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ROLLING STRIP THICKNESS CONTROL USING I-P, I-PD AND PI-FIRST ORDER OMPENSATORS COMPARED WITH AN ADAPTIVE PI CONTROLLER

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ABSTRACT

The control of strip thickness in rolling mills is essential to maintain uniform accurate thickness for the produced metallic strips. The paper presents the control of strip thickness using three compensators from the second generation of control compensators: I-P, I-PD and PI-first order compensators. A proper tuning technique is selected to tune the compensators using a proper performance index. The step time response of the control system using the three proposed compensators is presented and compared with using an adaptive PI controller to control the same rolling mill and the time-based characteristics are compared. The comparison reveals the best compensator among the four controllers/compensators depending on a graphical and quantitative comparison study.

KEYWORDS: Rolling strip thickness control, I-P compensator, I-PD compensator, PI-first order compensator, adaptive PI controller, compensator tuning.

INTRODUCTION

Rolling mills are one of the strategic processes used for metal strips and shapes production required for too many metallic industries and construction purposes. Rolling mills have key processing variables such as rolling force, strip thickness and strip roughness. This paper proposes control compensators from the second generation for the control of rolled strip thickness. We start by taking an idea about some of the research work regarding strip thickness modeling and control:

Brown, Maliotis and Gibby (1999) described the application of self-tuning PID controller to a single strand cold rolling aluminum mill. Their design was based on an adaptive control scheme where the gain parameters were adjusted according to estimates of the process parameters. They discussed also process parameters estimator algorithm.[1] Hu and Ehmann (2000) proposed an enhanced analytical rolling process model capable of handling dynamic variations exerted by roll vibrations. They established a linearized form of the model and presented experiments verifying its accuracy.[2] Zarate (2005) presented a method for strip thickness adjustment in a single strand rolling mill using three control parameters: roll gap, front tension and back tension using a predictive model based on the process sensitivity equation. The proposed control system calculated the necessary adjustment based on a a predictive model for the output thickness. He used a first-order dynamic model for the strip thickness with an integrator and used a PD-PI controller to perform the control action.[3] Gazina, Yong and Xinming (2008) developed a fuzzy-neural network control applied to the screw-down mechanism of a cold rolling mill. The application of the fuzzy-neural network control wqs superior in the static and dynamic control performance (as their claim).[4]

Cavazzana and Dentifilho (2014) proposed a gain scheduling control for industrial rolling mills. They proposed two controllers acting on gap sub-system to compensate process disturbances. They used the optimal quadratic regulator method to tune the controllers. They claimed that their technique led to less output thickness variations compared with other proposals.[5] Kucsera and Beres (2015) analyzed the automatic gauge control system of a hot rolling mill and described different methods to improve its performance. They compensated the process disturbances and developed an adaptive PI controller to achieve fine thickness control. The model used in their control scheme was a first-order with time delay. They discussed also the use of a predictive controller using Smith Predictor.[6] Ahang, Zhang and Chen (2016) discussed the design and implementation of a steel plate mill and the design of precession models and control actuators. They discussed also control loop strategies and presented the performance results achieved during the startup of a steel plate mill.[7]

Saxena and Sharma (2017) used the automatic gauge control system to realize high accuracy in the strip exit thickness in a rolling mill. They designed a PI controller in the outer-loop for strip thickness control and a PD controller in an inner-loop the actuator position. For eccentricity compensation, they used a fuzzy-neural network with online tuning. They used a first-order model with an integrator for the actuator position control.[8] Asghar (2018) established a multivariable control strategy for the tandem rolling process. He proposed a cost function characterizing the performance of the control system. He defined the form of a DOF controller (class and size).[9] Li, Fang and Liu (2020) presented a decoupled predictive control method based on convolution neural network. They introduced the model of the automatic control for flatness and thickness and designed a flatness and thick ness controller using model predictive control algorithm.[10]

