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Effect of Model-plant Mismatch on MPC Controller Performance

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Abstract: This study present the effect of model-plant mismatch on MPC controller performance for set-point tracking. The methodology of this study is based on the analysis of closed loop data from the process. Four types of mismatch has been investigated: (1) gain mismatch, (2) reverse gain mismatch, (3) time constant mismatch and (4) time delay mismatch are illustrated to a case study of Wood and Berry distillation column. This study shows that the gain mismatch has significant effect on MPC controller performance compared to time constant and time delay mismatch. For set-point tracking, MPC controller performance is bad in the presence of gain mismatch but it is good in the presence of time constant and time delay mismatch.

Key words: Controller performance, model-plant mismatch, model predictive control, multi-input-multi-output, re-identification

INTRODUCTION

All industries tend to increase their production efficiency and reduce as much cost as possible (Seborg *et al*., 2004). This situation leads to more complexity in processing plants, in which more variables are involves. Besides that, most industries are facing massive challenges such as tighter product quality specifications, increasing productivity demands, the existence of new environmental regulations and the fast changes in the economical market. The conventional Proportional-Integral-Derivative (PID) controllers cannot really capture the complexity of this type of process, as well as these challenges. So advanced process control is a promising solution for this problem. One class of advanced process controller is Model Predictive Control (MPC). MPC has been used because it is able to respond in an effective way to these challenges.

MPC has been developed and extensively used in the process industry for controlling key unit operations in chemical plants over the last two decades (Badwe *et al*., 2008). This is not a surprising fact since MPC is the most general way of posing the process control problem in the time domain. Difficult multivariable control problem with the presence of inequality constrains on input and outputs also can be handled by this type of model-based control strategy. MPC uses a process model and the current state to predict future values of the output. However, poor modeling of the model based multi-input-multi-output (MIMO) controller in a single channel can affect multiple outputs.

It is important to detect a model-plant mismatch (MPM) to assist in re-identification. About 60% of all industrial controllers have some performance problem (Harris *et al*., 1999). Re-identification of the process model with large number of inputs and outputs is costly due to potential production losses and high manpower effort. For the purpose of model-plant mismatch detection, it is necessary to identify the effect of the mismatch in the process model.

An MPC controller is similar to the structure of Internal Model Control (IMC) as presented by Seborg *et al*. (2004). For some cases, the MPC control system is using IMC structure because there is no explicit model in the linear-time invariant (LTI) framework capable of describing an MPC (Carlsson, 2010). IMC approach has advantage that it allows model uncertainty as well as considered the tradeoff between performance and robustness in systematic manner. Dynamic matrix control (DMC) is one type of MPC that used this IMC structure (Wang and Wang, 2010). The feedback structure in DMC algorithm makes this controller robust and suitable for use in controlling complex and highly interacting processes such as distillation columns and chemical reactors (Alvarez-Ramirez *et al*., 2004).

Figure 1 shows a block diagram of a closed-loop system. G is the model representing n×m MIMO plant

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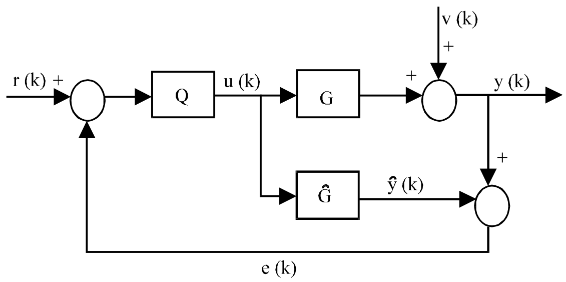

Fig. 1: Closed-loop system: IMC structure, adapted from (Badwe *et al*., 2008)

and G is the plant. The model-plant mismatch, $\hat{G}$ is described in Eq. 1.

$$\Delta = G - \hat{G} \quad (1)$$

Plant output:

$$y\,(k) = Gu\,(k) + v\,(k) \quad (2)$$

where, u (k) and v (k) is the vector of manipulated variables (MVs) and Gaussian disturbances acting on the process, respectively.

