kept for the possibility of advanced research in the future and will not be falsely pressed since the HMI is not shown in the operating room, but it was shown in the electrical control room for the programmers.

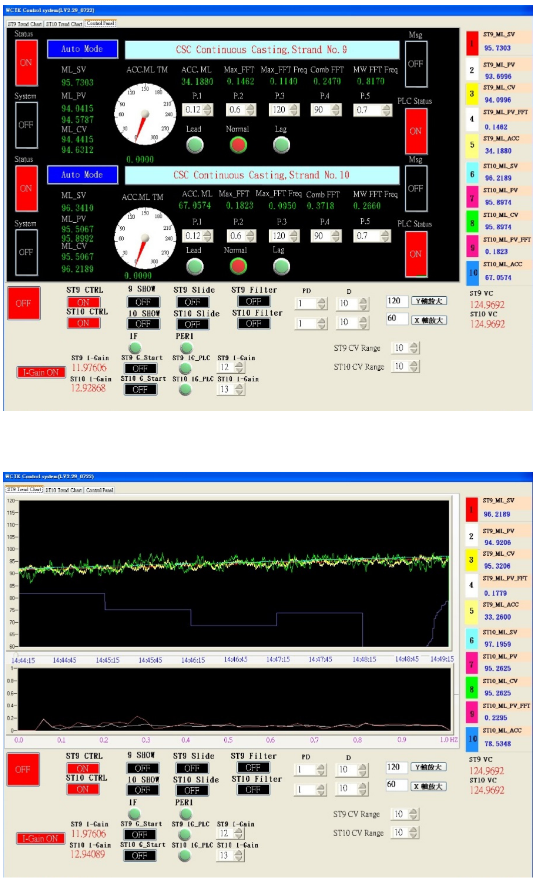

Fig.3. HMI of the adaptive controller.

The HMI of the software switch in the PLC is shown in Fig.4. The adaptive controller is termed compensator in the PLC and its function will be enabled automatically when all the conditions are satisfied, and also it will be disabled if any of them failed. For example, when at the start or the end of casting, a break out alarm, or the ML PV was out of a specified range, the activation of the adaptive controller will be deactivated immediately by the software switch.

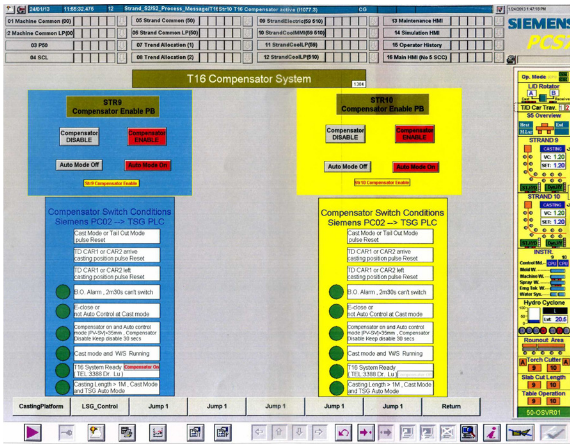

Fig.4. HMI of the software switch.

The transient response of the MLC is enhanced after the phase-lead compensator was turned on and one of the testing results is shown in Fig.5. Both the frequencies of the mold level fluctuations and the sliding gate motions were accelerated, but the mold level fluctuating amplitude was suppressed from 5 to 2 mm. The mold level fluctuating amplitude of 15 mm at a frequency below 0.1 Hz was ever observed, but after the phase-lead compensator was realized and run in real-time, it was able to be suppressed below 3 mm. Depending on the statistical test result, the phase-lead compensator is mostly triggered during the silicon steel casting.