Schulte, Li, Abel and Hirt (2021) identified a nonlinear roll stand deflection model to a self-calibration for roll gap. They used the identified model in a model-based control for the strip thickness. They claimed that experimental results showed a high precision tracking performance.[11] Yu, Zeng, Xue and Zhao (2023) established the model of a rolling mill plate thickness control system. They tuned the parameters of a PID controller using Ziegler-Nichols method, particle swarm optimization and linear weight particle swarm optimization. They concluded that the linear weight particle swarm optimization algorithm was the best of the three in reducing the maximum overshoot and settling time.[12] Sun, Li, Sun, Yang and Wang (2024) introduced a shape control based on metal flow and stress release with the application of varying contact rolling parameters. They proposed the digital twin framework of the shape control. Their proposed model provided operators with a reference for parameters settings for the production process.[13]

Controlled Rolling Strip Thickness

To control the strip thickness in a hot rolling mill, Kucsera and Beres used a first-order with time delay.[6] Their model is given by[6]:

$$G_p(s) = 1.5 \exp(-3s) / (0.2s+1) \qquad (1)$$

The exponential form is approximated by a second-order Pade approximation as[14]:

$$\exp(-3s) = (9s^2-18s+12) / (9s^2+18s+12) \qquad (2)$$

Combining Eqs.1 and 2 gives the strip thickness transfer function, $G_p(s)$ as:

$$G_p(s) = (13.5\, s^2-27\, s+18) / (1.8s^3+12.6s^2+20.4s+12) \qquad (3)$$

The unit step time response of the strip thickness having the dynamics defined by Eq.3 is shown in Fig.1 as generated by the '*step*' command of MATLAB.[15]

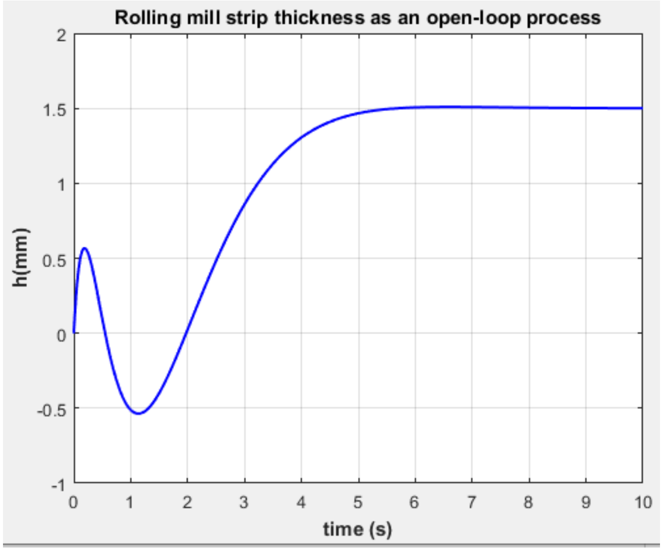


Figure 1: Step time response of the strip thickness.

Comments

- The strip thickness process is stable.
- It has a steady-state time response for a unit step input of 1.5 mm.
- It has a steady-state error of – 0.5 mm.
- It has a maximum undershoot of – 0.536 mm.
- It has a settling time of 5.04 s.
- The maximum undershoot is due to the exponential series approximation. It can be decreased if high order approximation is used.
- This means that this process has a time delay and a large steady-state error which is a challenge of any proposed control scheme to overcome the two deficiencies.

Controlling the Strip Thickness Using a Novel I-P compensator

The I-P compensator is a novel control compensator belonging to the second generation of control compensators presented by the author since 2014. Its proposed structure is shown in Fig.2.

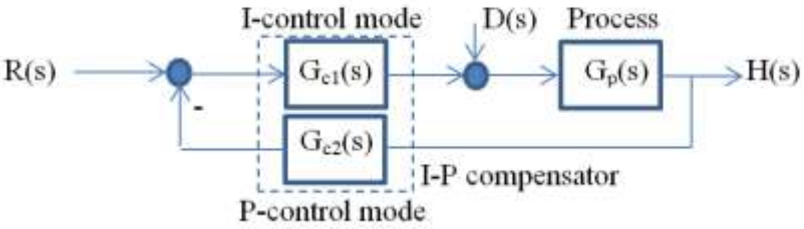


Figure 2: I-P compensator controlled strip thickness.

The novel compensator is composed of an integral control mode of $G_{c1}(s)$ transfer function in the forward path and a proportional control mode of $G_{c2}(s)$ transfer function in the feedback path. $G_{c1}(s)$ and $G_{c2}(s)$ are given by:

$$G_{c1}(s) = K_i/s,\ G_{c2}(s) = K_{pc} \qquad (4)$$

Where: K_i = integral gain of the I-P compensator.

