

Chapter 2

Human Body Based Intelligent Cooperative Decoupling Controllers

Decoupling control, a vital approach in control engineering, is one of the most critical and effective methods to solve complex coupling system. In this chapter, we discuss the developments of some effective decoupling control methods for the coupling phenomenon among complex systems. Firstly, a bio-inspired decoupling controller (BDC) from the bi-regulation principle of the growth hormone (GH) in neuroendocrine system is proposed [1]. Secondly, an intelligent bi-cooperative decoupling controller (IBCDC) inspired from the modulation mechanism of internal environment in body is proposed [2]. Finally, an intelligent cooperative decoupling controller (ICDC) based on the neuroendocrine regulation principle of human body is proposed [3].

2.1 Introduction

Coupling is also a very popular phenomenon in multiple-input-multiple-output (MIMO) systems. For example, during the industrial process, many control loops are designed for a control plant to guarantee the product quality. Usually, there exists coupling influence among these loops. If the influence is not eliminated successfully, these loops will not be auto-controlled or controlled stably. As such, it will affect the stability of the process and the product quality. Hence, it is of great importance to eliminate the coupling influence. Decoupling control is one of the most critical and effective methods to solve this problem. And the essentiality of the decoupling control is to reduce or eliminate the coupling influence among various loops via control compensation based on the mathematical model or the process mechanism. The conventional decoupling control methods include diagonal matrix

decoupling, identification matrix decoupling, feed forward compensation decoupling [4, 5], and pole assignment decoupling [6, 7]. However, the existing methods may be a little complicated, or lack very satisfactory decoupling effectiveness. And, most of them are based on the mathematical models, which is more or less impractical for the industrial control.

As we know, bio-systems are highly stable with harmonious regulation and accurate control, and have been imitated to develop some novel intelligent control methods for complex systems. Since the early 1990s, many intelligent decoupling control technologies have been developed, such as fuzzy decoupling [8–11], neural networks decoupling [12–14], self-adaptive decoupling [15], genetic algorithm-based decoupling [16–18], and kernel decoupling [19]. Some researchers focus on the regulation principles of human body and try to apply such principles to the industrial control domain [20–22]. Under the control of the nervous system, a number of human physiological regulation systems build a highly complex and stable regulation network which maintains physiological homeostasis through the cooperative regulation mechanisms in human body [23–25]. Besides from the above intelligent control methods, some novel ones are recently developed from neuroendocrine (NE) system [26, 27]. NE system involves nervous system and endocrine system, which are two important physiological modulation systems in body. Endocrine is responsible for secrete some hormones and modulate the secreting process via complex feedback mechanism. Nervous system also regulates the hormone-secreting process by neurotransmitters secreted in it. As thus, the hormone concentration in body can be controlled stable and quickly [28, 29]. NE system is a complex coupling one, and several simple decoupling architectures are introduced to simulate the process of the hormone release in the medical field [28–32].

2.2 Intelligent Decoupling Control System Inspired from Regulation of the Growth Hormone

In this section, we present a bio-inspired decoupling controller (BDC) from the bi-regulation principle of the growth hormone (GH) in neuroendocrine system, and provide its decoupling algorithm for complex coupling system. The BDC consists of an identification unit and two or more control units. The identification unit can obtain the mathematical model via the step-response method and correct the model online. The control unit is composed of a control module, a coupling error prediction (CEP) module, an inverse control (INC) module, and an output module. The CEP module can predict the coupling error between loops, while the INC module can calculate the corresponding decoupling output. The control units communicate with each other to exchange the control information and to adjust the actuators harmoniously. As thus, the coupling influences among the various control loops can be reduced or eliminated. In order to examine the decoupling control

effectiveness of the BDC, we apply it to the methanol-water distillation column model [33, 34] that is a two-input-two-output (TITO) strong coupling system. The simulation results demonstrate that the BDC can completely eliminate the coupling influence with better control performance and adaptability. Compared with other decoupling control algorithms, the BDC can be implemented more easily and practically.

2.2.1 *Bi-Regulation Principle of the Growth Hormone*

GH is one of vital endocrine hormone secreted by pituitary, which is indispensable to the body growth. The secretion of GH is regulated by the GH-releasing hormone (GHRH) and the GH-release-inhibiting hormone (SRIF). Both GHRH and SRIF are secreted by hypothalamus. GHRH stimulates the synthesis and release of GH, while SRIF antagonizes the secretion of GH. The concentration of GH in blood circulation system or interstitial fluid is fed back to neurons of GHRH and SRIF in body via the cell sensors to modulate their release. When the concentration of GHRH exceeds that of SRIF, the concentration of GH will increase, and vice versa.

In addition, there is an interaction between the regulating neural unit of GHRH and that of SRIF. The increase of GHRH concentration may also cause the increase of SRIF, which may inhibit the secretion of GHRH in turn. Similarly, the increase of SRIF concentration may cause the increase of GHRH, which may inhibit the secretion of SRIF in turn. In addition, the concentration of GH is also fed back to the central nervous system, which includes spinal cord, brain, white matter, gray matter, and so on. Then the central nervous systems can further modulate the GHRH and SRIF regulation process in hypothalamus. Through the harmonious regulation of GHRH and SRIF, the secretion of GH can be controlled accurately and stably [31, 32]. The regulating loop of GH is as shown in Fig. 2.1 [1].

2.2.2 *Design of the Bio-Inspired Decoupling Controller*

2.2.2.1 The Structure of the BDC

According to Fig. 2.1, we design the BDC for the decoupling control system as shown in Fig. 2.2 [1]. The regulating neural unit of GHRH and that of SRIF are corresponding to the control unit A and unit B with the output u_1 and u_2 , respectively. The central nervous system is corresponding to the identification unit. The pituitary is corresponding to the process plant. The concentration of the GH in body is corresponding to the output variables y_1 and y_2 .

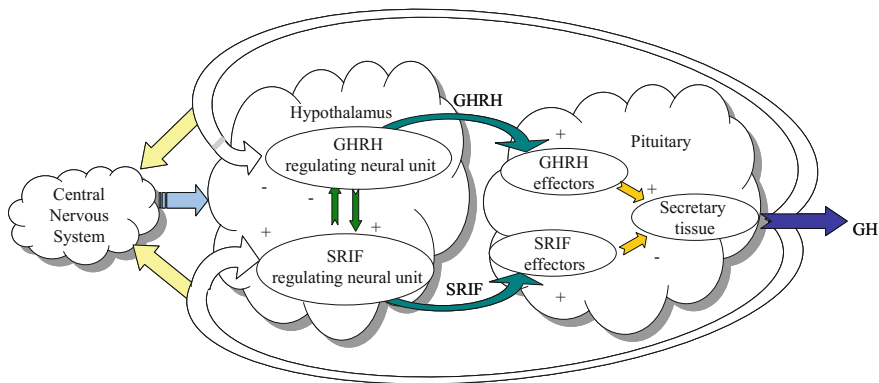


Fig. 2.1 The regulating loop of the GH

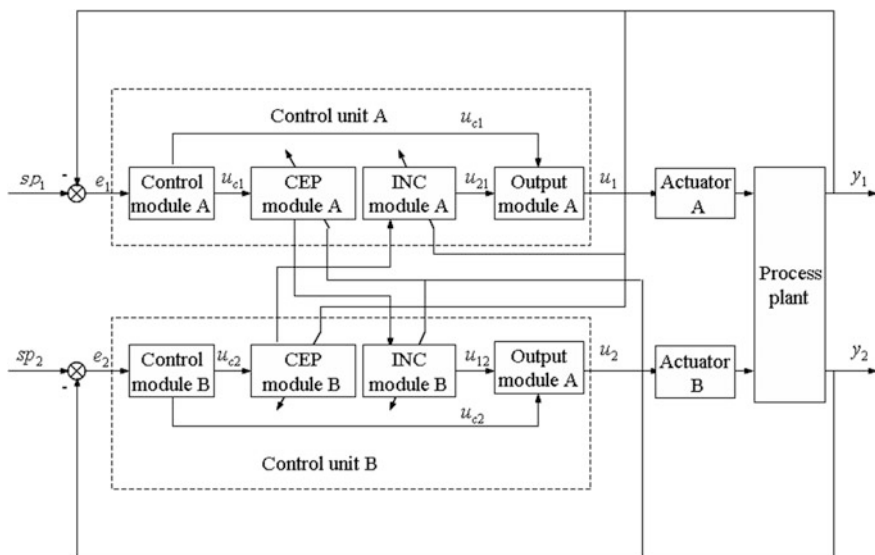


Fig. 2.2 The structure of the BDC

The corresponding relationship between the bi-regulation of the GH and the structure of the BDC is as shown in Table 2.1 [1].

The BDC consists of an identification unit and two or more control units. The identification unit can obtain the mathematical model via the step-response method and correct the model online. The control unit is composed of a control module, a coupling error prediction module (CEP), an inverse control module (INC), and an output module. The CEP can predict the coupling error between two control loops,

Table 2.1 The relationship between the Bi-regulation of the GH and the structure of the BDC

No.	Bi-regulation of the GH	Structure of the BDC
1	Regulating neural unit of GHRH	Control unit A
2	Regulating neural unit of SRIF	Control unit B
3	GHRH	u_1
4	SRIF	u_2
5	Central nervous system	Identification unit
6	Pituitary	Process plant
7	Concentration of GH	Output variables y_1 and y_2

while the INC can calculate the corresponding decoupling output. Based on the decoupling algorithm explained in the next section, the control units communicate with each other to exchange the control information and to adjust the actuators harmoniously. As thus, the coupling influences among the various control loops can be reduced or eliminated.

The mathematical description for the BDC is as follows. For convenience, we denote the transfer function of the decoupling unit as $D(s)$, including CEP, INC and output module, and that of the conventional control unit and the process plant as $C(s)$ and $G(s)$, respectively. As thus, the transfer function $W(s)$ of the closed loop control system can be denote as,

$$W(s) = \frac{C(s)D(s)G(s)}{1 + C(s)D(s)G(s)}$$

2.2.2.2 The Decoupling Control Algorithm

In order to describe the decoupling control algorithm conveniently, we take a TITO linear coupling plant as an example. For a TITO linear coupling plant

$$\begin{bmatrix} y_1(s) \\ y_2(s) \end{bmatrix} = \begin{bmatrix} G_{11}(s), G_{21}(s) \\ G_{12}(s), G_{22}(s) \end{bmatrix} \begin{bmatrix} u_1(s) \\ u_2(s) \end{bmatrix}$$

where $G_{ij}(s)$ ($i, j = 1, 2$) is the transfer function between the i -th input and the j -th output; $y_1(s)$ and $y_2(s)$ are the process output variables; and $u_1(s)$ and $u_2(s)$ are the outputs of the controllers. If $G_{ij}(s)$ is known, we can predict the coupling influence from the input u_i to the output variables y_j ($i, j = 1, 2$, and $i \neq j$), and then take a measure to reduce the influence.

We define the following variables for the BDC. uc_1 and uc_2 are the outputs of the control modules A and B, respectively, u_{12} is the decoupling signal of the INC B, and u_{21} is the decoupling signal of the INC A.

The output of the control unit A is

$$u_1 = u_{c1} + u_{21}$$

and that of the control unit B is

$$u_2 = u_{c2} + u_{12}$$

According to the predicted coupling error, the corresponding compensation output can be obtained via the inverse control model. In the following, we introduce the decoupling algorithm by taking the decoupling process from $u_1(s)$ to $y_2(s)$ as an example.

When y_1 is regulated, y_2 should be kept unchanging in order to eliminate the coupling influence from u_1 to y_2 . The coupling influence $\Delta de_{12}(s)$ from $u_1(s)$ to $y_2(s)$ with the dynamic changing output $\Delta u_1(s)$ can be predicted based on the following equation,

$$\Delta de_{12}(s) = G_{12}(s)\Delta u_1(s) \quad (2.1)$$

To keep y_2 unchanged, we should let $\Delta u_{21}(s) = 0$ and $\Delta u_1(s) = \Delta u_{c1}(s)$. To eliminate the coupling influence, we employ the inverse model control, noted as $IC_{12}(s)$, and make the following equation true,

$$\Delta de_{12}(s) + \Delta u_{c1}(s)F_{12}(s)IC_{12}(s)G_{22}(s) = 0 \quad (2.2)$$

where, $F_{12}(s)$ is the transfer function of the CEP A. It is well-known that the coupling transfer function $G_{12}(s)$ in most process systems may be described as a first-order plant with time delay,

$$G_{12}(s) = \frac{K_{12}e^{-\tau_{12}s}}{T_{12}s + 1} = G'_{12}(s)e^{-\tau_{12}s} \quad (2.3)$$

To predict the coupling influence, we make $F_{12}(s)$ equal to $G'_{12}(s)$. Then, from Eqs. (2.1)–(2.3), we have

$$IC_{12}(s) = -\frac{e^{-\tau_{12}s}}{G_{22}(s)}.$$

Obviously, $IC_{12}(s)$ is an inverse model of $G_{22}(s)$ with a time delay. Similarly, $G_{22}(s)$ can be noted as

$$G_{22}(s) = \frac{K_{22}e^{-\tau_{22}s}}{T_{22}s + 1}$$

Then, we get

$$IC_{12}(s) = -\left(\frac{1}{K_{22}} + \frac{T_{22}}{K_{22}}s\right)e^{(\tau_{22}-\tau_{12})s} \quad (2.4)$$

Compare with the conventional PID control algorithm, we can find that $IC_{12}(s)$ in Eq. (2.4) is a PD controller with a differentiation/lead or lag element. In fact, τ_{22} should be less than τ_{12} , which means $IC_{12}(s)$ is a controller with lag element that is easily implemented. If τ_{22} is larger than τ_{12} , $IC_{12}(s)$ is a PD controller with a differentiation/lead element, which is difficult or impossible to be implemented in computer.

Finally, we can get the decoupling control signal from the control unit A to B,

$$\Delta u_{12}(s) = F_{12}(s)IC_{12}(s)\Delta u_{c1}(s).$$

In the same way, for regulating y_2 , we can get the decoupling compensation equation from $u_2(s)$ to $y_1(s)$ as follows,

$$IC_{21}(s) = -\left(\frac{1}{K_{11}} + \frac{T_{11}}{K_{11}}s\right)e^{(\tau_{11}-\tau_{21})s}.$$

The decoupling signal from the control unit B to A is

$$\Delta u_{21}(s) = F_{21}(s)IC_{21}(s)\Delta u_{c2}(s)$$

where,

$$F_{21}(s) = \frac{K_{21}}{T_{21}s + 1}$$

As such, we can obtain the dynamic decoupling output of the control unit A,

$$\Delta u_1(s) = \Delta u_{c1}(s) + F_{21}(s)IC_{21}(s)\Delta u_{c2}(s) \quad (2.5)$$

and that of the control unit B,

$$\Delta u_2(s) = \Delta u_{c2}(s) + F_{12}(s)IC_{12}(s)\Delta u_{c1}(s) \quad (2.6)$$

Then, we can get the transfer function of the decoupling unit as follows,

$$D(s) = \begin{bmatrix} 1 & F_{21}(s)IC_{21}(s) \\ F_{12}(s)IC_{12}(s) & 1 \end{bmatrix}$$

2.2.2.3 Mathematical Model Identification

If the mathematical model of the process plant is available, Eqs. (2.5) and (2.6) can be derived from it easily. However, the mathematical model is not always available in some control systems. In this case, the step-response identification is employed to obtain the approximate transfer matrix $G(s)$ online. In the BDC, we design a harmonious adjusting method for the control units A and B by exchanging the control information between them. When the BDC is taken into effect for the first time, the control unit A sends “HOLD” signal to the control unit B, then the output of the conventional control module B will be unchanged. At same time, the control unit A outputs a step signal. When both control loops become stable, $G_{11}(s)$ and $G_{12}(s)$ can be obtained by using the step-response identification. In the same way, the control unit B sends “HOLD” signal to the control unit A and outputs a step signal, then $G_{22}(s)$ and $G_{21}(s)$ can be obtained. As thus, the mathematical model can be obtained quickly and easily.

In practice, the values of the plant parameters are always changing, so the mathematical model should be corrected online. There are some methods to correct the model, such as neural networks, fuzzy logic, and least squares method. In the BDC, the identification unit is to perform this task. To implement it more easily, we use the least squares method to correct the mathematical model. For the least squares method, the input variables include control output signals u_1 , u_2 , and the process variables y_1 , y_2 . The identified results are used to adjust the INC and CFP models.

2.2.2.4 Extension to MIMO Systems

The BDC and its decoupling control algorithm for TITO systems can be easily extended to MIMO systems. For a MIMO system,

$$\begin{bmatrix} y_1(s) \\ \vdots \\ y_n(s) \end{bmatrix} = \begin{bmatrix} G_{11}(s) & G_{21}(s) & \cdots & G_{n1}(s) \\ \vdots & \vdots & \vdots & \vdots \\ G_{1n}(s) & G_{2n}(s) & \cdots & G_{nn}(s) \end{bmatrix} \begin{bmatrix} u_1(s) \\ \vdots \\ u_n(s) \end{bmatrix} \quad (2.7)$$

where $y_i(s)$ ($i = 1, 2, \dots, n$) are the output variables; $G_{ij}(s)$ ($i, j = 1, 2, \dots, n$) are the transfer functions between the i -th input and the j -th output; and $u_i(s)$ ($i = 1, 2, \dots, n$) are the outputs of the BDC. According to the proposed decoupling algorithm, while regulating the state variables $y_i(s)$, all the values of the dynamics influences of $y_1, y_2, \dots, y_{i-1}, y_{i+1}, \dots, y_n$ should be equal to zero. Based on the derived algorithm, the coupling influence can be eliminated by adjusting n actuators harmoniously. The corresponding dynamic decoupling output of every control unit can be derived in the similar way as the decoupling control algorithm for TITO systems. For example, if the dynamical changing output of conventional control model of i -

th control unit is Δu_{ci} . Suppose that the dynamic changes of the other control units are equal to zero. For the first control unit, we have

$$\Delta u_{i1}G_{11}(s) + \Delta u_i G_{i1}(s) = 0$$

where, Δu_{i1} is the decoupling output of first control unit for regulating $y_i(s)$, and.

$$\Delta u_i = \Delta u_{ci}.$$

Then we can get,

$$\Delta u_{i1} = \frac{-G_{i1}(s)}{G_{11}(s)} \Delta u_i$$

In the similar way, we can get the decoupling output of j -th control unit for regulating $y_i(s)$,

$$\Delta u_{ij} = \frac{-G_{ij}(s)}{G_{jj}(s)} \Delta u_i$$

We note that the number of control variables need not be equal to that of output variables.