Model output:

$$\hat{y}\,(k) = \hat{G}u\,(k) \quad (3)$$

Model residuals:

$$e\,(k) = y\,(k) - \hat{y}\,(k) = \Delta u\,(k) + v\,(k) \quad (4)$$

The objective of this study is to investigate the effect of model-plant mismatch on the performance of MPC controller. The effect of model-plant mismatch was demonstrated on Wood and Berry distillation column for four types of mismatch: (1) gain mismatch, (2) reverse gain mismatch, (3) time constant mismatch and (4) time delay mismatch.

METHODOLOGY

The process started with the process modeling and MPC controller design. MPC controller designed is done by specifying tuning parameters and a discrete process model to represent the actual plant. Then mismatch is added to the process model with several cases. Set-point change is done to the inputs before the simulation is done. After that data from the process are collected and the response is plotted. All the responses are compared each other. The process is repeated for other different cases.

CASE STUDIES

In this study, the effect of model-plant mismatch on the performance of MPC controller are illustrated through a case study of Wood and Berry distillation column. MPC controller performance has been tested by introduced mismatch in the model plant to portray the real situation in the plant. Several scenarios have been tested independently: (1) Gain mismatch, (2) Reverse gain mismatch, (3) Time constant mismatch and (4) Time delay mismatch. In this study, the controller performance in set-point tracking was evaluated by making a step change in an input. In all cases, the disturbance was set to zero.

Wood and Berry distillation column model is a distillation column model based on the study conducted by Wood and Berry (1973) which later will be called Wood and Berry distillation column.

The model is shown as follow:

$$\begin{bmatrix} X_D\,(S) \\ X_B\,(S) \end{bmatrix} = \begin{bmatrix} \frac{12.8e^{-s}}{16.7s+1} & \frac{-18.9e^{3s}}{21s+1} \\ \frac{6.6e^{-7s}}{10.9s+1} & \frac{-19s+1}{14.4s+1} \end{bmatrix} \begin{bmatrix} R\,(S) \\ S\,(S) \end{bmatrix}$$

This is MIMO system with two controlled variables and two manipulated variables. In this study, unmeasured disturbance part is eliminated to simplify the process. The controlled variables and manipulated variables are listed below:

- Cvs
  X_D: The distillate composition (output 1)
  X_B: The bottom composition (output 2)
- Mvs
  R: Reflux flow rate (input 1)
  S: Steam flow rate (input 2)

Since the distillation column process is interacting, the controlled variables and manipulated variables are interrelated each other. The relationship between controlled variables and manipulated variables is shown in Table 1.

For all the four scenarios, MATLAB simulation was performed by introducing a step change at 5th min with magnitude of 1 in reflux flow rate. Simulink model was

Table 1: Relationship between controlled variables and manipulated variables for each channel

Channel	Description
G_{11}	Transfer function relating distillate composition and reflux flow rate
G_{12}	Transfer function relating distillate composition and steam flow rate
G_{21}	Transfer function relating bottom composition and reflux flow rate
G_{22}	Transfer function relating bottom composition and steam flow rate

linked with MATLAB script to provide controller tuning parameters to MPC controller. The responses of each mismatch variation are then observed and the data is collected. Distillate composition and bottom composition responses with the mismatch variation are plotted.

Gain mismatch (Variation in Magnitude): Underestimated gain mismatch with 10 to 70% variation of G_{11} gain magnitude was added to the process model. For underestimated gain mismatch, the mismatch was added so that the new gain magnitude is smaller than its original value. The original value of G_{11} gain is 12.8. The mismatch variation in magnitude as well as the corresponding values of new gain for underestimated gain mismatch is listed in Table 2. In Table 2, it can be seen that as mismatch variation increases, the value of G_{11} new gain become smaller.

From Fig. 2, it can be seen that as there is no mismatch in process model, the process was able to achieve the new desired set-point of 1 mole % as shown by red line. With the existence of gain mismatch in the process model, the MPC controller cannot bring the process to the desired set-point. This is because process gain has significant effect to the process. Decreasing process gain can reduce the process output and vice versa. For underestimated gain mismatch, as the mismatch variation in the process model is higher, the values of G_{11} new gain become smaller thus make the process farther from the set-point. For comparison, the response for 30% mismatch (yellow line) is farther from the set-point compared to the 10% mismatch (green line). From the graph, it shows that with 10% underestimated gain mismatch of G_{11}, the desired set-point of distillate composition cannot be achieved by 0.2 mole %. It is also found that the distillate composition decreases as the gain mismatch is exceeding 50%. For example, 70% gain mismatch of G_{11} reduces the composition of distillate by 0.4 mole % from the steady state value.