K_{pc} = proportional gain of the I-P compensator.

The I-P compensator has two gain parameters to be tuned to achieve stability and good performance. It is tuned as follows:

- The transfer function of the closed-loop control system in Fig.2 for reference input tracking is derived with the help of the block diagram in Fig.2 and the process and compensator equation in Eqs.3 and 4.
- The integral of absolute error (IAE) performance index is chosen as a performance index.[16]
- Investigating the closed-loop transfer function of the control system for reference input tracking reveals important characteristics for the resulting control system for the strip thickness control. That is a zero steady-state error is possible if the I-P compensator has a unit proportional gain ($K_{pc} = 1$).
- This reduced the tuning process of the I-P compensator to the adjustment of only one gain parameter.
- The performance index is minimized in terms of the compensator parameter K_i using the MATLAB optimization technique.[17]
- The tuning result is as follows:
  - $K_i = 0.084072$, $K_{pc} = 1$ (5)

- The transfer function of the control system for the disturbance input, D(s) is obtained using the block diagram in Fig.2 with R(s) =0 and using Eqs.3 and 4. A second-order high-pass filter[18] is used in the forward path of the disturbance input to improve the performance of the disturbance rejection process using the I-P compensator.
- Using the tuned controller parameters of the I-P compensator, the unit step time response of the strip thickness process when controlled by the I-P compensator is shown in Fig.3.

COMMENTS:

➢ The I-P compensator provided a reference input tracking step time response having the following characteristics:

- Maximum overshoot: zero
- Maximum undershoot: -0.024 mm (compared with -0.536 mm for the process)
- Settling time: 17.1 s
- The success of the I-P compensator to reject the disturbance input is measured by the following characteristics:
- Maximum strip thickness step time response: 0.219 mm
- Time of maximum step time response: 0.07 s
- Settling time: 4.47 s

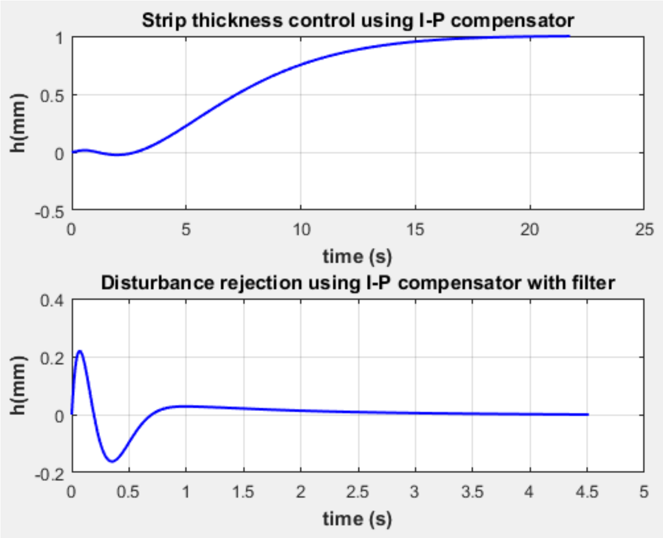


Figure 3: Strip thickness controlled by an I-P compensator.

Controlling the Strip Thickness Using an I-PD compensator

The I-PD compensator was introduced by the author to control second-order-like processes[19], greenhouse temperature[20], boiler steam pressure[21] and rocket pitch angle.[22] It has the structure shown in Fig.4.[19] It has an integral control mode in the forward path just before the process to be controlled and a PD- control mode in the feedback path of the closed-loop control system.

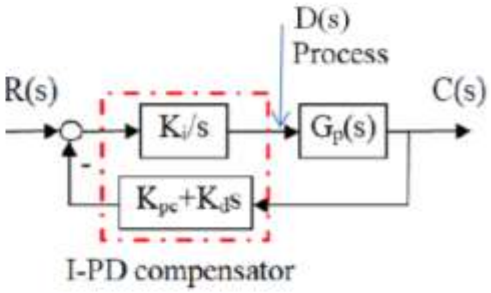


Figure 4: Structure of the I-PD compensator.[19]

The I-PD compensator has the transfer functions $G_I(s)$ and $G_{PD}(s)$ given by:

$$G_I(s) = K_i/s \text{ and } G_{PD}(s) = K_{pc} + K_d s \qquad (6)$$

Where: K_i = integral gain of the integral control mode

K_{pc} = proportional gain of the PD control mode

K_d = derivative gain of the PD control mode

It has three gain parameters to be tuned for stable control system and for good performance in terms of the control system steady-state error, maximum overshoot and settling time.