Moreover, if the mathematical model of a MIMO system is not available, we can also obtain the approximate transfer matrix $G(s)$ via the step-response identification, and correct the mathematical model online by applying the least squares method. Then, the decoupling equations can be obtained from the identified mathematical model.

2.2.2.5 Simulation Results

In order to examine the decoupling control effectiveness of the BDC, we apply it to the methanol-water distillation column model that is a two-input-two-output (TITO) strong coupling system [42, 43]. The Wood and Berry's FOPDT transfer function model is considered:

$$\begin{bmatrix} y_1(s) \\ y_2(s) \end{bmatrix} = \begin{bmatrix} \frac{12.8e^{-s}}{16.7s+1} & \frac{-18.9e^{-3s}}{21.0s+1} \\ \frac{6.6e^{-7s}}{10.9s+1} & \frac{-19.4e^{-3s}}{14.4s+1} \end{bmatrix} \begin{bmatrix} u_1(s) \\ u_2(s) \end{bmatrix} + \begin{bmatrix} \frac{3.8e^{-8s}}{14.9s+1} \\ \frac{4.9e^{-s}}{13.2s+1} \end{bmatrix} F(s) \quad (2.8)$$

where, y_1 is the mole fraction of the methanol at the top; y_2 is the mole fraction of the methanol at the bottom; u_1 is the reflux flow rate; u_2 is the steam flow rate; and $F(s)$ is the feed flow rate. The model (2.8) is for a methanol-water distillation column, which is a coupling TITO system with large time delay. There are strong coupling influences between the mole fraction of the methanol at the top and that at the bottom. The steady state values of the methanol composition at the top and at

the bottom are 96.25 mol% and 0.5 mol%, respectively. The conventional control scheme is that y_1 and y_2 is controlled through adjusting u_1 and u_2 , respectively.

Following, we apply the BDC to the model (2.8) with ignoring the dynamical changing rate of feed flow $F(s)$ in Fig. 2.2. We choose the control unit A for y_1 , and the control unit B for y_2 . We first identify the mathematical model via step-response identification method. The identified mathematical model is as follows:

$$\begin{bmatrix} y_1(s) \\ y_2(s) \end{bmatrix} = \begin{bmatrix} \frac{12.6e^{-s}}{16.9s+1} & \frac{-18.7e^{-3s}}{21.1s+1} \\ \frac{6.5e^{-7s}}{10.9s+1} & \frac{-19.6e^{-3s}}{14.5s+1} \end{bmatrix} \begin{bmatrix} u_1(s) \\ u_2(s) \end{bmatrix}$$

Based on the decoupling algorithm discussed in Sect. 2.2.3, we obtain the dynamic decoupling output to control y_1 ,

$$\Delta u_1(s) = \Delta u_{c1}(s) + \frac{1.48}{21.1s+1}(16.9s+1)e^{-2s}\Delta u_{c2}(s)$$

and that to control y_2 ,

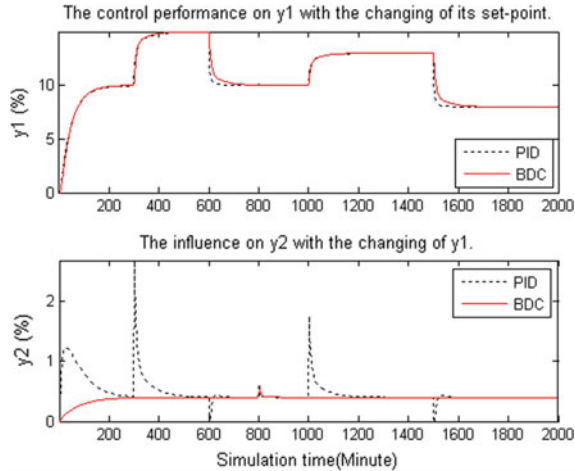
$$\Delta u_2(s) = \Delta u_{c2}(s) + \frac{0.33}{10.9s+1}(14.5s+1)e^{-4s}\Delta u_{c1}(s)$$

Using the BDC, we can obtain satisfactory control performance for the coupling TITO system (2.8), as shown in Fig. 2.3 [1].

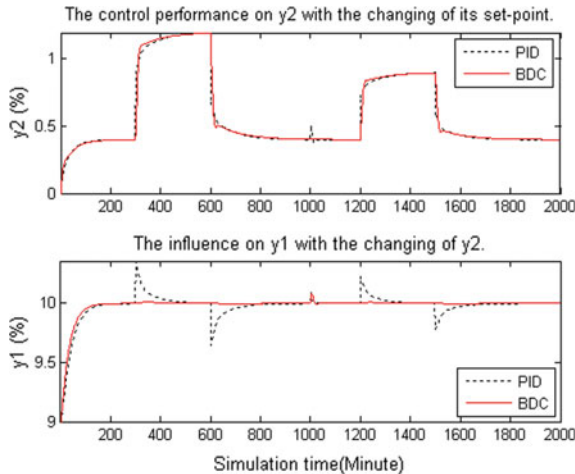
Compare the control effectiveness of the BDC with that of the conventional control scheme. Here, the conventional PID control algorithm is adopted in the control units A and B. To make the comparison be fair, the control parameters of the PID controller are same with those of control units A and B, as shown in Table 2.2 [1]. In order to illustrate the contrast effectiveness of the influence on y_2 with the changing of y_1 , we change the set points of y_1 at the 300-th, 600-th, 1000-th, and 1500-th minute in Fig. 2.3(a). From Fig. 2.3(a), we can see that the influence of y_1 on y_2 is very large in PID control scheme, while y_2 can be kept unchanging in the BDC scheme. Also, we examine the influence on control performance with the changing of the plant parameters. In Fig. 2.3(a), the plant parameter K_{c12} is changed from 6.5 to 10.2 and T_{12} is changed from 21.1 to 18.5 at 800-th minute. The BDC can eliminate the coupling influences successfully with online identification. At the same time, the contrast effectiveness of the influence on y_1 with the changing of y_2 is as shown in Fig. 2.3(b). The plant parameter K_{c12} is changed from -18.9 to -15.6 and T_{21} is changed from 10.9 to 11.5 at 1000-th minute. The set points of y_2 at the 1200-th and 1500-th minute are changed. From Fig. 2.3(b), we can see that y_2 influences on y_1 badly in the PID scheme, but y_1 is kept unchanging in the BDC scheme. Also, we can see that even with the plant parameters changing, the BDC can eliminate the coupling influences successfully, as shown in Table 2.3 [1].

The simulation results demonstrate that the BDC can almost eliminate the coupling influence, and has better control performance and adaptability than that of

Fig. 2.3 The performance comparison between the BDC and PID control scheme



(a) The influence on y_2 with the changing of y_1



(b) The influence on y_1 with the changing of y_2

Table 2.2 The values of the parameters in the BDC and those of the conventional PID controller

Controller	K_p	T_i	T_d
PID for y_1	1.5	30.0	0.0
Control unit A	1.5	30.0	0.0
PID for y_2	0.5	50.0	0.0
Control unit B	0.5	50.0	0.0

the conventional control scheme. Also, the BDC has better robustness under the changing of the plant parameters.

Table 2.3 The performance comparison among the BDC, PID, and GANN

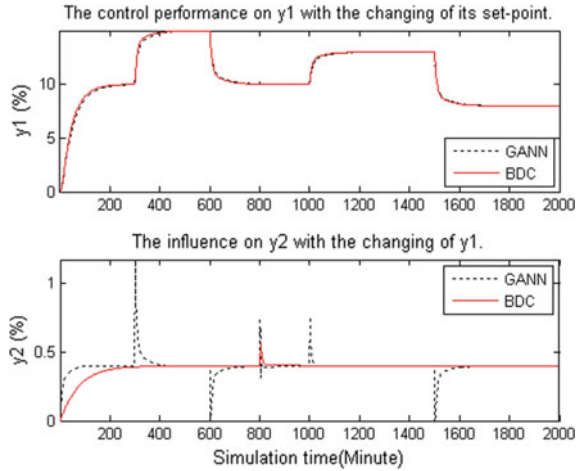
Operations		Maximum coupling influences (absolute value)	
		Set-point change	Parameter change
Regulating y_1	PID	2.23	1.81
	GANN	0.78	0.4
	BDC	0.01	0.01
Regulating y_2	PID	0.41	0.26
	GANN	0.36	0.34
	BDC	0.01	0.01

Moreover, we compared the decoupling control effectiveness of the BDC with that of other decoupling control algorithms, for example, the genetic algorithm-based neural network (GANN). The GANN is composed of three layers, i.e. input layer, middle layer and output layer. The input layer of every decoupling unit includes $\Delta u_{ci}(k)$, $\Delta u_{ci}(k-1)$, $\Delta u_{ci}(k-2)$, where $i = 1, 2$, and k is the time step. The middle layer consists of eight neurons. The output layer includes one neuron, $\Delta u_{di}(k)$, which is the final output of every decoupling unit. In the simulation, the individual number of every population is 50, and the probability of crossover and mutation is 0.9 and 0.05, respectively. The number of iterative steps is 2000. The contrast decoupling effectiveness of the BDC and the GANN decoupling control are as shown in Fig. 2.4 [1]. The simulation results show that the GANN decoupling controller cannot completely eliminate the coupling influence, even after 2000 steps, as shown in Table 2.3 [1] but the BDC can almost eliminate the coupling influence. Hence, the BDC has better decoupling control performance than that of the GANN decoupling control scheme.

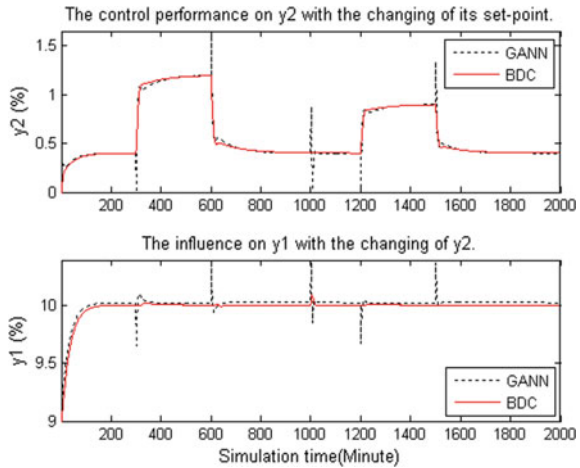
2.3 An Intelligent Bi-Cooperative Decoupling Controller

This section presents an intelligent bio-cooperative decoupling controller (IBCDC) from the bi-cooperative regulation mechanism of some physiological indexes in the internal environment of the human body, and provides its decoupling algorithm for complex coupling systems. In order to examine the decoupling control effectiveness of the IBCDC, we apply it to the methanol-water distillation column model [33] that is a two-input-two-output (TITO) strong coupling system. Compared with other decoupling control methods, the IBCDC can be implemented more easily and practically with better control performance and adaptability. The decoupling control algorithm can also be easily generalized to the MIMO coupling control systems. The study not only favors the design of intelligent decoupling controllers for complex coupling systems, but also benefits the future studies of coordination mechanism of physiological systems or biological systems.

Fig. 2.4 The decoupling performance comparison between the BDC and the GANN decoupling control scheme



(a) The influence on y_2 with the changing of y_1



(b) The influence on y_1 with the changing of y_2

2.3.1 Bi-Cooperative Regulation of Internal Environment in Body

Under the control of the nervous system, a number of human physiological regulation systems build a highly complex and stable regulation network, which maintains physiological homeostasis through the cooperative regulation mechanisms in the body. Among them, the body temperature (BT) regulation system and the blood pressure (BP) regulation system belong to a typical multi-coordination control system [30, 35, 36].

The core regulation institution of the body temperature is the hypothalamic thermoregulation center. This center coordinates the heat-production organs and the heat-dissipation tissues to maintain the body temperature at a stable level, according to the temperature signals sent by the temperature sensor cells from the whole body. When the body temperature arises, the nervous system modulates the surface pore to open for sweat secretion, and makes skin blood vessels expand to decrease blood flow for promoting skin cooling. At the same time, the hypothalamic temperature regulation center reduces the release of thyroid hormones and lowers basal metabolic rate to reduce the heat production. On the contrary, the nervous system modulates the surface pore to close and makes skin vessel contracts to reduce blood flow for reducing the skin cooling. At the same time, the hypothalamus increases the release of thyroid hormones to improve the basal metabolic rate and increase the heat release, or makes the muscles increase tension and even tremble to achieve temperature equilibrium through the regulation of the nervous system.

The regulation mechanism of the blood pressure system in the body is that blood pressure sensor cells distribute the whole-body transmit pressure signals to the cerebral cortex of the central nervous system. Then, the conditioned signals re-transmit them to the hypothalamic blood-pressure regulation center. Finally, the blood pressure is controlled stably through the following three modulation ways.

- (1) Pressure regulation: When the blood pressure arises, the hypothalamic blood pressure (HBP) regulation center makes the depressor reflex activity strengthened so that the cardiac contractility decreases and blood vessels expand. As a result, the blood pressure declines. On the contrary, the HBP regulation center makes the depressor reflex activity weakened, so that the cardiac contractility enhances and blood vessels contract. Finally, the blood pressure ascends to a normal level.
- (2) Capacity regulation: When the arterial blood pressure drops, the nervous system will stimulate juxtaglomerular cells to secrete therennin and activates the rennin-angiotensin-aldosterone system. This makes the absorption of sodium and water increase, so that the blood volume expands and blood pressure arises again. On the contrary, the excretion of sodium and water increases to reduce the blood volume. As a result, the blood pressure declines to a normal level quickly.
- (3) Body fluid regulation: Adrenaline, norepinephrine, angiotensin, etc. in blood and tissue have a role in contracting the blood vessel, which may make the blood pressure ascend. However, bradykinin, prostaglandin E, atrial natriuretic peptide, etc. have a strong vasodilative effect, which can make the blood pressure down.

During the regulation process of the body temperature and the blood pressure, when the blood flow increases or decreases for regulating the body temperature, the blood pressure also changes. In the same way, with the increase or decrease of the blood flow for the regulation of blood pressure, the body temperature also alters.

Therefore, there are serious coupling effects between the body temperature regulation system and the blood pressure regulation system.

During the regulation process of the above two systems, not only the temperature signal and the blood pressure signal are rapidly fed back to the cerebral cortex, but also the secretions of central hormone concentration information from hypothalamus temperature and blood pressure control centers are timely fed back there. Under the regulation of the senior nervous system, the body temperature and the blood pressure control systems not only adjust their own parameters to provide a steady change, but also are able to quickly eliminate the coupling influence between them. The coordinated approaches of the blood flow and the blood vessel contraction and dilation are the main ways to eliminate the coupling influence. The above bi-cooperative regulation mechanism can be abstracted to be the control structure as shown in Fig. 2.5. In Fig. 2.5, BT, BP, HT, and HBP is body temperature, blood pressure, hypothalamus temperature, and hypothalamus blood pressure, respectively.

2.3.2 Design of the Bi-Cooperative Decoupling Controller

If the regulation processes of multiple physiological indexes are parallel studied in the human bio-information regulation network, we can find a special bi-cooperative mechanism for complex decoupling control, for example, the ascend and descend bi-cooperative modulation mechanism in the body temperature and the blood pressure regulation systems. In order to design a novel decoupling controller, we make the multiple physiological indexes corresponding to the MIMO process variables, the central nervous system to the supper control unit, the hypothalamus

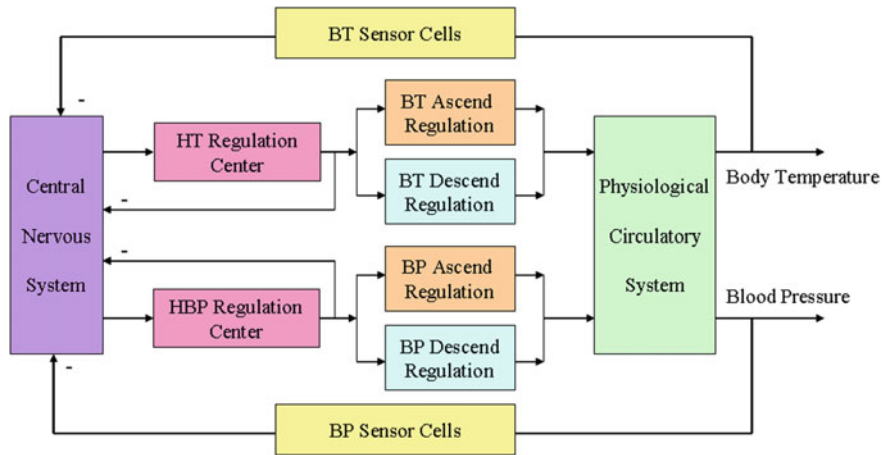


Fig. 2.5 The regulation structure of a physiological system

and the pituitary to the control unit and the decoupling control unit, respectively. Following, we will discuss the bio-inspired IBCDC architecture and its decoupling compensation algorithm.