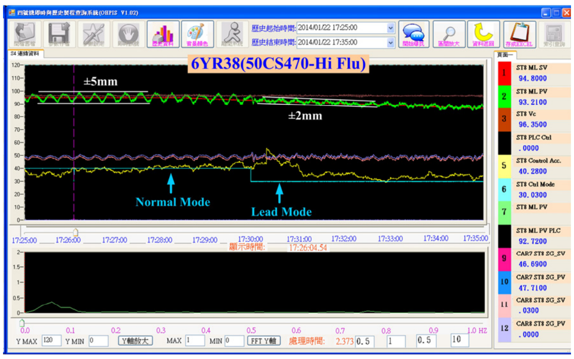

Fig.5. Phase-lead compensator testing result.

The steady state response of the MLC is improved after the phase-lag compensator was enabled and one of the testing results is shown in Fig.6. Both the frequencies of the mold level fluctuations and the sliding gate motions were slowed down as shown in the figure. The mold level fluctuating amplitude was not depressed but even expanded in some cases especially when the intensity of the control output was enlarged. However, the calculation of the ACC.ML was lower when it was activated, which is a quality control threshold for the slab machine scarfing process. The phase-lag compensator is the most often triggered control mode to eliminate the relatively aperiodic or temporary unstable mold level fluctuations.

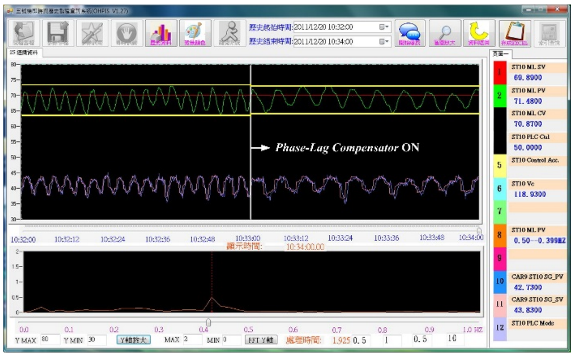

Fig.6. Phase-lag compensator testing result.

The efficacy of the sliding mode controller in the MLC circuit is shown in Fig.7. The ML CV was raised approximately 0.5 to 0.8 seconds earlier than the ML PV when the periodic mold level was fluctuating, normally caused by unsteady bulging of the peritectic steel casting. The MLC is not impeded by the chattering phenomenon of the sliding mode controller because of the effect of the followed PID controller and the limitation of the sliding gate mechanical response. One of the testing results realized at DSC #2 slab C.C. is shown in Fig.8. The maximum mold level deviation was suppressed from 15 to 3 mm.

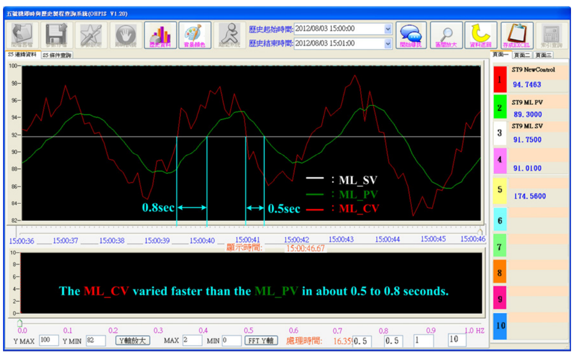

Fig.7. Effect of the sliding mode controller in the MLC circuit.

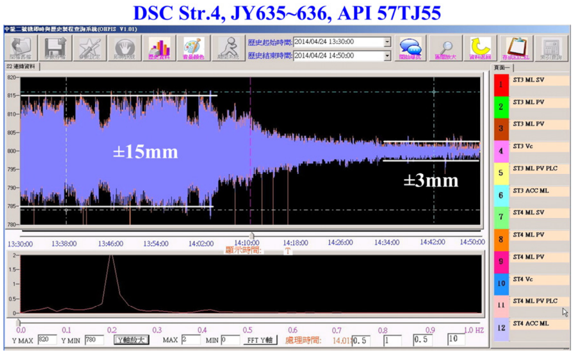

Fig.8. Sliding mode controller testing result.

A second order Butterworth low pass filter with a cutoff frequency of 0.5 Hz was adopted to be the standing wave filter in the adaptive controller. One of the testing results is shown in Fig.9, the mold levels can be isolated from the interference of standing waves. A significant peak of 0.76 Hz was observed in the online FFT plot while the standing wave was taking place. The standing wave filter is triggered automatically and independently while the FFT amplitude between some specific frequencies was detected.