The I-PD compensator is tuned following the same procedure used with the I-P compensator.

- Through the investigation of the closed-loop transfer function for reference input tracking it was found that the step time response will have a zero steady-state error if the proportional gain K_{pc} of the I-PD compensator is set to a unit value. That is:

$$K_{pc} = 1 \qquad (7)$$

- The other parameters of the I-PD compensator are tuned using the MATLAB optimization toolbox[17] and an ITAE performance index.[23] The tuned integral and derivative gain parameters of the I-PD compensator are:

$$K_i = 0.130248,\ K_d = 0.803739 \qquad (8)$$

- The unit step time response of the closed-loop control system the reference input is evaluated using the transfer function and the step command of MATLAB.[15]
- The unit step time response of the control system for the rolling strip thickness with reference and disturbance inputs using Eqs.3, 6, 7 and 8 derived from the block diagram in Fig.4 is shown in Fig.5.
- A second-order high pass Sallen-Key filter is used with the disturbance input to improve the characteristics of the control system regarding the disturbance rejection.

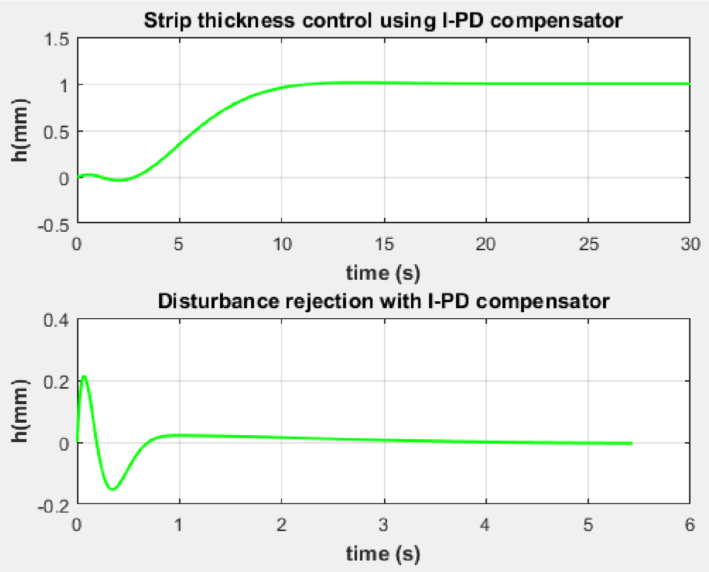


Figure 5: Strip thickness controlled by an I-PD compensator.

COMMENTS

- The I-PD compensator provided a reference input tracking step time response having the following characteristics:
- Maximum overshoot: 1.183 %
- Maximum undershoot: -0.036 mm (compared with -0.536 mm for the process)
- Settling time: 10.5 s
- The success of the I-PD compensator to reject the disturbance input is measured by the following characteristics:
- Maximum strip thickness step time response: 0.213 mm
- Time of maximum step time response: 0.07 s
- Settling time: 4.08 s

Controlling the Rolling Strip Thickness Using a PI-First-order Compensator

The feedback first-order compensator was introduced by the author to control a number of difficult processes including: single pole plus double integrator process[24], highly oscillating second-order process[25], very slow second-order process[26], fractional time delay double integrating process[27], coupled dual liquid tank process[28], greenhouse temperature[20], boiler steam pressure[21] and rocket pitch angle.[22]

The PI- first order compensator is composed of two elements: PI-control mode, $G_{c1}(s)$ in cascade with the controlled process and a feedback lag-lead element, $G_{c2}(s)$ as shown in Fig.6.