2.3.2.1 Bio-Inspired Architecture of the IBCDC

Inspired from the mutual cooperative regulation mechanism in the body temperature system and the blood pressure system, a novel cooperative decoupling control architecture and its algorithm can be designed according to Fig. 2.5.

The IBCDC consists of a coordination control unit (CCU), a model identification unit (MIU), a decoupling control evaluation unit (DCEU), control unit 1 and control unit 2. The DCEU includes a reinforcing decoupling control block (RDCB) and a suppression decoupling control block (SDCB). Each control unit or block is designed according to different physiological organs or systems, it includes an original control block (OCB) and a decoupling compensation block. As shown in Fig. 2.6, the CCU and the MIU are designed corresponding to the cerebral cortex; the DCEU and two control units are designed corresponding to the hypothalamus temperature and the blood pressure regulation centers, respectively; the OCB and the DCB are corresponding to hypothalamus and hormone secretion glands.

Inspired from the multi-level complicated feedback mechanism of the physiological regulation systems, we design a feedback network of control information.

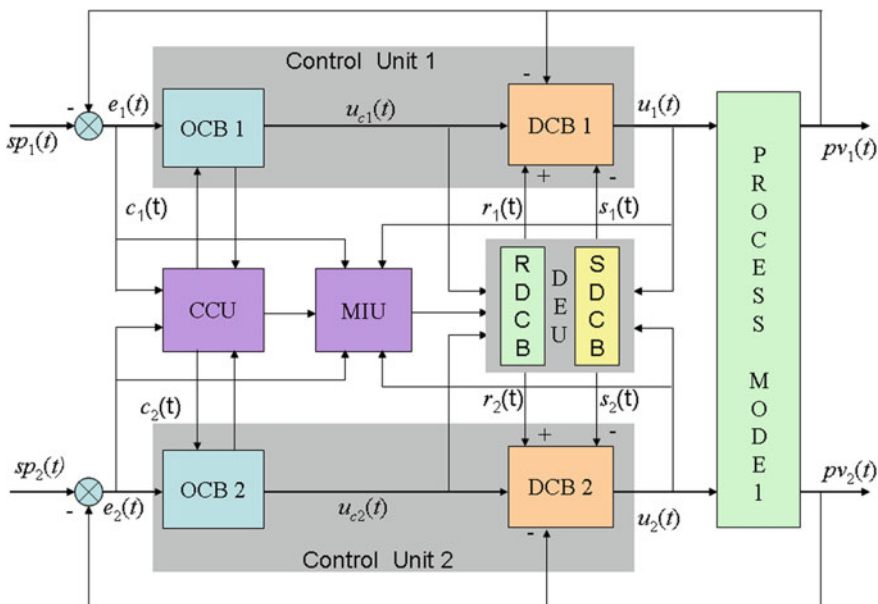


Fig. 2.6 The architecture of the IBCDC

The process variables are not only fed back to the OCB, but also to the DCB; the output signals of the OCBs are fed back to the CCU separately; and all the control output and the decoupling compensation signals are fed back to the DCEU for the effectiveness evaluation of the decoupling control.

In Fig. 2.6, $u_{c1}(t), u_{c2}(t)$ denotes the original control signals of RCB 1 and RCB 2, respectively; $\Delta u_{c1}(t)$ may be calculated according to one control algorithm, such as PID control algorithm. $u_1(t), u_2(t)$ denotes the output of DCB 1 and DCB 2, respectively; $c_1(t), c_2(t)$ denotes the coordination signal sent from the CCU for control unit 1 and control unit 2, respectively; $e_1(t), e_2(t)$ denotes the control error of two loops, respectively. $r_i(t), s_i(t), (i = 1, 2)$ denotes the reinforcing and the suppression regulation signals of the decoupling compensation, respectively.

Under the coordination of the CCU, all the control units or blocks communicate with each other to exchange the control or decoupling control information. Through adjusting the actuators harmoniously, the coupling influences among different control loops can be reduced or eliminated in time.

2.3.2.2 General Decoupling Control Algorithm

For convenience to introduce the principle of the IBCDC, we define $G_{c1}(s), G_{c2}(s)$ as the transfer function of RCB 1 and RCB 2, respectively; $\Delta d_1(t), \Delta d_2(t)$ as the dynamic decoupling compensation for the two loops, respectively. The output of the control unit 1 is $\Delta u_1(t) = \Delta u_{c1}(t) + \Delta d_1(t)$, and that of the control unit 2 is $\Delta u_2(t) = \Delta u_{c2}(t) + \Delta d_2(t)$.

For a two-input-two-output (TITO) linear discrete coupling plant

$$\begin{bmatrix} y_1(z) \\ y_2(z) \end{bmatrix} = \begin{bmatrix} G_{11}(z), G_{21}(z) \\ G_{12}(z), G_{22}(z) \end{bmatrix} \begin{bmatrix} u_1(z) \\ u_2(z) \end{bmatrix} \quad (2.9)$$

where $G_{ij}(z), (i, j = 1, 2)$ is the transfer function between the i -th input and the j -th output; $y_1(z)$ and $y_2(z)$ are the process output variables; and $u_1(z)$ and $u_2(z)$ is the output of control unit 1 and control unit 2, respectively.

If $G_{ij}(z)$ is obtained, we can predict the coupling influence from the input $u_i(z)$ to the output variable $y_j(z)$ ($i, j = 1, 2$, and $i \neq j$), then take a measure to reduce the influence. In the following, we take the decoupling process from $u_1(z)$ to $y_2(z)$ as an example to introduce the decoupling algorithm.

When $y_1(z)$ is regulated, $y_2(z)$ should be kept unchanged, i.e. $\Delta y_2(z) = 0$, to eliminate the coupling influence from $u_1(z)$ to $y_2(z)$. If the output of control unit 1 is $\Delta u_1(z) = \Delta u_{c1}(z)$, the coupling influence from $u_1(z)$ to $y_2(z)$ can be predicted according to the following equation,

$$\Delta c_{12}(z) = G_{12}(z)\Delta u_{c1}(z) \quad (2.10)$$

where, $\Delta c_{12}(z)$ is the coupling influence from $u_1(z)$ to $y_2(z)$ with the dynamic changing output $\Delta u_1(z)$.

Based on the cooperative process narrated above, control unit 2 is in decoupling control status at this time, and the output of its original control block is equal to zero, i.e. $\Delta u_{c2}(z) = 0$. The output of control unit 2 is just the decoupling compensation output of DCB 2, i.e. $\Delta u_2(z) = \Delta d_2(z)$.

To eliminate the coupling influence, the following equation should be true,

$$\Delta c_{12}(z) + \Delta d_2(z)G_{22}(z) = \Delta y_2(z) = 0 \quad (2.11)$$

Take Eq. (2.10) into Eq. (2.11), the decoupling compensation of control unit 2 can be gotten as

$$\Delta d_2(z) = -\frac{G_{12}(z)}{G_{22}(z)} \cdot \Delta u_{c1}(z) \quad (2.12)$$

Similarly, when $y_2(z)$ is regulated, $y_1(z)$ must be kept unchanged to eliminate the coupling influence from $u_2(z)$ to $y_1(z)$, through the decoupling compensation $\Delta d_1(z)$ of DCB 1. The decoupling compensation $\Delta d_1(z)$ can be gotten as follows,

$$\Delta d_1(z) = -\frac{G_{21}(z)}{G_{11}(z)} \cdot \Delta u_{c2}(z) \quad (2.13)$$

As most plants in the industrial process can be approximately represented as a first order with time delay, i.e.

$$G_{ij}(z) = \frac{K_{ij}}{T_{ij}} \frac{z^{-\tau_{ij}/T_s}}{1 - \exp(-T_s/T_{ij})z^{-1}} \quad (2.14)$$

where K_{ij} , T_{ij} , τ_{ij} are the open-loop gain, time constant, and delay time, respectively. Substituting Eq. (2.14) into Eq. (2.12), we can get the decoupling compensation of DEB 2,

$$\Delta d_2(z) = -\Delta u_{c1}(z) \cdot K_{12}^* \cdot \left(\frac{1 - \exp(-T_s/T_{22})z^{-1}}{1 - \exp(-T_s/T_{12})z^{-1}} \right) \cdot z^{-(\tau_{12}-\tau_{22})/T_s} \quad (2.15)$$

where $K_{12}^* = K_{12}/K_{22} \cdot T_{22}/T_{12}$.

In the same way, we can get the decoupling compensation of DEB 1,

$$\Delta d_1(z) = -\Delta u_{c2}(z) \cdot K_{21}^* \cdot \left(\frac{1 - \exp(-T_s/T_{11})z^{-1}}{1 - \exp(-T_s/T_{21})z^{-1}} \right) \cdot z^{-(\tau_{21}-\tau_{11})/T_s} \quad (2.16)$$

where $K_{21}^* = K_{21}/K_{11} \cdot T_{11}/T_{21}$.

Consider the difference expression of Eq. (2.15) as follows,

$$\Delta d_2(k_2) = \exp(-T_s/T_{12}) \cdot \Delta d_{12}(k_{12} - 1) - K_{12}^* \cdot (\Delta u_{c1}(k_{12} - l_{12}) - \exp(-T_s/T_{22}) \cdot \Delta u_{c1}(k_{12} - l_{12} - 1)) \quad (2.17)$$

where k_2 is the discrete step of control unit 1, and l_{12} is the delay step of the decoupling compensation output, $l_{12} = (\tau_{12} - \tau_{22})/T_s$.

Similarly, we can get the difference expression of Eq. (2.16) as follows,

$$\Delta d_1(k_1) = \exp(-T_s/T_{21}) \cdot \Delta d_{21}(k_{21} - 1) - K_{21}^* \cdot (\Delta u_{c2}(k_{21} - l_{21}) - \exp(-T_s/T_{11}) \cdot \Delta u_{c2}(k_{21} - l_{21} - 1)) \quad (2.18)$$

where k_1 is the discrete step of control unit 2, and l_{21} is the delay step of the decoupling compensation output, $l_{21} = (\tau_{21} - \tau_{11})/T_s$.

- (1) If $\tau_{ij} = 0$ or $\tau_{12} = \tau_{22}$, $\tau_{21} = \tau_{11}$, the pure delay time has no effect on the decoupling compensation, i.e. $l_{12} = 0$, $l_{21} = 0$.
- (2) If $\tau_{12} > \tau_{22}$ or $\tau_{21} > \tau_{11}$, the affection of the pure delay time should be counted, and $l_{12} > 0$, $l_{21} > 0$.
- (3) If $\tau_{12} < \tau_{22}$ or $\tau_{21} < \tau_{11}$, the pure delay time changes to the lead time, which makes it impossible to implicate the decoupling algorithm. On this condition, we let $l_{12} = 0$ and $l_{21} = 0$.

From Eq. (2.17), we can get the following general decoupling compensation expression of DEB 1,

$$\Delta d_1(k_1) = \alpha_{21} \cdot \Delta d_{21}(k_{21} - 1) - \beta_{21} \cdot \Delta u_{c2}(k_{21} - l_{21}) + \gamma_{21} \cdot \Delta u_{c2}(k_{21} - l_{21} - 1) \quad (2.19)$$

where $\alpha_{21} = \exp(-T_s/T_{21})$, $\beta_{21} = K_{21}/K_{11} \cdot T_{11}/T_{21}$, $\gamma_{21} = \beta_{21} \cdot \exp(-T_s/T_{11})$.

In the same way, we can also get the general decoupling compensation expression of DEB 2,

$$\Delta d_2(k_2) = \alpha_{12} \cdot \Delta d_{12}(k_{12} - 1) - \beta_{12} \cdot \Delta u_{c1}(k_{12} - l_{12}) + \gamma_{12} \cdot \Delta u_{c1}(k_{12} - l_{12} - 1) \quad (2.20)$$

where $\alpha_{12} = \exp(-T_s/T_{12})$, $\beta_{12} = K_{12}/K_{22} \cdot T_{22}/T_{12}$, $\gamma_{12} = \beta_{12} \cdot \exp(-T_s/T_{22})$.

As a result, the discrete control expressions of control unit 1 and control unit 2 are as follows,

$$u_1(k_1) = \begin{cases} u_1(k_1 - 1) + \Delta u_{c1}(k_1), & (k_1 = 2k + 1) \\ u_1(k_1 - 1) + \Delta d_1(k_1), & (k_1 = 2k) \end{cases} \quad (2.21)$$

$$u_2(k_2) = \begin{cases} u_2(k_2 - 1) + \Delta u_{c2}(k_2), & (k_2 = 2k) \\ u_2(k_2 - 1) + \Delta d_2(k_2), & (k_2 = 2k + 1) \end{cases} \quad (2.22)$$

If the accurate mathematical model of a process plant is obtained, the decoupling compensation parameters α_{12} , β_{12} , γ_{12} , α_{21} , β_{21} , γ_{21} may be calculated easily. However, in most cases, it is impossible to get the accurate mathematical model of the process plant. Here, the step-response identification method is employed to obtain the approximate transfer matrix $G_{ij}(z)$ online. When the IBCDC is taken into effect for the first time, the CCU sends “*HOLD*” signal to control unit 2, then the output of control unit 2 will be unchanged. At the same time, control unit 1 outputs a step signal. When both control loops become stable, $G_{11}(s)$ and $G_{12}(s)$ can be obtained by using the step-response identification. Similarly, CCU sends “*HOLD*” signal to control unit 1 and outputs a step signal, then $G_{21}(s)$ and $G_{22}(s)$ will be obtained. Thus, the mathematical model can be obtained quickly and easily, and the parameters of α_{12} , β_{12} , γ_{12} , α_{21} , β_{21} , γ_{21} can be calculated approximately.

2.3.2.3 Bi-Cooperative Decoupling Control Algorithm

As the mathematics models used in Eqs. (2.19) and (2.20) are approximate models, and if only the decoupling compensation algorithms shown in Eqs. (2.19) and (2.20) are used, the decoupling control effectiveness may not be satisfactory. To improve the decoupling control performance, we design the reinforcing decoupling control block (RDCB) and the suppression decoupling control block (SDCB) in the DEU.

(1) Evaluation for the decoupling control effectiveness

To improve the decoupling control algorithm, it is important to evaluate the decoupling control effectiveness. Obviously, the ideal goal of the decoupling control is to make the coupling influence or the error minimal during every control period. Considering the pure delay time in the process, the current decoupling control result may depend on the decoupling compensation during the time period $(k - l_{ii})^{th}$, ($i = 1, 2$), where k is the discrete control steps and l_{ii} is the delay steps or time of control plant $G_{ii}(z)$, $l_{ii} = \tau_{ii}/T_s$. As thus, we can evaluate the decoupling result according to the following steps.

- (1) Judge the future change direction of the decoupling control error, according to the decoupling compensation $\Delta d_1(z)$ or $\Delta d_2(z)$ and the open loop gain k_{ii} of the corresponding transfer function $G_{ii}(z)$. When the decoupling compensation $\Delta d_1(z)$ or $\Delta d_2(z)$ is the output, the future change direction of the decoupling control may be predicted based on the following equation,

$$dir_{ij}(k) = \text{sign}(\Delta d_j(k)) \cdot \text{sign}(k_{jj}) \quad (2.23)$$

where $dir_{ij}(k)$ indicates the change direction. When $dir_{ij}(k) > 0$, the corresponding decoupling control error $e_j(k + l_{jj})$, ($j = 1, 2$) should descend, i.e. $\Delta e_j(k + l_{jj}) < 0$. Otherwise, $\Delta e_j(k + l_{jj}) > 0$.

2. Evaluate the decoupling control effect based on $dir_{ij}(k)$ and its corresponding decoupling control error $e_j(k + l_{jj})$. According to the mathematics model, l_{jj} can be obtained. Thus, the current decoupling control effect may be evaluated based on the current decoupling control error $e_j(k)$ and its corresponding decoupling compensation $\Delta d_j(k - l_{jj})$ and the predicted change direction $dir_{ij}(k - l_{jj})$. As thus, we can estimate the decoupling control error according to the following criterion.

- (i) If $\text{sign}(dir_{ij}(k - l_{jj})) \otimes \text{sign}(\Delta e_j(k)) = 0$, the direction of the corresponding decoupling compensation is consistent with the change trend of the decoupling control error. If the decoupling control error is not equal to zero, the compensation should be reinforced according to the current control error.
- (ii) If $\text{sign}(dir_{ij}(k - l_{jj})) \otimes \text{sign}(\Delta e_j(k)) = 1$, the decoupling compensation direction is not right, or the decoupling compensation may overshoot. The compensation output should be suppressed according to the current control error.