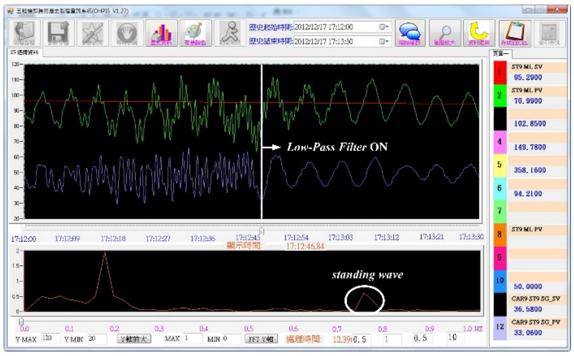

Fig.9. Standing wave filter testing result.

3. LIMITATION

Motion responses of the sliding gate in CSC #4 and #5 slab C.C. were found to be not fast enough to track ML CV while the sliding mode controller was triggered. Figure 10 shows the motion of the sliding gate under the control of the sliding mode controller and Figure 11 shows the response of the stopper in DSC #2 slab C.C. under the same control mode. An insufficient motion response of the sliding gate is represented between these two figures. Due to the design structure difference between the sliding gate and the stopper, the stroke of the sliding gate was 10 times longer than the stopper under the same control mode in mold level fluctuations. Compared to DSC #2 slab

C.C., the operators at CSC #4 and #5 slab C.C. had to slow down the casting speed to make the sliding gate able to catch up with the frequency of the mold level fluctuations. This bandwidth limitation of sliding gate motions makes the efficacy of the sliding mode controller repressed.

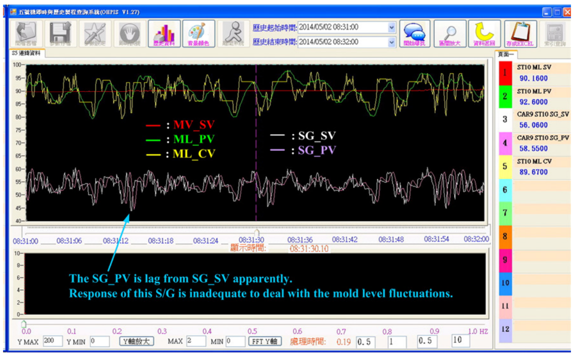

Fig.10. Response of the sliding gate at CSC #5 slab C.C.

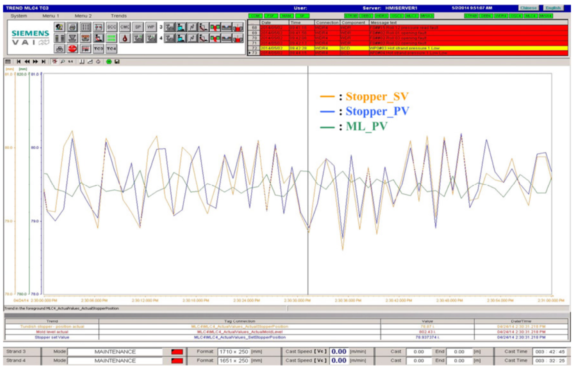

Fig.11. Response of the stopper at DSC #2 slab C.C.

4. CONCLUSIONS

1. A phase-lead compensator, a phase-lag compensator, a sliding mode controller and a standing wave filter were developed as the parts of an adaptive mold level controller in a continuous steel slab casting process.
2. A MLC compensator decision logic based on the calculation of Acc.ML deviations and mold level FFT results was able to plug-in a suitable compensator automatically to a password locked MLC loop to restrain disturbances.
3. The adaptive controllers were resident online at CSC #5 and #4 slab C.C. in 2011 and 2012 respectively and also tested at DSC #2 slab C.C. in 2013.
4. The improvement on MLC stability is obvious after the realization of the adaptive controller.

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