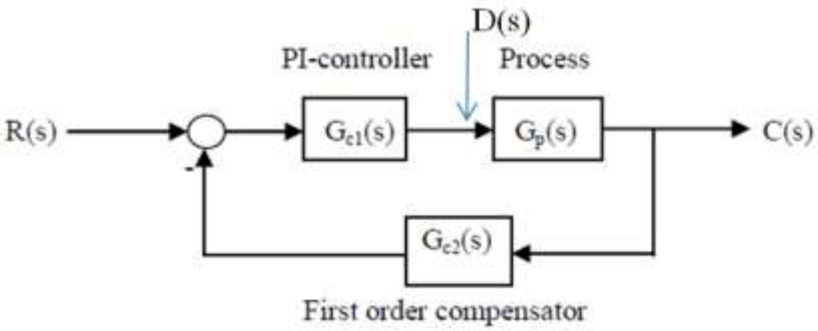


Figure 6: Structure of the PI-First order compensator.[28]

The two elements have transfer functions given by:

$$G_{c1}(s) = K_{pc} + K_i/s \text{ and } G_{c2}(s) = K_c[1+T_z(s)]/(1+T_p(s) \quad (9)$$

Where: K_{pc} = proportional gain of the PI-control mode.

K_i = integral gain of the PI-control mode.

K_c = gain of the lag-lead element.

T_z = zero of the lag-lead element.

T_p = pole of the lag-lead element.

- The PI- first order compensator has five gain parameters (K_{pc}, K_i, K_c, T_z and T_p) to be tuned to satisfy the objectives of using the controller to control the Boiler steam pressure and provide good control system performance for reference and disturbance inputs.
- To control the rolling strip thickness for reference input tracking, the transfer function of the closed loop control system is derived using the block diagram in Fig.6 and Eqs.3 and 6.
- The PI-first order compensator is tuned using the same tuning procedure used with the I-P and I-PD compensators.
- Investigating the overall transfer function of the control system incorporating the PI-first order compensator for reference input tracking reveals the fact that it is possible to attain a step time response with zero steady-state error if the compensator parameter K_c is set to 1 (unit value). This reduces the tuning effort to adjusting only K_{pc}, K_i, T_z and T_p.
- The tuned parameters of the PI-first order compensator using an ISTE performance index[29] are as follows:

$K_{pc} = 0.066082$, $K_i = 0.04987$

$K_c = 1$, $T_z = 2.200068$, $T_p = 3.371145$ s (10)

- Using the closed-loop transfer function of the closed-loop control system for reference and disturbance inputs using the compensator parameters in Eq.10, the unit step time response is shown in Fig.7.

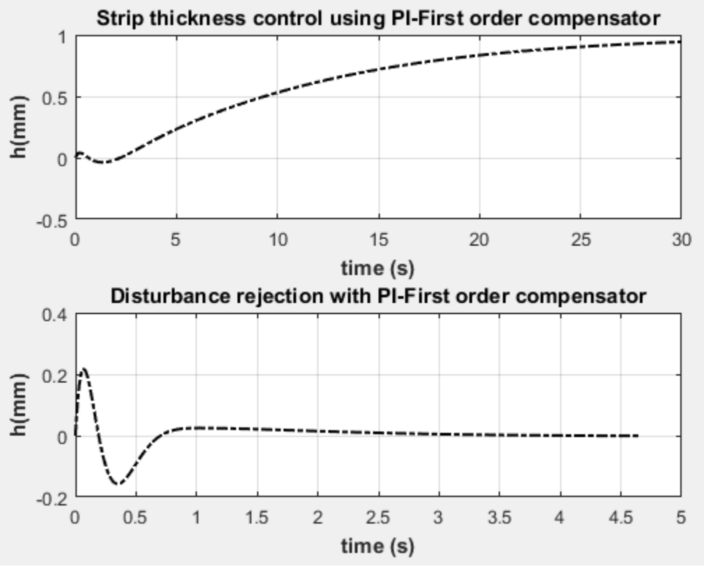


Figure 7: Strip thickness controlled by a PI-First order compensator.