Table 2: Mismatch variation (magnitude) and the values of G_{11} new gain for underestimated gain mismatch

Mismatch variation (%)	G_{11} new gain
0	12.80
10	11.52
30	8.96
50	6.40
70	3.84

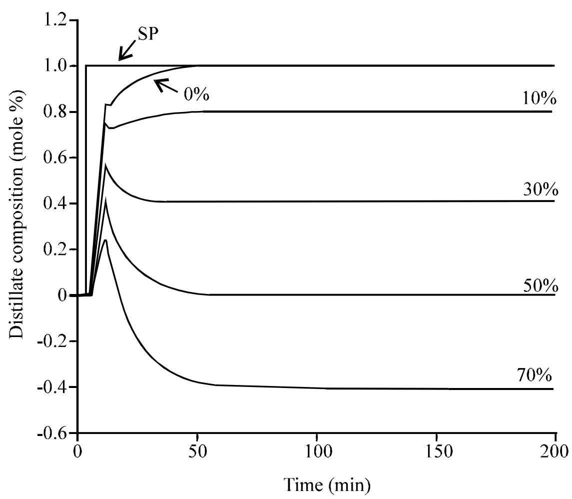

Fig. 2: Distillate composition responses in variation of underestimated gain mismatch (magnitude) in G_{11} channel

In Fig. 3, when step change is done to the reflux flow rate, the process can go back to its initial steady state at 0 whether gain mismatch exist or not. But there is a difference between the response with and without mismatch in the process model. With no mismatch (light green line) in the process model, the bottom composition is increases a bit before going back to its initial steady state. For the process with gain mismatch in the process model, the response is increasing and achieved the highest peak at 20 min and then decreasing before it is going back to the initial steady state. This is shows that MPC controller can bring back the bottom composition to its initial set-point although there is a mismatch in the process model. It can be seen that the responses are close among each other but as the mismatch variation is higher, the response achieved its steady state in longer time. The bottom composition was also affected even though the step input is done to the reflux flow rate. This is due to the additive effect on each outputs (distillate and bottom composition) when the step

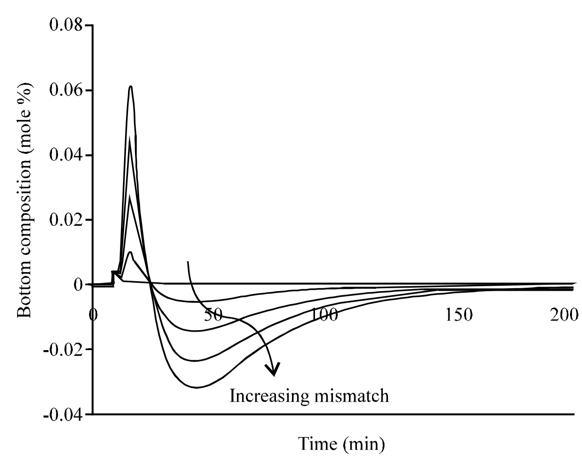

Fig. 3: Bottom composition responses in variation of underestimated gain mismatch (magnitude) in G_{11} channel

Table 3: Mismatch variation (magnitude and direction) and the values of new gain for underestimated gain mismatch

Mismatch variation (%)	G_{11} new gain
0	-12.8
10	-11.52
30	-8.96
50	-6.4
70	-3.84