According to the evaluation result of the decoupling compensation, the original decoupling control output, as shown in Eqs. (2.19) and (2.20), may be strengthened or weakened.

$$Eva_{ij}(k) = \begin{cases} 1 & (\text{sign}(dir_{ij}(k - l_{jj})) \otimes \text{sign}(\Delta e_j(k)) = 0) \\ -1 & (\text{sign}(dir_{ij}(k - l_{jj})) \otimes \text{sign}(\Delta e_j(k)) = 1) \end{cases} \quad (2.24)$$

(2) Algorithm of the RDCU and the SDCU

According to the original decoupling control algorithm in Eqs. (2.19) and (2.20), we design the improved decoupling control algorithm with the reinforcing or suppression function Eqs. (2.25) and (2.26) as follows,

$$\Delta d_1(k_1) = \{ \alpha_{21} \cdot \Delta d_{21}(k_1 - 1) - \beta_{21} \cdot \Delta u_{c2}(k_1 - l_{21}) + \gamma_{21} \cdot \Delta u_{c2}(k_1 - l_{21} - 1) \} \cdot (1 + \eta_1(k_1)) \quad (2.25)$$

$$\Delta d_2(k_2) = \{ \alpha_{12} \cdot \Delta d_{12}(k_2 - 1) - \beta_{12} \cdot \Delta u_{c1}(k_2 - l_{12}) + \gamma_{12} \cdot \Delta u_{c1}(k_2 - l_{12} - 1) \} \cdot (1 + \eta_2(k_2)) \quad (2.26)$$

where $\eta_1(k_1)$, $\eta_2(k_2)$ is the strengthen and weaken factor, respectively. If the original decoupling compensation needs to be reinforced, the factors $\eta_1(k_1)$, $\eta_2(k_2)$ should be larger than zero, i.e. $\eta_1(k_1) > 0$, $\eta_2(k_2) > 0$. Otherwise, the factors should be smaller than zero, i.e. $\eta_1(k_1) < 0$, $\eta_2(k_2) < 0$. Thus, when $\eta_1(k_1) > 0$, $\eta_2(k_2) > 0$, the expression $(1 + \eta_1(k_1))$, $(1 + \eta_2(k_2))$ are larger than 1. So the decoupling compensation, as shown in Eqs. (2.25) and (2.26), can be strengthened. Otherwise, if $0 < (1 + \eta_1(k_1)) < 1$ and $0 < (1 + \eta_2(k_2)) < 1$, then the decoupling compensation is weakened.

Inspired from the hormone modulation law in endocrine system [37], we make the decoupling control error $e_j(k)$ correspond with the stimulation signal of hormone, and $\eta_1(k_1)$, $\eta_2(k_2)$ with the secreting concentration of hormone in the body. Thus, we design the regulation algorithm as follows,

$$\begin{cases} \Delta\eta_1(k_1) = Eva_{21}(k) \cdot \frac{abs(e_1(k))}{\alpha_{21} + exp(abs(e_1(k)))} \\ \eta_1(k_1) = \eta_1(k_1 - 1) + \Delta\eta_1(k_1) \end{cases} \quad (2.27)$$

$$\begin{cases} \Delta\eta_2(k_2) = Eva_{12}(k) \cdot \frac{abs(e_2(k))}{\alpha_{12} + exp(abs(e_2(k)))} \\ \eta_2(k_2) = \eta_2(k_2 - 1) + \Delta\eta_2(k_2) \end{cases} \quad (2.28)$$

where $-1 < \eta_1(k_1) < 1$, $-1 < \eta_2(k_2) < 1$; α_{12} , α_{21} are real factors and may be set according to the real-time decoupling effect.

(3) Feedback of decoupling error

The corrections of reinforcement or suppression of the decoupling compensation algorithms in Eqs. (2.27) and (2.28), are delayed and a little rough. Because their evaluations are according to the $\Delta d_j(k - l_{ij})$ and the current control error $e_j(k)$. Therefore, the improved decoupling compensation should further consider the direct compensation according to the current decoupling error $e_j(k)$ in the IBCDC. Here, we employ the conventional proportional action to the designed decoupling algorithm. The final decoupling compensation is as follows,

$$\begin{aligned} \Delta d_1(k_1) = & \{ \alpha_{21} \cdot \Delta d_{21}(k_1 - 1) - \beta_{21} \cdot \Delta u_{c2}(k_1 - l_{21}) + \gamma_{21} \cdot \Delta u_{c2}(k_1 - l_{21} - 1) \} \cdot (1 + \eta_1(k_1)) \\ & + sign(k_{11}) \cdot K_{c1} \cdot (e_1(k) - e_1(k - 1)) \end{aligned} \quad (2.29)$$

$$\begin{aligned} \Delta d_2(k_2) = & \{ \alpha_{12} \cdot \Delta d_{12}(k_2 - 1) - \beta_{12} \cdot \Delta u_{c1}(k_2 - l_{12}) + \gamma_{12} \cdot \Delta u_{c1}(k_2 - l_{12} - 1) \} \cdot (1 + \eta_2(k_2)) \\ & + sign(k_{22}) \cdot K_{c2} \cdot (e_2(k) - e_2(k - 1)) \end{aligned} \quad (2.30)$$

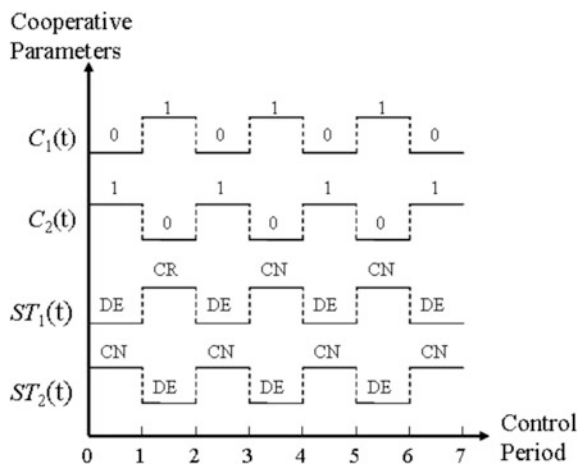
where K_{c1} , K_{c2} are the supplement proportional gains, and their value should be very small.

(4) The cooperative logical control

In order to eliminate the coupling influence, all controllers in a MIMO control system should work cooperatively. In most cases, each control unit not only modulates regularly the control error, but also makes compensation for the coupling influence at the same time. In such case, the decouple control algorithm may be very complicated or difficult to be realized. In order to make the decoupling algorithm be easier or simpler, the IBCDC is designed as follows. In the IBCDC, all the control units cooperatively work during different periods. To eliminate the control error and the coupling influence stably, the CCU can coordinate the work status of control unit 1 and control unit 2, according to the real-time control error information. The detail working sequence of the IBCDC is as shown in Fig. 2.7. In Fig. 2.7, control unit 1 and control unit 2, including the RCB and the DCB, always work in different status during every control period. In other words, when one control unit works normally during a period, the other must keep in decoupling control status at the same time. In Fig. 2.7, $C_1(t)$, $C_2(t)$ is the cooperative logical control signal of control unit 1 and control unit 2 sent from the CCU, and $ST_1(t)$, $ST_2(t)$ indicates the working status of control unit 1 and control unit 2, respectively. The detail working process is explained as follows.

- (1) If $C_1(t) = 0$, control unit 1 is in the decoupling status, and control unit 2 is in the normal work status. At this time, the real-time output of RCB 1 is equal to zero, i.e. $\Delta u_{c1}(t) = 0$, and the decoupling compensation output of DCB 1 is $\Delta d_{21}(t)$. As thus, the final output of control unit 1 is the compensation output of DCB 1, i.e. $\Delta u_1(t) = \Delta d_{21}(t)$. Otherwise, if $C_1(t) = 1$, control unit 1 is in normal control status, and the compensation output is equal to zero, i.e. $\Delta d_{21}(t) = 0$. As thus, the final output of control unit 1 is the original control output of OCB 1, i.e. $\Delta u_1(t) = \Delta u_{c1}(t)$.
- (2) Similarly, if $C_2(t) = 0$, control unit 2 is in decoupling control status. The original output of OCB 2 is equal to zero, i.e. $\Delta u_{c2}(t) = 0$. The output of DCB 2 is the decoupling compensation $\Delta d_{21}(t)$ for control loop 2. The final output

Fig. 2.7 Phase sequence of the IBCDC



of control unit 2 is $\Delta u_2(t) = \Delta d_{c12}(t)$. Otherwise, if $c_2(t) = 1$, control unit 2 is in normal control status, and its output is the original control output of RCB 2, i.e. $\Delta u_2(t) = \Delta u_{c2}(t)$.

With the cooperation of the CCU, control unit 1 and control unit 2 work cooperatively in asynchronous status. During the even control periods, control unit 1 is in normal control status, while control unit 2 is in decoupling control status. Similarly, during the odd control periods, control unit 2 is in normal control status, while control unit 1 is in decoupling control status, as shown in Fig. 2.7, where “CR” and “DE” indicates “control” and “decoupling”, respectively.

(5) Working process of the IBCDC

Before the IBCDC takes into effect, the following pre-tasks must be carried out.

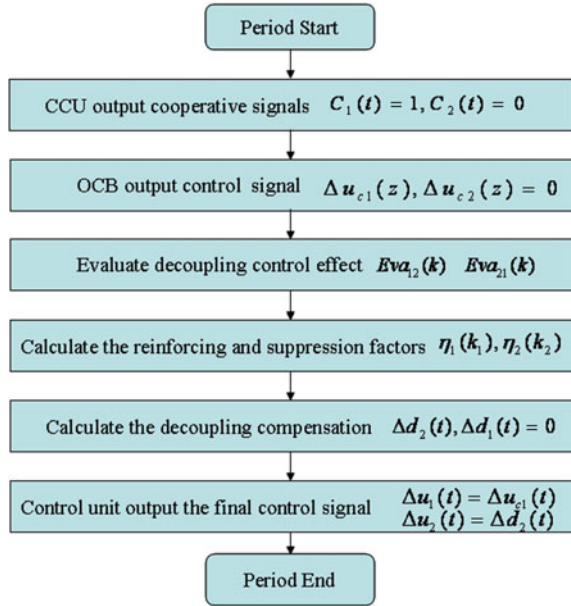
1. Identify the mathematics model $G_{ij}(z)$, ($i, j = 1, 2$) using the step response method.
2. Calculate the decoupling compensation factors α_{12} , β_{12} , γ_{12} , α_{21} , β_{21} , γ_{21} in Eqs. (2.19), (2.20), (2.25), and (2.26).
3. Adjust the reinforcement and suppression parameters α_{12} , α_{21} in Eqs. (2.27) and (2.28).
4. Set the proportional parameters K_{c1} , K_{c2} in Eqs. (2.28) and (2.29).

When the above work is finished, the IBCDC will take into effect. During every control period, the CCU needs to coordinate the work status of control unit 1 and control unit 2 according to the working sequence mentioned in Fig. 2.7. In fact, control unit 1 and control unit 2 work in dual working status during the even or odd control periods. Next, we take the process during the odd periods as an example to introduce the detail working process as follows.

During the odd periods, control unit 1 works in normal control status while control unit 2 is in decoupling status. The detail working process during the odd periods is,

1. The CCU outputs the cooperative control signals $C_1(t) = 1$, $C_2(t) = 0$.
2. The OCB 1 outputs the normal control signal $\Delta u_{c1}(t)$ according to the real-time control error $e_1(t)$. At this time, the output of the OCB 2 keeps unchanged, i.e. $\Delta u_{c2}(t) = 0$.
3. Evaluate the decoupling effect according to Eqs. (2.27) and (2.24).
4. The reinforcing and suppression factors $\eta_1(k_1)$, $\eta_2(k_2)$ are calculated according to Eqs. (2.27) and (2.28).
5. Calculate the decoupling compensation of the DEB 2, $\Delta d_2(t)$, according to Eq. (2.29). At this time, the dynamical changed decoupling compensation is kept zero, i.e. $\Delta d_1(t) = 0$.
- (6) Control unit 1 outputs the final control signal $\Delta u_1(t) = \Delta u_{c1}(t) + \Delta d_1(t) = \Delta u_{c1}(t)$; At this time, control unit 2 only outputs the decoupling compensation signal, i.e. $\Delta u_2(t) = \Delta u_{c2}(t) + \Delta d_2(t) = \Delta d_2(t)$.

Fig. 2.8 The work process during the odd control period



The detail working process (**Algorithm 2.1**) during the odd periods is illustrated in Fig. 2.8. The process during the even periods is similar to that during the odd periods.

2.3.2.4 Stability Analysis on the IBCDC

First, we discuss the stability of the IBCDC during even periods. From Eq. (2.9) we can get the dynamical mathematical model as follows,

$$\begin{bmatrix} \Delta y_1(z) \\ \Delta y_2(z) \end{bmatrix} = \begin{bmatrix} G_{11}(z), G_{21}(z) \\ G_{12}(z), G_{22}(z) \end{bmatrix} \begin{bmatrix} \Delta u_1(z) \\ \Delta u_2(z) \end{bmatrix} \quad (2.31)$$

During the even periods, the original control output of RCB 2 is equal to zero, i.e. $\Delta u_{c2}(z) = 0$. According to work principle of the IBCDC, the output of control unit 1 and control unit 2 can be obtained, i.e. $\Delta u_1(z) = \Delta u_{c1}(z)$, $\Delta u_2(z) = \Delta d_2(z)$. As thus, the following expression holds,

$$\Delta y_1(z) = G_{11}(z)\Delta u_{c1}(z) + G_{21}(z)\Delta d_2(z) \quad (2.32)$$

According to Eqs. (2.12) and (2.30), we get the final expression of $\Delta d_2(z)$ as follows (ignore the proportional action term),

$$\Delta d_2(z) = -\frac{G_{12}(z)}{G_{22}(z)} \cdot \Delta u_{c1}(z) \cdot (1 + \eta_2(z)) = -\frac{G_{12}(z)}{G_{22}(z)} \cdot \Delta u_{c1}(z) \cdot \mu_2(z) \quad (2.33)$$

where $\mu_2(z)$ is equal to $(1 + \eta_2(z))$, and $0 < \mu_2(z) < 2$. Substituting Eq. (2.33) into Eq. (2.32), we get the following expression,

$$\Delta y_1(z) = \frac{G_{11}(z) \cdot G_{22}(z) - G_{21}(z) \cdot G_{12}(z) \cdot \Delta \mu_2(z)}{G_{22}(z)} \cdot \Delta u_{c1}(z) \quad (2.34)$$

Moreover, the original dynamical output of OCB 1 is $\Delta u_{c1}(z) = G_{c1}(z) \cdot \Delta e_1(z)$, and $\Delta e_1(z) = \Delta sp_1(z) - \Delta y_1(z)$. Thus,

$$\Delta u_{c1}(z) = G_{c1}(z) \cdot (\Delta sp_1(z) - \Delta y_1(z)) \quad (2.35)$$

where $\Delta sp_1(z)$ is the dynamical set value change of control loop 1. Substituting Eq. (2.35) into Eq. (2.34), we get the following expression,

$$\Delta y_1(z) = \frac{(G_{11}(z) \cdot G_{22}(z) - G_{21}(z) \cdot G_{12}(z) \cdot \mu_2(z))G_{c1}(z)}{G_{22}(z) + (G_{11}(z) \cdot G_{22}(z) - G_{21}(z) \cdot G_{12}(z) \cdot \mu_2(z))G_{c1}(z)} \cdot \Delta sp_1(z) \quad (2.36)$$

According to **Algorithm 2.1** in Fig. 2.8, the dynamical change output of $y_2(z)$ is equal to zero at this time, i.e. $\Delta y_2(z) = 0$.

In the similar way, during the odd periods the dynamical output of loop 2 is obtained as follows,

$$\Delta y_2(z) = \frac{(G_{11}(z) \cdot G_{22}(z) - G_{21}(z) \cdot G_{12}(z) \cdot \mu_1(z))G_{c2}(z)}{G_{11}(z) + (G_{11}(z) \cdot G_{22}(z) - G_{21}(z) \cdot G_{12}(z) \cdot \mu_1(z))G_{c2}(z)} \cdot \Delta sp_2(z) \quad (2.37)$$

where $\Delta sp_2(z)$ is the dynamical set value change of loop 2, where $\mu_1(z)$ is equal to $(1 + \eta_1(z))$ (where $0 < \mu_1(z) < 2$) and the dynamical output of loop 1 is equal to zero, i.e. $\Delta y_1(z) = 0$.

From Eqs. (2.36) and (2.37), the stability of the IBCDC during the odd and even periods depends on the characteristic roots of its close loop characteristic equation,

$$G_{22}(z) + (G_{11}(z)G_{22}(z) - G_{21}(z)G_{12}(z)\mu_2(z))G_{c1}(z) = 0$$

and

$$G_{11}(z) + (G_{11}(z)G_{22}(z) - G_{21}(z)G_{12}(z)\mu_1(z))G_{c2}(z) = 0.$$

Obviously, it is only when its characteristic root lies in the unit circle that the decoupling control system is stable. As $\mu_1(z)$ and $\mu_2(z)$ are both larger than 0 and

smaller than 2, i.e. $0 < \mu_1(z) < 2$ and $0 < \mu_2(z) < 2$, the stability of the control system is mainly determined by the transfer functions of control unit 1 and control unit 2, i.e. $G_{c1}(z)$, $G_{c2}(z)$, and the process plant model $G_{ij}(z)$, ($i, j = 1, 2$).

Extension to MIMO Systems

The IBCDC and the decoupling control algorithm for TITO systems can be easily extended to MIMO systems. For a MIMO system,

$$\begin{bmatrix} y_1(z) \\ \vdots \\ y_n(z) \end{bmatrix} = \begin{bmatrix} G_{11}(z) & G_{21}(z) & \cdots & G_{n1}(z) \\ & \vdots & & \vdots \\ G_{1n}(z) & G_{2n}(z) & \cdots & G_{nn}(z) \end{bmatrix} \begin{bmatrix} u_1(z) \\ \vdots \\ u_n(z) \end{bmatrix} \quad (2.38)$$

where $y_i(z)$ ($i = 1, 2, \dots, n$) is the output variable; $G_{ij}(z)$ ($i, j = 1, 2, \dots, n$) is the discrete transfer function between the i -th input and the j -th output; $u_i(z)$ ($i = 1, 2, \dots, n$) is the output of the controller. For the decoupling algorithm mentioned above, when regulating the state variable $y_i(z)$, we should ensure that all the values of the dynamics influence of $y_1, y_2, \dots, y_{i-1}, y_{i+1}, \dots, y_n$ are equal to zero. Based on the derived algorithm, the coupling influence can be eliminated by adjusting n actuators harmoniously. The corresponding dynamic decoupling output of every control unit can be derived in the similar way. Moreover, if the mathematical model of the MIMO system is not available, we can also obtain the approximate transfer matrix $G(z)$ via the step-response identification. Then, the decoupling equations can be obtained from the identified mathematical model.