COMMENTS

- The PI-First order compensator provided a reference input tracking step time response having the following characteristics:
- Maximum overshoot: zero
- Maximum undershoot: -0.037 mm (compared with -0.536 mm for the process)
- Settling time: 39.57 s
- The success of the PI-First order compensator to reject the disturbance input is measured by the following characteristics:
- Maximum strip thickness step time response: 0.216 mm
- Time of maximum step time response: 0.07 s
- Settling time: 4.15 s

Characteristics Comparison of the Three Compensators with an Adaptive PI controller

- The reference for the comparison of the performance of the proposed compensators is an adaptive PI controller used in a previous work to control the same process.[6]
- The characteristics comparison takes two forms: graphical and quantitative ones as follows:
- *Graphical comparison*:

- For the reference input: The comparison is shown in Fig.8 for adaptive PI controller, I-P, I-PD and PI-first-order compensators.

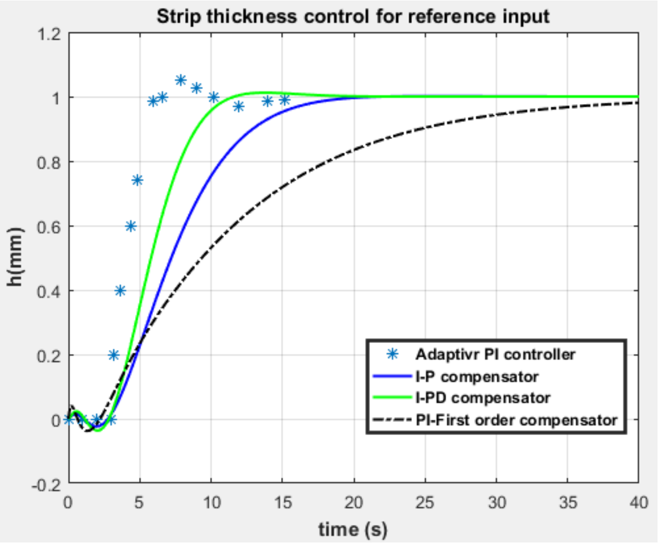


Figure 8: Comparison of reference input step time responses for the strip thickness process.

- For the disturbance input: The comparison is presented in Fig.9.
- *Quantitative comparison*: The time-based characteristics of the control system for the rolling strip thickness control are quantitatively compared in Table 1 for reference input tracking and Table 2 for disturbance input.

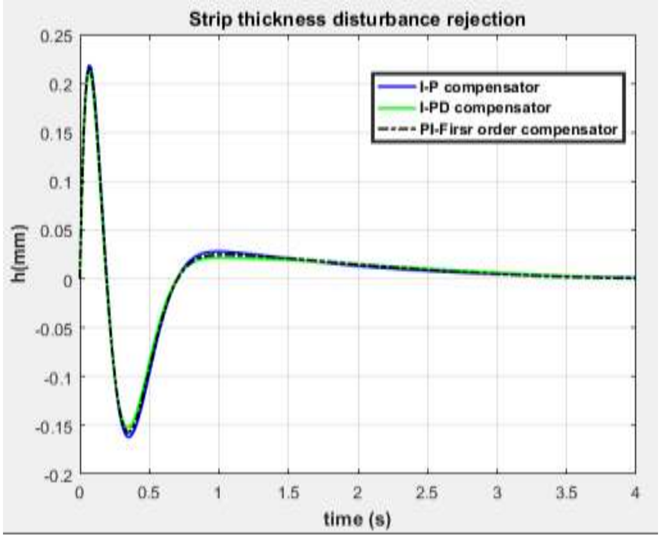
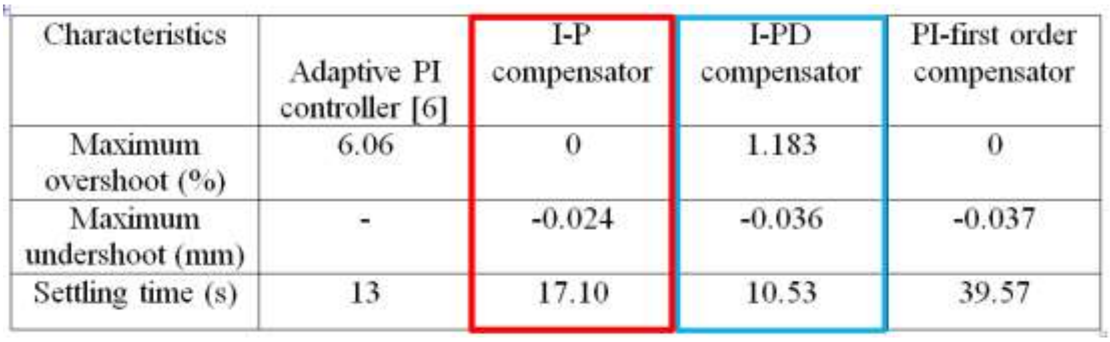