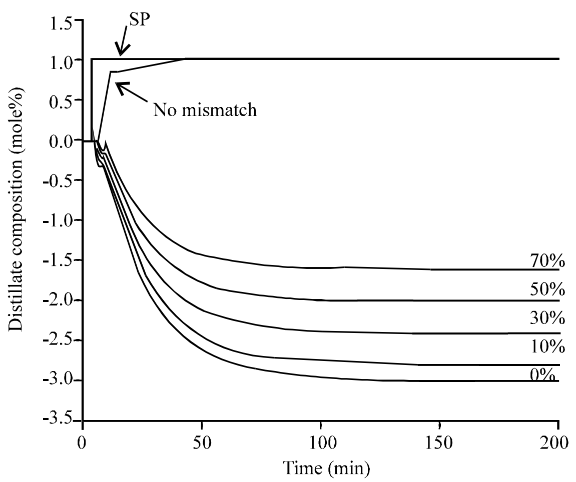

Fig. 4: Distillate composition responses in variation of underestimated gain mismatch (magnitude and direction) in G_{11} channel

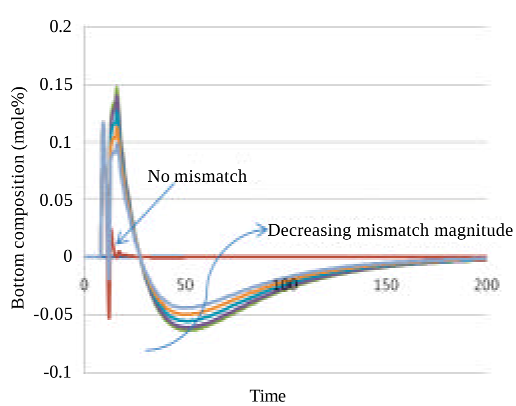

Fig. 5: Bottom composition responses in variation of underestimated gain mismatch (magnitude and direction) in G_{11} channel

changes was done to the reflux flow rate. All responses come back to the initial steady state after about 150 min.

Gain mismatch (variation in magnitude and direction): For this case, underestimated gain mismatch with variation of G_{11} gain magnitude from 10 to 70 % as well as reverse gain sign was added to the process model. The mismatch variation (magnitude and direction) and the values of new gain for underestimated gain mismatch are listed in Table 3.

Changing the sign of the G_{11} gain was significantly affected the process. When the gain sign is reverse from its actual sign, the process is away and unable to achieve the desired set-point. In this case, the actual gain is 12.8. With 0% magnitude gain mismatch and the sign is reverse from the actual sign, the new gain value is -12.8. With this new gain, the process tends to reverse from its actual direction. This is because the relationship between input and output determine by process gain. For example, as the reflux flow rate increases, the distillate composition will also increase when process gain is positive sign. But when the gain sign is reverse (negative), as the reflux flow rate increases, the distillate composition will be decrease. The response also depends on the magnitude of mismatch, as the magnitude increases, the process farther from the set point. As shown in Fig. 4, increasing underestimated gain mismatch as well as reversing the gain sign makes the reduction in distillate composition become smaller. For comparison, 0% mismatch (blue line) reduces the distillate composition by 3 mole % while 50% mismatch (orange line) reduce only 2 mole% of distillate composition. From the graph, it indicates that MPC controller cannot perform well (unable to bring the distillate composition to its desired set-point) in the presence of gain mismatch with variation in magnitude and reverse gain direction.

From Fig. 5, it can be seen that the process can go back to its initial steady state at 0 whether gain mismatch exist or not. This is shows that MPC controller can bring back the bottom composition to its initial set-point although there is a mismatch in the process model. It can be seen as the mismatch magnitude smaller, the response achieved its steady state in shorter time. The bottom composition was also affected even though the step input is done to the reflux flow rate. As mention earlier, this is due to the additive effect on each outputs (distillate and bottom composition) when the step changes was done to the reflux flow rate. All responses come back to the initial steady state after about 200 min.

Time constant mismatch: In this case, mismatch is added in the process model with G_{11} time constant varies by 10, 30, 50 and 70%. For underestimated time constant mismatch, the mismatch was added so that the value of new time constant is smaller than its original value. The mismatch variation and the values of new time constant for underestimated time constant mismatch are listed in Table 4.