2.3.2.5 Simulation Results

In order to examine the decoupling control effectiveness of the IBCDC, we consider the Wood and Berry's FOPDT transfer function model of a methanol-water distillation column [35]:

$$\begin{bmatrix} y_1(s) \\ y_2(s) \end{bmatrix} = \begin{bmatrix} \frac{12.8e^{-s}}{16.7s+1} & \frac{-18.9e^{-3s}}{21.0s+1} \\ \frac{6.6e^{-7s}}{10.9s+1} & \frac{-19.4e^{-3s}}{14.4s+1} \end{bmatrix} \begin{bmatrix} u_1(s) \\ u_2(s) \end{bmatrix} + \begin{bmatrix} \frac{3.8e^{-8s}}{14.9s+1} \\ \frac{4.9e^{-s}}{13.2s+1} \end{bmatrix} F(s) \quad (2.39)$$

where, y_1 is the mole fraction of methanol at the tops; y_2 is the mole fraction of methanol at the bottoms; u_1 is the reflux flow rate; u_2 is the steam flow rate; and $F(s)$ is the feed flow rate. The system (2.39) is a coupling TITO system with large time delay. The conventional control scheme is that y_1 and y_2 is controlled using PID controller to adjust u_1 and u_2 , respectively. However, there is a violent coupling influence between the control loops.

Following, we control the system (2.39) by the IBCDC in Fig. 2.6, and ignore the feed flow rate $F(s)$. We choose the control unit 1 for y_1 , and the control unit 2

for y_2 . We simulate the actual process field using the mathematical model, and identify the mathematical model via step-response identification method. The identified mathematical model is as follows:

$$\begin{bmatrix} y_1(s) \\ y_2(s) \end{bmatrix} = \begin{bmatrix} \frac{12.6e^{-s}}{16.9s+1} & \frac{-18.7e^{-3s}}{21.1s+1} \\ \frac{6.5e^{-7s}}{10.9s+1} & \frac{-19.6e^{-3s}}{14.5s+1} \end{bmatrix} \begin{bmatrix} u_1(s) \\ u_2(s) \end{bmatrix}$$

Based on the decoupling algorithm discussed in Sect. 2.1.3 and the selected sample time T_s is 0.5 s, the dynamic decoupling output to control y_1 is

$$\begin{cases} \Delta d_{21}(k_{21}) = \{0.9535 \cdot \Delta d_{21}(k_{21} - 1) + 1.1742 \cdot \Delta u_{c2}(k_{21} - 4) + 0.8981 \cdot \Delta u_{c2}(k_{21} - 5)\} \cdot (1 + \eta_{21}) \\ \eta_{21} = Eva_{21}(k) \cdot \frac{abs(e_1(k))}{\alpha_{21} + exp(abs(e_1(k)))} \\ Eva_{21}(k) = \begin{cases} 1 & (sign(dir_{21}(k - l_{11})) \otimes sign(\Delta e_1(k)) = 0) \\ -1 & (sign(dir_{21}(k - l_{11})) \otimes sign(\Delta e_1(k)) = 1) \end{cases} \end{cases} \quad (2.40)$$

where $\alpha_{21} = 0.4$. In the same way, we can also get the dynamic decoupling compensation to control y_2 is,

$$\begin{cases} \Delta d_{12}(k_{12}) = \{0.9123 \cdot \Delta d_{12}(k_{12} - 1) + 0.4494 \cdot \Delta u_{c1}(k_{12} - 8) - 0.41 \cdot \Delta u_{c1}(k_{12} - 9)\} \cdot (1 + \eta_{12}) \\ \eta_{12} = Eva_{12}(k) \cdot \frac{abs(e_2(k))}{\alpha_{12} + exp(abs(e_2(k)))} \\ Eva_{12}(k) = \begin{cases} 1 & (sign(dir_{12}(k - l_{22})) \otimes sign(\Delta e_2(k)) = 0) \\ -1 & (sign(dir_{12}(k - l_{22})) \otimes sign(\Delta e_2(k)) = 1) \end{cases} \end{cases} \quad (2.41)$$

where $\alpha_{12} = 0.5$.

Using the IBCDC, we can obtain the satisfactory control performance for the coupling TITO system with large time delay, as shown in Figs. 2.9 and 2.10.

Fig. 2.9 Comparison of decoupling control effect among the IBCDC, PID and Fuzzy control

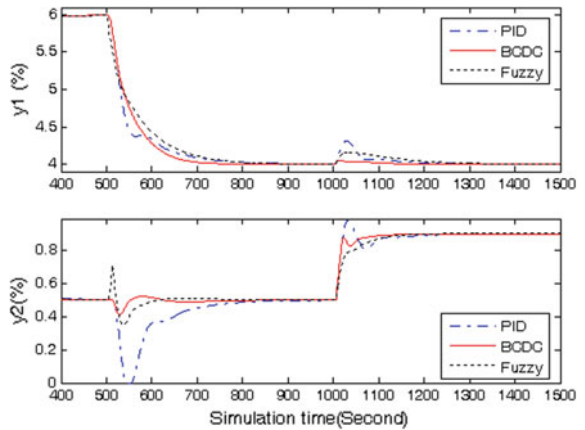
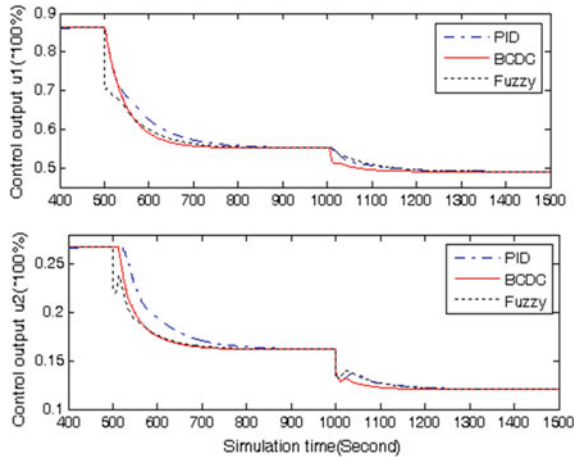


Fig. 2.10 Comparison of control output among the IBCDC, PID and Fuzzy control



We also compare the control effectiveness of the IBCDC with that of the conventional control scheme and fuzzy control algorithm. Here, the conventional PID control algorithm is adopted in control unit 1 and control unit 2. The fuzzy control algorithm is used in the decoupling control unit, and the dynamical change output of original control in every control unit and the dynamical control error of the other loop are selected as fuzzy control variables. In the fuzzy controller, the domains of input and output are both selected as $[-1, 1]$, and triangle function is chosen as fuzzy membership function. In order to conveniently compare the decoupling control effectiveness of different control algorithms, the control parameters of two control units of the IBCDC and the main control unit of the fuzzy controller are set to be same, as shown in Table 2.4.

The comparison of decoupling control effectiveness among the IBCDC, the fuzzy decoupling control and the conventional control is as shown in Fig. 2.9. In Fig. 2.9, when the system is stable, the set value of methanol concentration in the tower top is changed from 6 to 4% at the 250-th second, and the set value of methanol concentration in the tower bottom is changed from 0.5 to 0.9% at the 500-th second. From the coupling effectiveness of the methanol concentration at the tower bottom, we can find that the maximum decoupling error of the IBCDC is 0.093%, while the largest absolute coupling deviations of the fuzzy decoupling control and the

Table 2.4 Decoupling control parameters

Control algorithm	Control parameters	K_p	T_i	T_d
IBCDC	Control unit 1	0.45	5.5	0.08
	Control unit 2	0.35	10.3	0.06
Fuzzy	Control unit 1	0.45	5.5	0.08
	Control unit 2	0.35	10.3	0.06
PID	Loop 1	0.45	5.5	0.08
	Loop 2	0.35	10.3	0.06

Table 2.5 Coupling error in decoupling control process

Time	Term	IBCDC	Fuzzy	PID
250 s	Coupling peak-value of $y_2/\%$	0.407	0.71	0.01
	Absolute coupling error/ $\%$	0.093	0.21	0.49
500 s	Coupling peak-value of $y_1/\%$	4.04	4.16	4.32
	Absolute coupling error/ $\%$	0.04	0.16	0.32

conventional schedule are 0.21 and 0.49%, which are 2.3 times and 5.3 times larger than that of the IBCDC, respectively. In the same way, from the process of the decoupling control for methanol concentration at the tower top at the 500-th second, the maximum absolute coupling deviation of the IBCDC is 0.04%, while the largest absolute coupling deviations of the fuzzy decoupling control and the conventional control are 0.16 and 0.32%, which are 4 times and 8 times than that of the IBCDC at this time, respectively. The detail data is as shown in Table 2.5.

The output comparison of the IBCDC, the fuzzy controller and the conventional controller is as shown in Fig. 2.10. From the figure, we can see that the output of the IBCDC is more stable than that of the other two controllers. Consequently, the IBCDC has much better decoupling control effectiveness than the fuzzy decoupling controller and the conventional controller, according to Figs. 2.9 and 2.10.

2.4 A Neuroendocrine Regulation Based Intelligent Cooperative Decoupling Controller

In this section, an intelligent cooperative decoupling controller (ICDC) and its control scheme are presented based on the neuroendocrine regulation principle of human body, and applied to the coagulation bath of PANCF production. Compared with other decoupling control methods, the ICDC can be implemented more easily and practically but provides better control performance and adaptability. Also, it is the first to discuss the decoupling control method for the control in the coagulation bath of PANCF production, and can be easily extended to other phases of the production line.

2.4.1 Neuroendocrine Regulation Principle in Human Body

The biochemical systems in human body work cooperatively to establish a stable body environment which is critical to the human’s live and behaviors. Among these systems, the neuroendocrine system plays a comparatively more important role in the regulation process of human life [22]. Figure 2.11 illustrates the basic structure of the neuroendocrine system and its working principles.

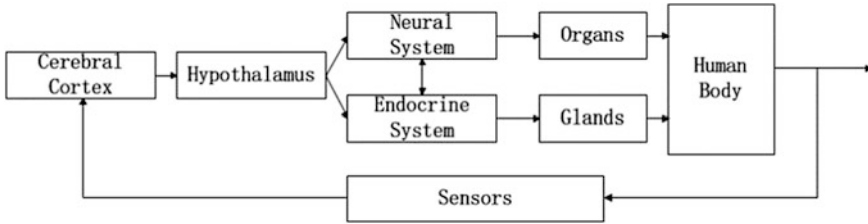


Fig. 2.11 The regulation mechanism of neuroendocrine system in human body

The neuroendocrine regulation system is a large feedback loop consisting of many organs. The core of the system is the cerebral cortex which takes action by secreting hormone to the hypothalamus. The hypothalamus sends instructions to two independent systems, namely, the neural system and endocrine system, respectively. For the neural system, the brain and spinal cord of human body act as the core and the millions of neurons with their varieties forms of connections act as the branches. The signals that the body receives, namely, the stimulations from the environment can be acquired by the neural system and then processed by the brain and spinal cord (in charge of signals of different importance). The instructions sent from the brain and spinal cord are finally transmitted to the corresponding organs to response to the stimulations. For the endocrine system, different types of glands are their actuators, which receive instruction and make regulation for the secretion of hormones. These two systems work independently, but there are some types of cooperation existed between them in order to achieve better control effect.

The structure of such biological system has some similarities with a common control system. The controller, the actuator, the target, and the feedback path in a control system can be replaced by the core (cerebral cortex, hypothalamus, neural system, and endocrine system), the organs and glands, the body, and the sensors, respectively. The principle of working independently with cooperation can also be regarded as the foundation of some decoupling regulation control schemes. Here the only problem left is to extend the origin neuroendocrine system structure from two subsystems to three or more subsystems and this can be done by adding and tuning carefully more interactions among the subsystems, which requires deep analysis on the target control plant.

2.4.2 Design of the ICDC

2.4.2.1 System Structure

Based on the principle of neuroendocrine regulation in human body, the ICDC controller is designed. Figure 2.12 shows the overall system structure of the controller. The whole system consists of four parts, the control center unit (CCU), the

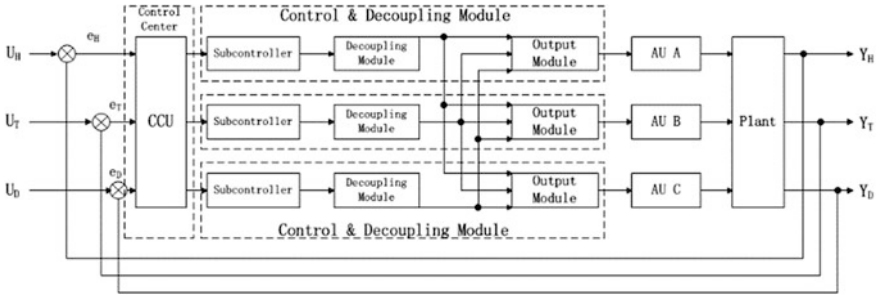


Fig. 2.12 The system structure of the ICDC

control and decoupling unit (CDU), the actuator unit (AU), and the industrial plant to be controlled. These four parts work together according to the principle of the organs in the neuroendocrine regulation system. The CCU includes a control algorithm switching module to determine whether the neuroendocrine decoupling algorithm should be added according to the dynamic plant error, and whether the parameters of the applied CDUs should be tuned. The number of the CDUs in the system is determined by the number of the variables to be controlled (here three CDUs are equipped for the liquid-level, the temperature, and the concentration, respectively). Each CDU consists of a subcontroller module, a decoupling module and an output module. The CDUs take effect independently, but the information of the target plant can be exchanged among them, so the cooperative control scheme can be realized. The AU receives signals from the CDU it connects to and sends them to the plant.

2.4.2.2 The Algorithm of the ICDC Scheme

(1) The PID-DC scheme as a foundation

The whole ICDC scheme consists of two components, namely, a PID decoupling controller (PID-DC) component and a neuroendocrine decoupling component. The PID-DC component is responsible for the basic regulation which also acts as a foundation of the following neuroendocrine decoupling component.

The control plant shown in Fig. 2.12 can be written as follow.

$$\begin{bmatrix} H(s) \\ T(s) \\ D(s) \end{bmatrix} = \frac{1}{Ss + \frac{1}{R}} \begin{bmatrix} \frac{e^{-\tau_1 s}}{h_0} & \frac{e^{-\tau_2 s}}{h_0} & \frac{e^{-\tau_3 s}}{h_0} \\ \frac{T_{DMSO}-T_0}{h_0} e^{-\tau_1 s} & \frac{T_{H_2O,H}-T_0}{h_0} e^{-\tau_2 s} & \frac{T_{H_2O,L}-T_0}{h_0} e^{-\tau_3 s} \\ \frac{D_{DMSO}-D_0}{h_0} e^{-\tau_1 s} & \frac{D_{H_2O,H}-D_0}{h_0} e^{-\tau_2 s} & \frac{D_{H_2O,L}-D_0}{h_0} e^{-\tau_3 s} \end{bmatrix} \begin{bmatrix} U_H(s) \\ U_T(s) \\ U_D(s) \end{bmatrix} \quad (2.42)$$

where the H , T , D are the control outputs, a_{ij} are the corresponding coefficients, U_H , U_D and U_T are the control signals generated by three PID controllers of the PID-DC scheme.