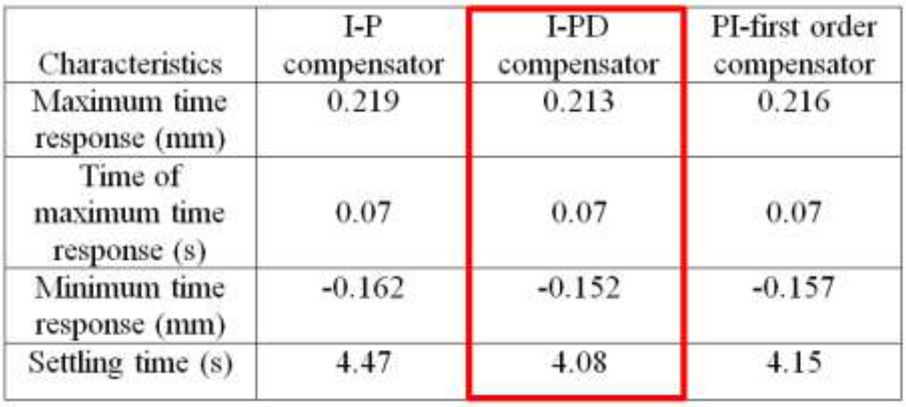
Figure 9: Comparison of disturbance input step time responses for strip thickness control.

Table 1: Reference input time-based characteristics of the strip thickness control using adaptive PI controller, I-P, I-PD and PI-first order compensators.



Characteristics	Adaptive PI controller [6]	I-P compensator	I-PD compensator	PI-first order compensator
Maximum overshoot (%)	6.06	0	1.183	0
Maximum undershoot (mm)	-	-0.024	-0.036	-0.037
Settling time (s)	13	17.10	10.53	39.57

Table 2: Disturbance input time-based characteristics of the strip thickness control using I-P, I-PD and PI-first order compensators.



Characteristics	I-P compensator	I-PD compensator	PI-first order compensator
Maximum time response (mm)	0.219	0.213	0.216
Time of maximum time response (s)	0.07	0.07	0.07
Minimum time response (mm)	-0.162	-0.152	-0.157
Settling time (s)	4.47	4.08	4.15

CONCLUSION

- The objective of the paper was to investigate the use and tuning of I-P, I-PD and PI-first order compensators to control rolling strip thickness.
- The three compensators are from the second generation of control compensators presented by the author since 2014.
- The three compensators were tuned using the MATLAB optimization toolbox and the best performance index as investigated by the author.
- An adaptive PI controller from previous work was compared with the three proposed compensators.
- The I-P compensator succeeded to eliminate completely the maximum overshoot of the control system compared with 6.06 % with the adaptive PI controller and succeeded to settle after 17.1 s compared with 13 s for the adaptive PI controller for reference input tracking.

- The I-PD compensator succeeded to reduce the maximum overshoot of the control system to 1.183% compared with 6.06% for the adaptive PI controller and succeeded to settle after 10.53 s compared with 13 s for the adaptive PI controller for reference input tracking.
- The PI-first order compensator succeeded to eliminate completely the maximum overshoot of the control system compared with 6.06 % with the adaptive PI controller and had a relatively large settling time of 39.57 s compared with 13 s for the adaptive PI controller for reference input tracking.
- The performance of the proposed compensators regarding disturbance rejection was enhanced through the use of a high pass Sallen-Key filter receiving the disturbance input.
- Regarding the disturbance rejection, the I-PD compensator provided the minimum maximum time response, minimum time response and settling time to zero.
- If the interest of the control engineer is to satisfy the condition of minimum maximum overshoot, then the proposed I-P compensator comes first, then the I-PD compensator comes next.
- If the interest of the control engineer is to satisfy the condition of minimum settling time, then the proposed I-PD compensator is the best choice.
- Regarding the disturbance rejection of the closed loop control system, the I-PD compensator is the best choice.

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