Table 4: Mismatch variation and the values of new time constant for underestimated time constant mismatch

Mismatch variation (%)	G_{11} new time constant
0	16.7
10	15.03
30	11.69
50	5.835
70	5.01

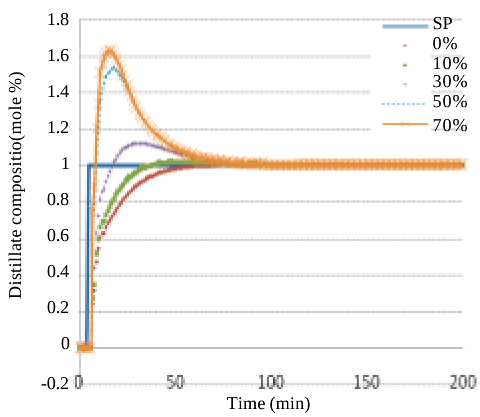

Fig. 6: Distillate composition responses in variation of underestimated time constant mismatch in G_{11} channel

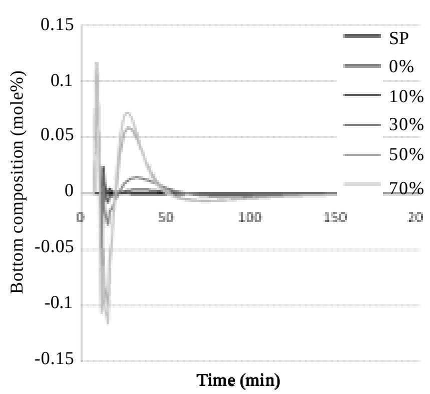

Fig. 7: Bottom composition responses in variation of underestimated time constant mismatch in G_{11} channel

From Fig. 6, it can be seen as the mismatch variation higher, the response is initially faster but the responses became slower in achieving the desired set-point.

Figure 7 shows bottom composition responses in variation of underestimated time constant mismatch in G_{11} channel. It can be seen that the process can go back to its initial steady state at 0 whether time constant mismatch exist or not. This is shows that MPC controller can bring back the bottom composition to its initial set-point

Table 5: Mismatch variation and the values of new time delay

Mismatch variation (sample time)	G_{11} new time delay
0	1
-1	0
+1	2
+2	3

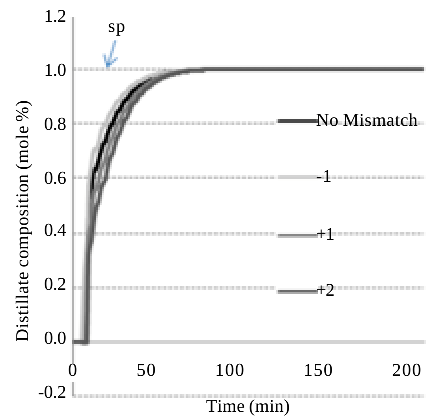

Fig. 8: Distillate composition responses in variation of time delay in G_{11} channel

although there is a mismatch in the process model. It can be seen as the mismatch magnitude greater, the response of the process is slower and achieved its initial steady state in longer time. The bottom composition was also affected even though the step input is done to the reflux flow rate. As mention earlier, this is due to the additive effect on each outputs (distillate and bottom composition) when the step changes was done to the reflux flow rate. All responses come back to the initial steady state after about 100 minutes. In this case, it shows that MPC controller is perform well, where it can bring the bottom composition to the initial steady state even with the presence of time constant mismatch in the process model. It can be conclude that the time constant mismatch does not affect the direction of the process; it only can make the process slower toward reaching the initial steady state.

Time delay mismatch: For this case, mismatch is added in the process model with G_{11} time delay varies by addition and deduction of sample time. The original time delay for G_{11} is 1. The mismatch variation and the values of new time delay are listed in Table 5.

From Fig. 8, it can be seen that as time delay decreases, the response is faster and vice versa. For comparison, the distillate composition response of time delay reduction by 1 sample time (light green line) is faster than the distillate composition response of time delay addition by 1 sample time (purple line). This is means that

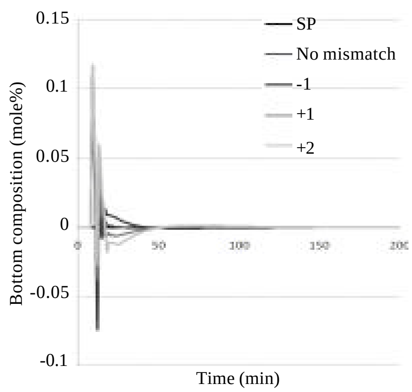

Fig. 9: Bottom composition responses in variation of time delay in G_{11} channel