For this plant shown in Eq. (2.42), a state space transformation is applied so that the interrelationship among variables can be expressed by their internal states and therefore observed clearly. Take the first vector H in Eq. (2.42) as an example, it can be achieved by the expression

$$H = H_H + H_T + H_D = (a_{11}U_H + a_{12}U_T + a_{13}U_D) \quad (2.43)$$

where H_H , H_T and H_D are the components of H contributed by the three control signals U_H , U_D and U_T , respectively. It can be observed that the coefficients a_{11} , a_{12} and a_{13} all have the form of the Laplace s -formula, compared with Eq. (2.42). Take the first component H_H for further transformation and its state space expression can be written as

$$\begin{cases} \dot{V}_{11} = A_{11}V_{11} + B_{11}U_H \\ H_H = C_{11}V_{11} \end{cases} \quad (2.44)$$

where V_{11} is the state matrix selected in the subsystem represented by Eq. (2.42), A_{11} is the state matrix, B_{11} is the input matrix, and C_{11} is the output matrix. For a practical industrial system with discrete sampling, Eq. (2.44) can be written as

$$\begin{cases} \Delta V_{11,k} = F_{11}V_{11,k-1} + G_{11}U_{H,k} \\ H_{H,k} = E_{11} + V_{11,k} \\ \quad = E_{11}(V_{11,k-1} + \Delta V_{11,k}) \\ \quad = H_{H,k-1} + E_{11}\Delta V_{11,k}, \quad k = 1, 2, \dots \end{cases} \quad (2.45)$$

where $V_{11,k}$ is the state matrix at the k -th sampling period and $\Delta V_{11,k}$ is its increment. F_{11} , G_{11} and E_{11} are the discrete forms of the matrices A_{11} , B_{11} and C_{11} , respectively. $U_{H,k}$ is the control signal at the k -th sampling period and $H_{H,k}$ is the corresponding output. It is clear that the value of H_H at every sampling period, $H_{H,k}$, can be calculated according to Eq. (2.45) as

$$H_{H,k} = H_{H,k-1} + E_{11}(F_{11}V_{11,k-1} + G_{11}U_{H,k}) \quad (2.46)$$

Note that $U_{H,k}$ is the dynamic output of the PID controller equipped for regulating the variable H in the PID-DC scheme. The value of the variable $H_{H,k}$ can be acquired in Eq. (2.46). Similarly, the other two components of H can also be acquired with the approach above and Eq. (2.43) at the k -th sampling period can be rewritten as

$$\begin{aligned}
H_k &= H_{H,k} + H_{T,k} + H_{D,k} \\
&= [H_{H,k-1} + E_{11}(F_{11}V_{11,k-1} + G_{11}U_{H,k})] \\
&\quad + [H_{T,k-1} + E_{12}(F_{12}V_{12,k-1} + G_{12}U_{T,k})] \\
&\quad + [H_{D,k-1} + E_{13}(F_{13}V_{13,k-1} + G_{13}U_{D,k})]
\end{aligned} \tag{2.47}$$

where E , F and G are the same as those of their ancestors before transformation as shown in Eq. (2.43). The dynamic value of the other two variables in the system represented by Eq. (2.42) can also be calculated with the procedures above. With the PID scheme, the control signals generated by the controllers for the liquid height, temperature and the density at the $k + 1$ -th sampling period can therefore be generated as

$$\begin{cases} U_{H,k+1} = PID(\Delta H_{k+1}, k+1) \\ U_{T,k+1} = PID(\Delta T_{k+1}, k+1) \\ U_{D,k+1} = PID(\Delta D_{k+1}, k+1) \end{cases} \tag{2.48}$$

where

$$\begin{cases} \Delta H_{k+1} = H_k - H_{k-1} \\ \Delta T_{k+1} = T_k - T_{k-1} \\ \Delta D_{k+1} = D_k - D_{k-1} \end{cases} \tag{2.49}$$

and

$$\begin{cases} PID(\Delta H_{k+1}, k+1) = K_{P,H} \times (\Delta H_{k+1} - \Delta H_k) \\ \quad + K_{I,H} \times \Delta H_{k+1} \\ \quad + K_{D,H} \times (\Delta H_{k+1} - 2\Delta H_k + \Delta H_{k-1}) \\ PID(\Delta T_{k+1}, k+1) = K_{P,T} \times (\Delta T_{k+1} - \Delta T_k) \\ \quad + K_{I,T} \times \Delta T_{k+1} \\ \quad + K_{D,T} \times (\Delta T_{k+1} - 2\Delta T_k + \Delta T_{k-1}) \\ PID(\Delta D_{k+1}, k+1) = K_{P,D} \times (\Delta D_{k+1} - \Delta D_k) \\ \quad + K_{I,D} \times \Delta D_{k+1} \\ \quad + K_{D,D} \times (\Delta D_{k+1} - 2\Delta D_k + \Delta D_{k-1}) \end{cases} \tag{2.50}$$

Equation (2.50) can therefore be applied to the plant at the next period. As such, an initial closed-loop control model is established with the PID-DC scheme. This scheme can be used as an instance for comparison with the one embedded with the proposed ICDC scheme which will be discussed next.

(2) The cooperative decoupling in the ICDC

Suppose T , D and H are the variables of the temperature, the concentration, and the liquid-level of a PANCF coagulation respectively, and the coagulation bath model with a MIMO linear expression in Eq. (2.42) under control can be written as

$$\begin{bmatrix} \dot{T} \\ \dot{D} \\ \dot{H} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \begin{bmatrix} T \\ D \\ H \end{bmatrix} + \begin{bmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ b_{31} & b_{32} & b_{33} \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix} = A \begin{bmatrix} T \\ D \\ H \end{bmatrix} + B \begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix} \quad (2.51)$$

where A , B are the matrices of linear coefficients representing by $a_{ij}, b_{ij} (i = 1, 2, 3; j = 1, 2, 3)$, $u_i (i = 1, 2, 3)$ are the output values of control units for each variable, respectively. There are three variables coupling with each other in this model, so the control signal for each variable is therefore composed by three different parts coming from three different control units.

For a dynamic model of the bath, suppose the set point of the temperature is changed, and the corresponding control unit, namely, the CDU for temperature should be regulated so that the actual temperature follows the change of the set point. According to the principle of the controller above, the control signal sent from the CDU for temperature will be also sent to the other two controllers, so the actual signal that each CDU sends to its controlled variable should consist of three parts. One part is the signal received from its own controller and the other two from the other controllers. The combination of the control signals is as follows

$$\begin{cases} u_1 = u_{11} + u_{21} + u_{31} \\ u_2 = u_{12} + u_{22} + u_{32} \\ u_3 = u_{13} + u_{23} + u_{33} \end{cases} \quad (2.52)$$

where $u_{ij} (i = 1, 2, 3; j = 1, 2, 3)$ is the control signals distributed from the i -th CDU that controls one of the three variables (the temperature, the concentration, and the liquid-level) to the j -th CDU, respectively.

On the other hand, the change of temperature should not affect the liquid-level and the concentration of the coagulation bath, or the effects should be kept within a strict range. So the following requirements should be met

$$\begin{cases} \dot{D} = 0 \\ \dot{H} = 0 \end{cases} \quad (2.53)$$

namely,

$$\begin{cases} a_{21}T + a_{22}D + a_{23}H + b_{21}u_1 + b_{22}u_2 + b_{23}u_3 = 0 \\ a_{31}T + a_{32}D + a_{33}H + b_{31}u_1 + b_{32}u_2 + b_{33}u_3 = 0 \end{cases} \quad (2.54)$$

Since the liquid-level and the concentration of the bath are supposed to be kept unchanged, $a_{22}D + a_{23}H$ and $a_{32}D + a_{33}H$ can be regarded as constant, so

$$\begin{cases} a_{21}T + b_{21}u_1 + b_{22}u_2 + b_{23}u_3 = -(a_{22}D + a_{23}H) = C_1 \\ a_{31}T + b_{31}u_1 + b_{32}u_2 + b_{33}u_3 = -(a_{32}D + a_{33}H) = C_2 \end{cases} \quad (2.55)$$

From Eqs. (2.54) and (2.55), it could be acquired that

$$\begin{cases} a_{21}T + b_{21}(u_{11} + u_{21} + u_{31}) + b_{22}(u_{12} + u_{22} + u_{32}) + b_{23}(u_{13} + u_{23} + u_{33}) = C_1 \\ a_{31}T + b_{31}(u_{11} + u_{21} + u_{31}) + b_{32}(u_{12} + u_{22} + u_{32}) + b_{33}(u_{13} + u_{23} + u_{33}) = C_2 \end{cases} \quad (2.56)$$

All the discussions above are based on a continuous system. For a practical system, these control models should be discrete, and the increments of components in Eq. (2.56) should be considered in replace of their full values as below

$$\begin{cases} a_{21}\Delta T + b_{21}\Delta u_{11} + b_{22}\Delta u_{12} + b_{23}\Delta u_{13} = 0 \\ a_{31}\Delta T + b_{31}\Delta u_{11} + b_{32}\Delta u_{12} + b_{33}\Delta u_{13} = 0 \end{cases} \quad (2.57)$$

which can be solved according to the Cramer principle. The values of Δu_{12} and Δu_{13} are the control signals that distribute by the CDU for temperature to the CDUs for liquid-level and concentration to satisfy the requirement that the liquid-level and the concentration should be kept constant. With $\Delta T = \Delta e_T(k) = e_T(k) - e_T(k-1)$, Eq. (2.57) can be solved as

$$\begin{cases} \Delta u_{12} = \frac{a_{31}b_{23} - a_{21}b_{33}}{b_{22}b_{33} - b_{23}b_{32}} \Delta e_T(k) + \frac{b_{23}b_{31} - b_{21}b_{33}}{b_{22}b_{33} - b_{23}b_{32}} \Delta u_{11} \\ \Delta u_{13} = \frac{a_{21}b_{32} - a_{31}b_{22}}{b_{22}b_{33} - b_{23}b_{32}} \Delta e_T(k) + \frac{b_{21}b_{32} - b_{22}b_{31}}{b_{22}b_{33} - b_{23}b_{32}} \Delta u_{11} \end{cases} \quad (2.58)$$

which is the expression of the decoupling signals transferred by the CDU for temperature to the CDUs for liquid-level and concentration. To make the structure of Eq. (2.58) more explicit, the polynomial form of it can be changed to a matrix form as follows

$$\begin{cases} \Delta u_{12} = \frac{-\begin{vmatrix} a_{21} & b_{23} \\ a_{31} & b_{33} \end{vmatrix}}{\begin{vmatrix} b_{22} & b_{23} \\ b_{32} & b_{33} \end{vmatrix}} \Delta e_T(k) + \frac{-\begin{vmatrix} b_{21} & b_{23} \\ b_{31} & b_{33} \end{vmatrix}}{\begin{vmatrix} b_{22} & b_{23} \\ b_{32} & b_{33} \end{vmatrix}} \Delta u_{11} \\ \Delta u_{13} = \frac{-\begin{vmatrix} a_{21} & b_{22} \\ a_{31} & b_{32} \end{vmatrix}}{\begin{vmatrix} b_{22} & b_{23} \\ b_{32} & b_{33} \end{vmatrix}} \Delta e_T(k) + \frac{-\begin{vmatrix} b_{21} & b_{22} \\ b_{31} & b_{32} \end{vmatrix}}{\begin{vmatrix} b_{22} & b_{23} \\ b_{32} & b_{33} \end{vmatrix}} \Delta u_{11} \end{cases} \quad (2.59)$$

Note that each denominator in Eq. (2.59) is identical and let $K_1 = -\begin{vmatrix} b_{22} & b_{23} \\ b_{32} & b_{33} \end{vmatrix}$ Eq. (2.59) can be rewritten as

$$\begin{cases} \Delta u_{12} = \frac{\begin{vmatrix} a_{21} & b_{23} \\ a_{31} & b_{33} \end{vmatrix}}{K_1} \Delta e_T(k) + \frac{\begin{vmatrix} b_{21} & b_{23} \\ b_{31} & b_{33} \end{vmatrix}}{K_1} \Delta u_{11} \\ \Delta u_{13} = \frac{\begin{vmatrix} a_{21} & b_{22} \\ a_{31} & b_{32} \end{vmatrix}}{K_1} \Delta e_T(k) + \frac{\begin{vmatrix} b_{21} & b_{22} \\ b_{31} & b_{32} \end{vmatrix}}{K_1} \Delta u_{11} \end{cases} \quad (2.60)$$

Take the system model in Eq. (2.43) into consideration, it is concluded that the expressions of the incremental decoupling signals can be achieved only by making some modifications on certain rows and columns in the system model without complicated calculations. So the incremental decoupling signals distributed by the CDU for concentration to the other CDUs with the changing of concentration D can be written as

$$\begin{cases} \Delta u_{21} = \frac{\begin{vmatrix} a_{12} & b_{13} \\ a_{32} & b_{33} \end{vmatrix}}{K_2} \Delta e_D(k) + \frac{\begin{vmatrix} b_{12} & b_{13} \\ b_{32} & b_{33} \end{vmatrix}}{K_2} \Delta u_{22} \\ \Delta u_{23} = \frac{\begin{vmatrix} a_{12} & b_{11} \\ a_{32} & b_{31} \end{vmatrix}}{K_2} \Delta e_D(k) + \frac{\begin{vmatrix} b_{12} & b_{11} \\ b_{32} & b_{31} \end{vmatrix}}{K_2} \Delta u_{22} \end{cases} \quad (2.61)$$

where $K_2 = -\begin{vmatrix} b_{11} & b_{13} \\ b_{31} & b_{33} \end{vmatrix}$. Similarly, the incremental decoupling signals with the changing of liquid-level H can be written as

$$\begin{cases} \Delta u_{31} = \frac{\begin{vmatrix} a_{13} & b_{12} \\ a_{23} & b_{22} \end{vmatrix}}{K_3} \Delta e_H(k) + \frac{\begin{vmatrix} b_{13} & b_{12} \\ b_{23} & b_{22} \end{vmatrix}}{K_3} \Delta u_{33} \\ \Delta u_{32} = \frac{\begin{vmatrix} a_{13} & b_{11} \\ a_{23} & b_{21} \end{vmatrix}}{K_3} \Delta e_H(k) + \frac{\begin{vmatrix} b_{13} & b_{11} \\ b_{23} & b_{21} \end{vmatrix}}{K_3} \Delta u_{33} \end{cases} \quad (2.62)$$

where $K_3 = -\begin{vmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{vmatrix}$.

The Eqs. (2.60)–(2.62) are all based on some rank-2 determinants which do not need much calculation, and the corresponding parameters such as $a_{ij}, b_{ij}, K_i (i = 1, 2, 3; j = 1, 2, 3)$ are all fixed when the whole production line is established in practice. Note that the procedures above only provide an increment for the control signal generated by the CDU, which is unlike that of the PID-DC that can generate an independent control signal. So the cooperative decoupling algorithm inspired by the neuroendocrine principle follows the former conventional PID-DC part and acts as an enhancement. Compared to the conventional PID-DC scheme, the proposed ICDC scheme takes the decoupling as its primary control objective, and the aim of the cooperative decoupling algorithm is to restrict the coupling effects to minimum, so it is reasonable to evaluate that the proposed ICDC should acquire better performance than the PID-DC. On the other hand, the Eqs. (2.60)–(2.62) are not just

independent operations but can be regarded as operators embedded in other ordinary control algorithms to take effect, so the original algorithms considering less on decoupling can be changed to those with intelligent decoupling features.

In some special cases, the discussion above may not be applied properly, e.g. some of the components among K_1 , K_2 and K_3 are zero. It means that some variables to be controlled have proportional relations which result in the failure of using the Cramer principle. As a result, the MIMO system degrades to a two-input-two-output (TITO) or even single-input-single-output (SISO) system. For the control system, only the disproportionate variables should be controlled by the cooperative decoupling algorithm referred above, on which the control signals for the other variables can be generated by simply multiplying the corresponding proportional factors.

(3) The overall procedures of the ICDC

The overall procedure of the proposed ICDC is illustrated as the flow diagram in Fig. 2.13. As mentioned above, it consists of two main components, namely, the conventional PID-DC as a foundation and the cooperative decoupling process inspired by the neuroendocrine principle as an enhancement, and a controller parameter switching process is implemented by the CCU before the decoupling module proceeds. The aim of realizing PID-DC in the ICDC is to provide a foundation to the whole controller so that the plant can be tuned to an approximately stable status, and the introduction of the neuroendocrine decoupling module is to make the process with more accuracy and proficiency. A CCU with a parameter reconfiguring scheme makes such decision by collecting the dynamic errors of variables under control and then determining whether the error is large enough so that the parameters of the controller should be reconfigured. A CCU without such a mechanism, however, is also acceptable, which means the function of such CCU is just collecting errors and transferring them to the CDUs. The strategy on how and when the neuroendocrine decoupling algorithm should take effect also depends on the instructions of the CCU, and the dynamic error is still the main criteria for selecting different decoupling strategies. With these procedures, the final control signal can be generated by

$$u_{final} = \begin{cases} u_{conv} + \Delta u_{idc}, & \text{if } e_k \geq e_{threshold} \\ u_{conv}, & \text{if } e_k < e_{threshold} \end{cases} \quad (2.63)$$

where u_{final} is the final control signal possibly synthesized by the output of PID-DC component and the cooperative decoupling component, or only that of the PID-DC component. u_{conv} is the output of the conventional PID-DC component, Δu_{idc} is the output of the cooperative decoupling component (the symbol Δ as a prefix means it is an increment), e_k is the real-time plant error and $e_{threshold}$ is the predefined switching threshold.

With Eq. (2.63) the CCU can make a selection between an individual PID-DC scheme and an integrated PID-DC and cooperative decoupling scheme. As a result, the rapidness and accuracy of the whole control system can be guaranteed by

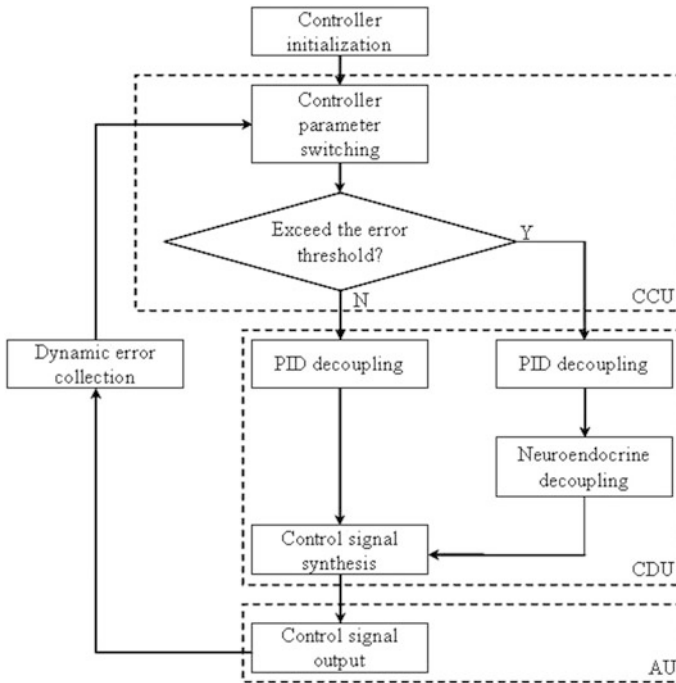


Fig. 2.13 Flow diagram of the overall procedure of the ICDC

introducing the proposed ICDC when the error is large, and the stability of it can also be maintained by only applying a single PID-DC when the error is small or zero so that the vibration possibly brought by the powerful regulation of the ICDC can be diminished. Next, each CDU receives the switching instructions from the CCU and generates the corresponding control signals, then sends it to the plant it takes responsibility for. The dynamic output of the plant are collected by sensors and then transferred to the CCU and each CDU, which guides them to make switching judgment or generate decoupling and control signals.