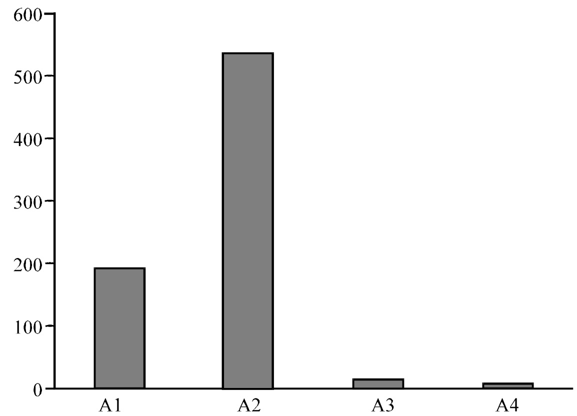

Fig. 10: Integral Absolute Value of the error (IAE) plot for all cases

when the time delay decreases, the process can react faster towards the desired set-point.

From Fig. 9, it can be seen that reduction and addition of time delay does not much affect the process. But as time delay greater, the response is slower in achieving the initial steady state (blue line). From this study, it can be concluded that time delay mismatch in the process does not have significant effect to the process, it only make the process slower towards achieving the set-point.

The previous study by Badwe *et al.* (2010) proposed a non-invasive methodology for quantifying the impact of MPM on control performance. The proposed methodology was aid for diagnosing poor quality of control and also for isolating the role of model-plant mismatch in poor control. In this work, set-point direction effect on model-plant mismatch was discussed and it was shown that the 'worst' and the 'best' set-point directions can be determined using closed-loop data. The technique proposed was able to successfully isolate the causes of degradation in quality of control. In the recent work, the effect of model-plant mismatch has been investigated. The methodology is based on the analysis of closed loop data. This works focused on the contribution of gain mismatch, time constant and time delay mismatch on the MPC controller performance. From this work, it shows that gain mismatch has greatest effect on MPC controller performance compared to time constant and time delay.

CONCLUSION

In MPC application, the accuracy of the process model plays a crucial role to the controller performance. Mismatch between the process model and plant may have significant effect to the process especially in gain mismatch. The gain mismatch can make the process away from the set-point and change the process direction if the magnitudes of gain mismatch higher than 50% from the original value. The direction of the process also will be reversing than the actual direction if the gain sign reverse from the actual sign. Hence, it is suggested that if the output of MPC process model is away from the set-point, the possible cause is gain mismatch. Time constant and delay mismatch also can affect the process but the effect is insignificant. In the presence of time constant and time delay mismatch, MPC controller can perform well because it can bring the process to the set-point. For time constant mismatch, when the magnitude of new time constant smaller than the actual time constant, the response is faster and vice versa. For time delay, increasing delay makes the process slower and vice versa. From this study, it shows that MPC controller performance is not good for set-point tracking in the presence of gain mismatch. The summary of all cases for study on the effect of model-plant mismatch to the MPC controller performance are shown in Table 6. The performance of MPC controller is shown by the integral absolute value of error (IAE) in Fig. 10. The IAE values are calculated based on 50% underestimate mismatch for all cases. As the IAE higher, the performance of MPC controller is worse. From Fig. 10, A2 shows highest value of IAE. This is followed by A1.

Table 6: Summary of all cases for study on the effect of model-plant mismatch to the MPC controller performance

Case	Scenario	Remarks
A1	Gain Mismatch (magnitude)	Performance is bad
A2	Gain Mismatch (magnitude and direction)	Direction of the process is reverse Bad performance
A3	Time Constant	Increase (slower) - Decrease (faster) Good performance
A4	Time delay	Increase (slower) - Decrease (faster) Good performance

IAE values for A3 and A4 are very small compared to the first two mismatch types. This is indicates that MPC controller performance is very bad in the presence of gain mismatch with variation in magnitude as well as for both magnitude and direction. Future study can be done to identify the performance of MPC controller in terms of disturbance rejection.

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