2.4.3 Verification and Results

The manufacture of PANCF includes a series of processes with high complexity such as polymerization, spun extrusion, coagulation, washing, stretching, pre-oxidation, carbonization and post treatment, etc. [38, 39]. The aim for utilizing such processes is to create excellent carbon fibers with high strength and elastic modulus. Nevertheless, these processes with different work conditions are closely connected, and the devices applied for each process have various mechanical and control characteristics [40]. The nature of the raw materials (mainly the PAN) also

vary within these processes and thus cannot be treated as stable during the whole production, and the coupling and lag existing in and between processes also bring challenge to the utilization of good control schemes.

The coagulation process of the PAN as-spun fiber in the water bath is one of the key processes during the whole carbon fiber production. The PAN solvent is firstly extruded out of the spinneret at a certain velocity, formed tiny streams and then submerged into a water bath slot that contains the coagulation solution of a certain concentration. The PAN streams there exchange components with the coagulation bath solution, and some components of the coagulation bath solution also infiltrate into the streams which is called double-diffusion [41, 42]. During this period, the streams start to coagulate and form the as-spun fibers that can be dragged to the following process. The quality of the as-spun fiber, which is mostly determined by the parameters of the coagulation bath, has great impact on the final performance of the PANCF. These parameters including temperature, concentration, and liquid-level of the bath have strong links which cannot be tuned independently and satisfactorily.

As to the control of the coagulation bath, a traditional scheme is to establish independent control units with conventional PID controllers for the variables, respectively [43]. The closed loop control model can therefore be established to each individual process several times for there are many variables to be controlled in the coagulation bath. Another practice is the cascade control system for some important parameters which are selected from the whole variables set while keeping others omitted [44, 45]. In some special cases (e.g. the educational and research scenarios), even the open-loop scheme can be applied for each variable by making the values of variables stable with the aid of auxiliary devices, e.g. a heating devices to regulate the temperature manually [46]. For the PANCF production, all the control strategies above do not take the interrelation and coupling among variables into consideration, which cannot guarantee the persistent stabilization of the coagulation bath. Consequently, the PAN precursor fibers produced by such systems can not enjoy a high quality. Another side of such issue is that some schemes or algorithms dealing with plant decoupling have been proposed but not applied to the PAN production process yet due to its special characteristics and complex decoupling relations among variables [47].

2.4.3.1 Modeling of the Coagulation Bath in PANCF Production

The coagulation system in the whole PANCF production line consists of two slots, a bath solution preparation slot and a coagulation slot. The main ingredients in the coagulation solution are dimethylsulfoxide (DMSO) and water (other trace components can be ignored). The coagulation solution is firstly made in the preparation slot by mixing three different kinds of solutions (including cold water, hot water, and high concentration DMSO solution) coming from three independent ports on the preparation slot, and then transferred to the coagulation slot for formal use. Through such two-step process, the fluctuation in the solution mixing can be eliminated,

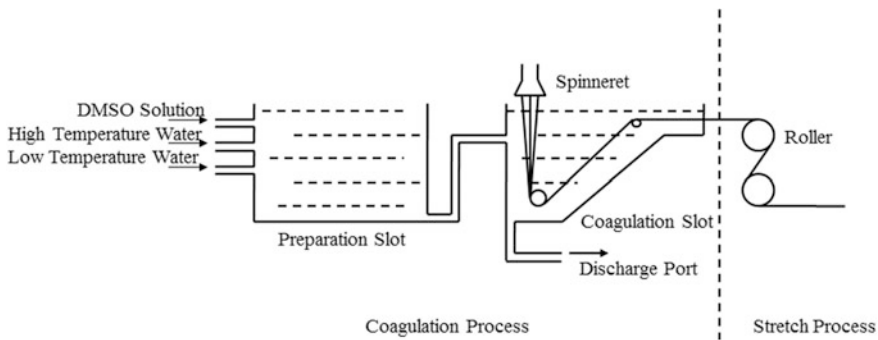


Fig. 2.14 The coagulation bath in PANCF production

which is beneficial to the stability of the coagulation. The shape of the preparation slot is supposed to be a standard cube. The coagulation slot is equipped with a discharge port, from which some solution can be discharged when the volume of the coagulation solution is more than required, and the discharged solution can be recycled for coagulation again. Figure 2.14 shows the main structure of the coagulation bath slot and the ports on it. There are many variables to be controlled in the coagulation bath of the PANCF production, and the liquid-level, the temperature, and the concentration of the bath play essential roles. However, these main variables often take effect together, namely, coupling with each other. It is the main challenge for the design of a control system for the coagulation bath. Meanwhile, other minor parameters may also affect the overall status of the bath. To simplify the problem discussed, three main variables of the coagulation bath referred above are selected as the main targets, and then its mathematic model is established.

(1) Regulation of the liquid-level

The relation between the liquid-level of the coagulation bath and the volume of solution components coming from each entrance port can be written as

$$S \frac{dh}{dt} + K \frac{h}{R} = V_{DMSO} + V_{H_2O,H} + V_{H_2O,L} \quad (2.64)$$

where S denotes the area of the slot bottom; h is the real-time liquid-level; R is the hydraulic resistance of the discharge port; K is the conversion factor (usually fixed to 1); V_{DMSO} , $V_{H_2O,H}$, and $V_{H_2O,L}$ are the volumes of the high concentration DMSO solution, the hot water and the cool water, respectively.

The stable state of the coagulation system can be expressed by the following equation

$$Sh_0 \frac{dD}{dt} = V_{DMSO}(D_{DMSO} - D) + V_{H_2O,H}(D_{H_2O,H} - D) + V_{H_2O,L}(D_{H_2O,L} - D) \quad (2.65)$$

where h_0 denotes the liquid-level at the stable state; $V_{0,DMSO}$, $V_{0,H_2O,H}$, and $V_{0,H_2O,L}$ are the volumes of the high concentration DMSO solution, the hot water, and the cool water, respectively; D_{DMSO} , $D_{H_2O,H}$, and $D_{H_2O,L}$ are the concentration values of the DMSO solution, the hot water, and the cool water, respectively (the solute in either kind of water is also DMSO, so $D_{H_2O,H} \approx 0$ and $D_{H_2O,L} \approx 0$). D_0 is the steady value of the concentration of the bath with a dynamic changing value labeled ΔD_0 . The Laplace transformation can be utilized to Eq. (2.65) and get the regulation model for the liquid-level of the coagulation bath as follows

$$H(s) = \frac{V_{DMSO}(s) + V_{H_2O,H}(s) + V_{H_2O,L}(s)}{Ss + \frac{K}{R}} \quad (2.66)$$

(2) Regulation of the temperature

Similar to the model for the liquid-level, the relation between the temperature and other variables of the coagulation bath are given by the equation as below

$$Sh_0 \frac{dT}{dt} = V'_{DMSO}(T_{DMSO} - T) + V'_{H_2O,H}(T_{H_2O,H} - T) + V'_{H_2O,L}(T_{H_2O,L} - T) \quad (2.67)$$

where

$$\begin{aligned} V'_{DMSO} &= V_{0,DMSO} + \Delta V_{0,DMSO} \\ V'_{H_2O,H} &= V_{0,H_2O,H} + \Delta V_{0,H_2O,H} \\ V'_{H_2O,L} &= V_{0,H_2O,L} + \Delta V_{0,H_2O,L} \\ T &= T_0 + \Delta T \end{aligned} \quad (2.68)$$

Here T_{DMSO} , $T_{H_2O,H}$, and $T_{H_2O,L}$ are temperatures of the high concentration DMSO solution, the hot water and the cool water, respectively; T_0 is the started-state value of the bath temperature with ΔT_0 as its transient change. As the coagulation bath becomes stable, its liquid-level keeps unchanged, so does the temperature. Here

$$\frac{h_0}{R} = V_{DMSO} + V_{H_2O,H} + V_{H_2O,L} \quad (2.69)$$

$$V_{0,DMSO}(T_{DMSO} - T_0) + V_{0,H_2O,H}(T_{H_2O} - T_0) + V_{0,H_2O,L}(T_{H_2O} - T_0) = 0$$

where the specific heat capacities of each kind of solution has been reduced as a common fraction. Take Eqs. (2.68) and (2.69) into consideration and then the regulation model for the temperature of the coagulation bath can be acquired as follows

$$T(s) = \frac{V_{DMSO}(s)(T_{DMSO} - T_0) + V_{H_2O,H}(s)(T_{H_2O,H} - T_0) + V_{H_2O,L}(s)(T_{H_2O,L} - T_0)}{Sh_0s + \frac{h_0}{R}} \quad (2.70)$$

(3) Regulation of the concentration

The principle for deducing the temperature model of the coagulation bath can be followed here to achieve the concentration model, in which the main idea is keeping the balance among different solutes. At the steady-state point of the dynamic regulating process for the coagulation bath, the DMSO also becomes stable, namely, the concentration of the bath solution is balanced (with minor fluctuations dynamically). Note that the double-diffusion process between the as-spun fibers and the bath solution keeps on running and can certainly bring extra DMSO. But such process has also reached its balance point when the system becomes stable. So the DMSO coming from the fibers to the bath is as much as that coming from the bath to the as-spun fibers, and the DMSO brought by such process can therefore be ignored. Here

$$V_{0,DMSO}(D_{DMSO} - D_0) + V_{0,H_2O,H}(D_{H_2O,H} - D_0) + V_{0,H_2O,L}(D_{H_2O,L} - D_0) = 0 \quad (2.71)$$

Referring to the deduction for the temperature above, the mathematical model for regulating the concentration of the coagulation bath can be generalized as follows

$$D(s) = \frac{V_{DMSO}(S)(D_{DMSO} - D_0) + V_{H_2O,H}(D_{H_2O,H} - D_0) + V_{H_2O,L}(D_{H_2O,L} - D_0)}{Sh_0s + \frac{h_0}{R}} \quad (2.72)$$

where D_0 denotes the set point of the concentration determined by the production specification.

(4) Comprehensive regulation model

In the sections above, the three main variables of the coagulation bath, the liquid-level, the temperature, and the concentration, have been described by a series of mathematical models (2.66), (2.70) and (2.72), respectively. So a comprehensive model of the coagulation bath for further regulation may have the form as below

$$\begin{bmatrix} H(s) \\ T(s) \\ D(s) \end{bmatrix} = \frac{1}{Ss + \frac{1}{R}} \begin{bmatrix} \frac{1}{\frac{T_{DMSO}-T_0}{h_0}} & \frac{1}{\frac{T_{H_2O,H}-T_0}{h_0}} & \frac{1}{\frac{T_{H_2O,L}-T_0}{h_0}} \\ \frac{D_{DMSO}-D_0}{h_0} & \frac{D_{H_2O,H}-D_0}{h_0} & \frac{D_{H_2O,L}-D_0}{h_0} \end{bmatrix} \begin{bmatrix} U_H(s) \\ U_T(s) \\ U_D(s) \end{bmatrix} \quad (2.73)$$

However, many processes in the practical manufacturing line require extra time to response for the regulations to take effect which results in some modifications on the model above (by adding some lag coefficients), so

$$\begin{bmatrix} H(s) \\ T(s) \\ D(s) \end{bmatrix} = \frac{1}{Ss + \frac{1}{R}} \begin{bmatrix} \frac{e^{-\tau_1 s}}{h_0} & \frac{e^{-\tau_2 s}}{h_0} & \frac{e^{-\tau_3 s}}{h_0} \\ \frac{T_{DMSO} - T_0}{h_0} e^{-\tau_1 s} & \frac{T_{H_2O,H} - T_0}{h_0} e^{-\tau_2 s} & \frac{T_{H_2O,L} - T_0}{h_0} e^{-\tau_3 s} \\ \frac{D_{DMSO} - D_0}{h_0} e^{-\tau_1 s} & \frac{D_{H_2O,H} - D_0}{h_0} e^{-\tau_2 s} & \frac{D_{H_2O,L} - D_0}{h_0} e^{-\tau_3 s} \end{bmatrix} \begin{bmatrix} U_H(s) \\ U_T(s) \\ U_D(s) \end{bmatrix} \quad (2.74)$$

where τ_1 , τ_2 and τ_3 are the lag coefficients in the regulation of the liquid-level, the temperature, and the concentration, respectively.

The coagulation bath can be regarded as a MIMO system with the coupling effects of the liquid-level, the temperature, and the solution concentration. According to the principle of the neuroendocrine cooperative regulation in the human body, the ICDC can be designed to meet the requirement of perfectly controlling the bath status and eliminating the coupling among variables.

A coagulation bath model as shown in Fig. 2.14 is applied here to verify the effectiveness of the ICDC above. The coagulation bath contains three entrance ports that are responsible for separately transmitting different solutions (hot/cold water and high concentration DMSO solution) and an exit port that connects directly to the entrance port of the bath slot. The proposed ICDC can be applied to conduct regulation to the bath slot. Here, Eq. (2.42) is extended by Eq. (2.74), and its parameters (the parameters of the preparation slot with the initial conditions of the coagulation system) are list in Table 2.6.

Note that the concentrations of the water, both hot and cold, are set to 0.001 instead of pure zero due to the actual circumstance that the DMSO exists as one kind of impurities in the water.

The control model for the coagulation bath with the actual system parameters in Table 1 substituted can be written as

Table 2.6 Slot Parameters and initial conditions of the coagulation system

Slot parameters		Initial conditions	
Parameter	Value	Parameter	Value
S/m^2	0.15	$T_{DMSO}/^\circ C$	30
R	0.1	$T_{H_2O,H}/^\circ C$	65
h_0/m	1	$T_{H_2O,L}/^\circ C$	10
τ_1/s	1	$T_0/^\circ C$	15
τ_2/s	2	$D_{DMSO}/\%$	80
τ_3/s	5	$D_{H_2O,H}/\%$	0.001
		$D_{H_2O,L}/\%$	0.001
		$D_0/\%$	0.65

$$\begin{bmatrix} H(s) \\ T(s) \\ D(s) \end{bmatrix} = \frac{1}{0.15s + 1} \begin{bmatrix} e^{-s} & e^{-2s} & e^{-5s} \\ 150e^{-s} & 500e^{-2s} & -50e^{-5s} \\ 1.5e^{-s} & -6.49e^{-5s} & -6.49e^{-5s} \end{bmatrix} \begin{bmatrix} U_H(s) \\ U_T(s) \\ U_D(s) \end{bmatrix} \quad (2.74)$$

where the lag coefficients of the temperature, the liquid-level, and the concentration are 1 s, 2 s and 5 s, respectively.

The ICDC is then applied to this target with conventional PID algorithm as the main control scheme of each CDU, but the parameters of the PID algorithm are fixed or dynamically changed according to the instructions of the CCU, and these two plans with their performances are simulated separately in the following experiments. The initial set point for the temperature is 15 °C. For the liquid-level and concentration, the set points are 0.1 m and 65%, respectively. A conventional PID-DC scheme mentioned in Sect. 2.3 for the coagulation bath is applied for comparison, and the initial PID parameters and the error thresholds for scheme switching applied in both the PID-DC and the ICDC schemes are listed in Table 2.7 (Both the schemes include three controllers, so each of them has three sets of PID parameters.). All the simulation processes are carried on with MATLAB R2009a on a workstation computer with a dual-core processor and 2 GB memory.

As the coagulation bath is a complex coupling object, the simulations should reach some requirements as follows.

- (1) The other two variables should not be influenced when one variable is regulated independently.
- (2) Each variable should not be influenced by other variables when these variables are regulated together.

Table 2.7 Initial PID parameters in the PID-DC and the ICDC schemes

	PID-DC	ICDC	$e_{threshold}$
Liquid-level			
P	0.6	0.6	$10\% \times H_{ref}^a$
I	5×10^{-2}	5×10^{-2}	
D	5×10^{-2}	5×10^{-2}	
Temperature			
P	10^{-3}	10^{-3}	$10\% \times T_{ref}^b$
I	5×10^{-4}	5×10^{-4}	
D	0	0	
Concentration			
P	5×10^{-2}	5×10^{-2}	$10\% \times D_{ref}^c$
I	10^{-2}	10^{-2}	
D	0	0	

Simulation with Fixed Parameters

To reach the goals below, a series of simulations consisting of two phases are designed to demonstrate the performance of the proposed ICDC, and the parameters for the controllers in both the PID-DC and the ICDC are fixed, as shown in Table 2.7.

a , b , c : The symbol H_{ref} , T_{ref} and C_{ref} are the references of the liquid-level, the temperature and the concentration, respectively. Note that there are several possible reference values for a single variant for simulation.

Phase I: Individual Regulation

Given that the total simulation time occupies 100 sampling periods (here one sampling period in simulation can be regarded as one second in practice, and a same configuration is also applied in the Phase II below). The system is firstly regulated from all-zero to a stable status with the initial set points of the three variables, then the set points of the liquid-level, the temperature and the concentration are changed to another value at the 20-th, 40-th and 60-th sampling period, respectively. That is to say, the simulation of this phase should be carried out three times and the variables should be changed each time one by one, while the others keep unchanged. The set point of temperature is supposed to change to 30 °C, and for the liquid-level and concentration the corresponding values are 0.2 m and 75%. The purpose of Phase I is to verify the effectiveness of the proposed ICDC against the variation occurred on each individual variable and the ability of the unaffected variables for not being disturbed by the deliberately changed variable.

Phase II: Integrated Regulation

Given the total simulation time occupies 100 sampling periods. As in Phase I, the system is also stable when the regulation begins. Then the set points of the liquid-level, the temperature and the concentration are changed to another value at the 20-th, 40-th and 60-th sampling period, respectively. At the 20-th sampling period, the set point of the liquid-level is firstly changed to 0.2 m, then followed by the changes for the temperature (to 30 °C) and the concentration (to 75%) at the 40-th and the 60-th sampling period. These steps in this phase are to verify the ability of the coagulation system with the proposed ICDC for dealing with concurrent regulations of all the variables.

The simulations above are carried out by applying large modifications to the set points of variables so that the effects of the proposed ICDC can be shown explicitly. However, such large changes cannot be tolerated in the practical production process. On most occasions, the status of the coagulation bath may only encounter tiny fluctuations, so the controller applied should be less sensitive to these fluctuations to maintain the overall state of the coagulation bath stable. Thus, the simulation for this condition should also be conducted to emulate the practical production. At the last part of the simulation, some small modifications are made to the set point of each variable, namely, changing the liquid-level from 0.1 m up to 0.12 m, the temperature from 15 °C up to 17 °C, and the concentration from 65% down to 60%.

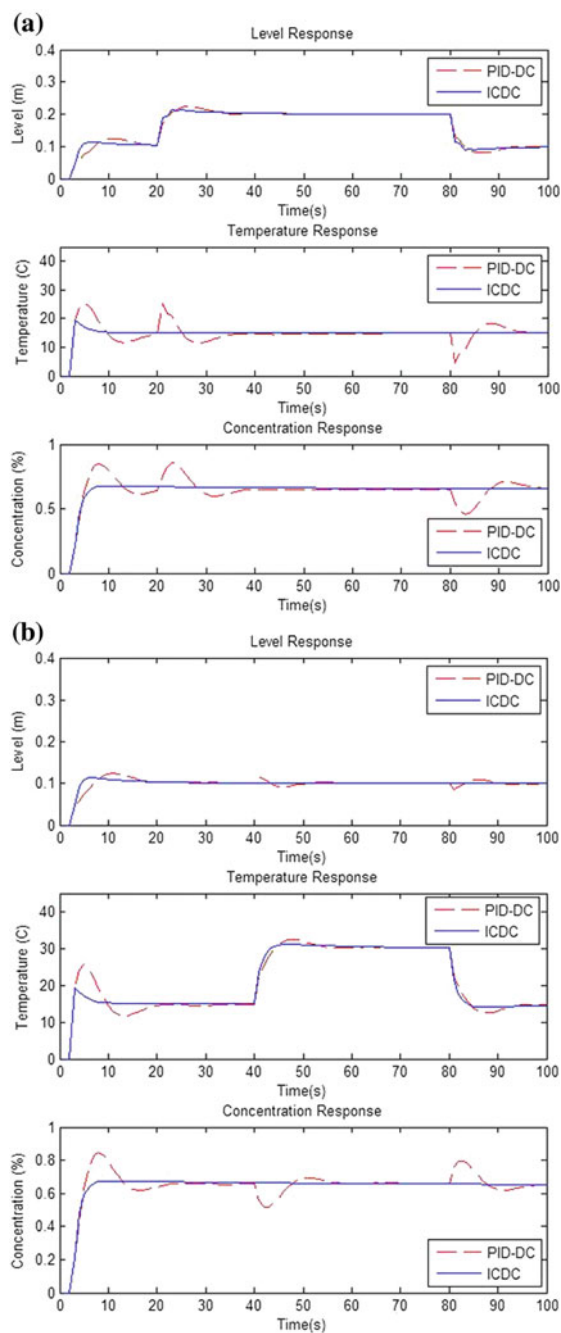
At the 80-th sampling period, all the variables are tuned to their origin values, namely, 0.1 m for the liquid-level, 15 °C for the temperature, and 65% for the concentration. The aim of doing so is to verify whether the system has the ability to return to its normal working status after a period of fluctuation.

Figure 2.15 shows the comparison between the PID-DC and the ICDC when an individual variable is regulated while the others are kept stable (Phase I). Figure 2.16 shows the performance of the two types of controllers for the integrated regulation (Phase II) and Fig. 2.17 is the performance of the ICDC against the PID-DC with practical modifications. Table 2.8 shows comparison of the performance between the ICDC and the PID-DC. The percent overshoot and the settling time at the beginning of the whole control process are calculated to evaluate the swiftness of the two types of decoupling controllers. The overshoot and settling time when the disturbance (means the set point modifications here) occurs are also collected to evaluate the robustness of the controllers. The simulation results show that the PID-DC is very sensitive toward the changes of the set points. The value of one variable to be controlled fluctuates much when another variable is changing, which means the decoupling between the two variables cannot be eliminated satisfactorily. Although the variables controlled by the PID-DC can finally reach to their set points, the regulating time elapsed is too long to be accepted in practice. Such phenomenon does not appear when the proposed ICDC is applied. The fluctuation of one variable can be restricted to a small scale when another variable is modified. Besides, the ICDC can guarantee the smooth regulation without overshoot, which is essential to the PANCF production process with high precision. That's because the parameters of the ICDC change dynamically according to the instruction of the CCU. Such mechanism can help the status of the product line switch from one state to another one smoothly without much fluctuation, which is benefit to reduce the amount of substandard PANCF.

2.4.3.2 Simulation with Variable Parameters

The simulation with variable controller parameters is conducted here to test the function of the CCU and its performance in the ICDC. Two schemes are available for the CCU, namely, the Scheme A for selecting controller parameters from a predefined set with multiple parameter configurations and the Scheme B for making them fluctuating with the dynamic response according to some rules. For Scheme A, three groups of controller parameters are predefined and take actions according to the dynamic error intensity. Table 2.9 provides the parameters for each level of controller parameters. For Scheme B, an original group of parameters is provided to the controllers, which can fluctuate with the dynamic error intensity by a certain percentage, and the details of such scheme are provided in Table 2.10. The switching strategies for the parameter tuning are determined according to the nature of the coagulation bath as the plant, and the changes on parameters, if necessary, should be built on a smooth and incremental basis. The conditions fortuning the parameters, namely, the ranges of error in Table 2.10 are determined by the

Fig. 2.15 Performance of the PID-DC and the ICDC for individual regulation of variables. **a** Effect of liquid level change on coagulation bath system. **b** Effect of temperature change on coagulation bath system. **c** Effect of concentration change on coagulation bath system



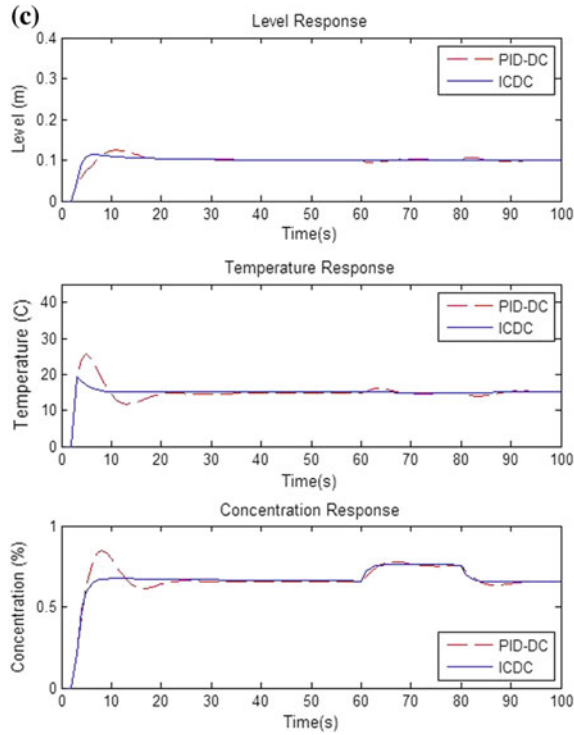
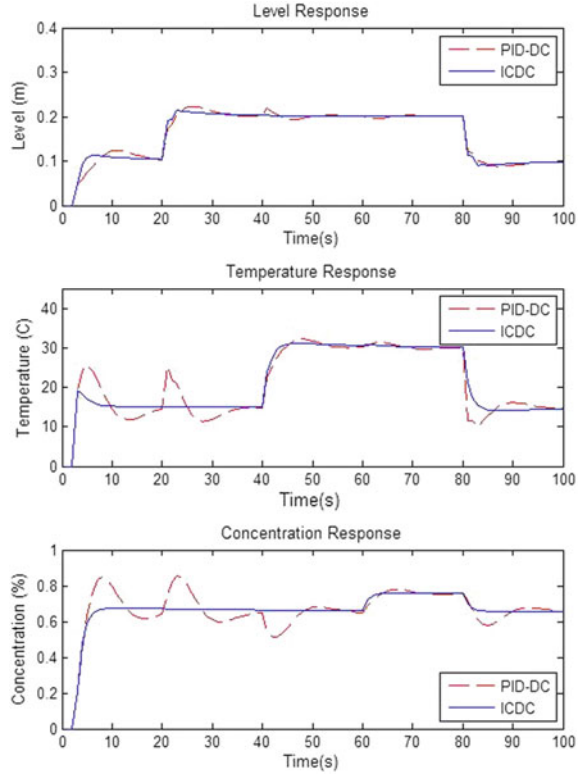


Fig. 2.15 (continued)

experimental simulations. It should be noted that all the parameters cannot be set below zero or it would go against the laws for the physical devices. The simulation procedures under the practical circumstance mentioned in Sect. 4.1 are carried out, and the system responses and the corresponding switching procedures of controller parameters are then recorded. The PID-DC is also taken as a comparison and its parameters are changed according to the rules listed in Table 2.10. Figures 2.18 and 2.19 are the responses of the coagulation bath model with the PID-DC and the ICDC enhanced by Scheme A and Scheme B, respectively. Figures 2.20 and 2.21 represent the switching processes of the controller sets (for Scheme A) or parameters (for Scheme B), respectively. For the PID-DC with Scheme A, the responses of liquid level, temperature and concentration all fluctuate at the beginning as the results of rapid changing of parameter sets, which can be observed in Fig. 2.18. The regulating time is therefore extended accordingly. Similar phenomenon can also be noticed in the system with the ICDC, but only happens during the regulation of temperature. Taken the parameters shown in Table 2.8 into consideration, it can be deduced that a selection of smaller parameters applied to the controller of temperature are more sensitive against changes, and the target variables, consequently, would vibrate more than those with larger parameters. It also can be observed that

Fig. 2.16 Performance of the PID-DC and the ICDC for comprehensive regulation of variables



the switching process of the ICDC with Scheme A is simpler than that of the PID-DC which means the enhancement brought by the neuroendocrine-inspired decoupling scheme has the ability to compensate the performance for a controller that may not be tuned well by other schemes. For the control system with Scheme B, the corresponding responses are much more like those with the fixed parameters, as shown in Fig. 2.17, and the fluctuations are smaller than those with Scheme A-embedded plans. But the overshoot of some variables, e.g. the temperature and concentration, can still not be neglected (e.g., the value of temperature at 4 s in Fig. 2.19 is over 20, while its correspondence in Fig. 2.17 is not more than 20), and the changes of the references may also lead to minor vibrations. Such simulation results demonstrate that the ICDC with dynamic parameters has better performance than the conventional PID-DC schemes.

$$a : e_{percent} = \frac{(actual\ output - reference)}{reference}.$$

Fig. 2.17 Performance of the PID-DC and the ICDC for comprehensive regulation of variables

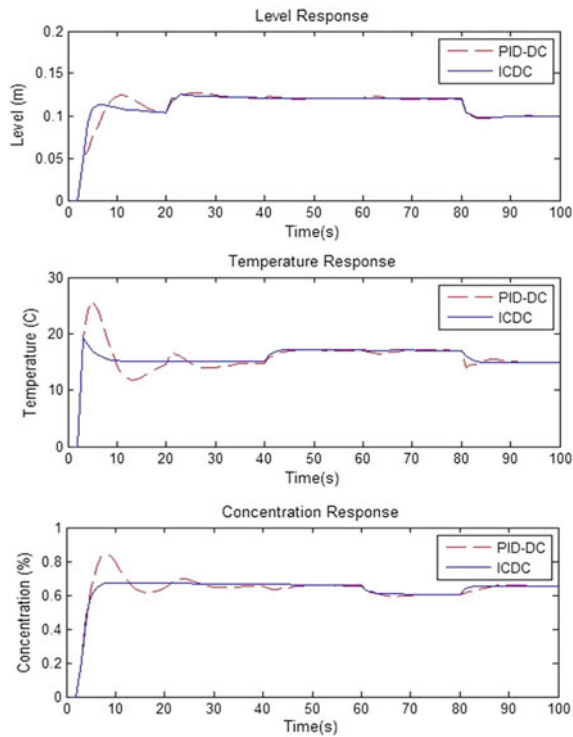


Table 2.8 Numerical performance of the ICDC against the PID-DC with practical parameters applied

	Liquid-level		Temperature		Concentration	
	PID-DC	ICDC	PID-DC	ICDC	PID-DC	ICDC
Initial overshoot/%	39.2	9.8	78.2	38.5	35.1	0
Settling time/s	27	15	31	7	27	6
Disturbance overshoot/%	1.9	0	13.7	0	10.4	0
Recover time/s	15	0	14	0	22	0

2.5 Conclusions

In this chapter, we presented the bio-intelligent cooperative decoupling controller BDC, IBCDC and ICDC for complex coupling systems. The BDC is based on the bi-regulation principle of the GH, the IBCDC is inspired from the modulation mechanism of internal environment in body, and the ICDC is inspired by the neuroendocrine regulation principle of human body.

Table 2.9 Controller parameters for fixed groups switching

Group no.	1	2	3
Conditions	$ e_{percent} \leq 0.2^a$	$0.2 < e_{percent} \leq 0.5$	$ e_{percent} > 0.5$
Controller for liquid-level			
P	0.6	0.9	1.1
I	5×10^{-2}	7×10^{-2}	9×10^{-2}
D	5×10^{-2}	6×10^{-2}	7×10^{-2}
Controller for temperature			
P	10^{-3}	1.5×10^{-3}	2×10^{-3}
I	5×10^{-4}	5.5×10^{-5}	6×10^{-5}
D	0	0	0
Controller for concentration			
P	5×10^{-2}	7×10^{-2}	9×10^{-2}
I	10^{-2}	3×10^{-2}	5×10^{-2}
D	0	0	0

Table 2.10 Controller parameters for incremental switching

Conditions	Controller for liquid-level	Controller for temperature	Controller for concentration
Original			
P	0.6	10^{-3}	5×10^{-2}
I	5×10^{-2}	5×10^{-4}	10^{-2}
D	5×10^{-2}	0	0
$ e_{percent} \leq 0.2$			
P	No operation		
I			
D			
$0.2 < e_{percent} \leq 0.5$			
P	Decrease by 5% based on the values of the last sampling period		
I			
D			
$ e_{percent} > 0.5$			
P	Increase by 5% based on the values of the last sampling period		
I			
D			

Fig. 2.18 Responses with fixed parameter groups switching

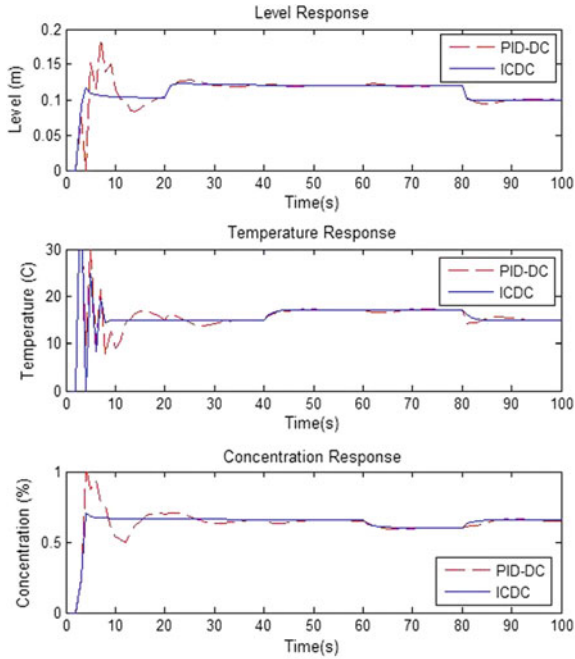


Fig. 2.19 Responses with parameter incremental switching

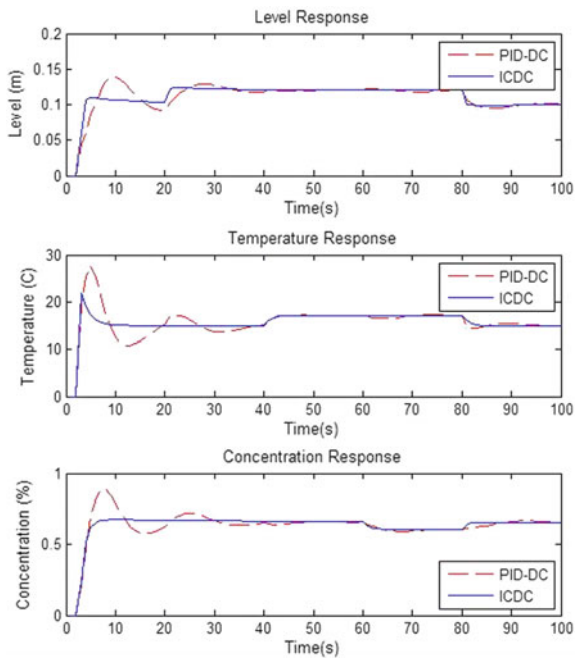


Fig. 2.20 Switching processes of fixed parameter groups

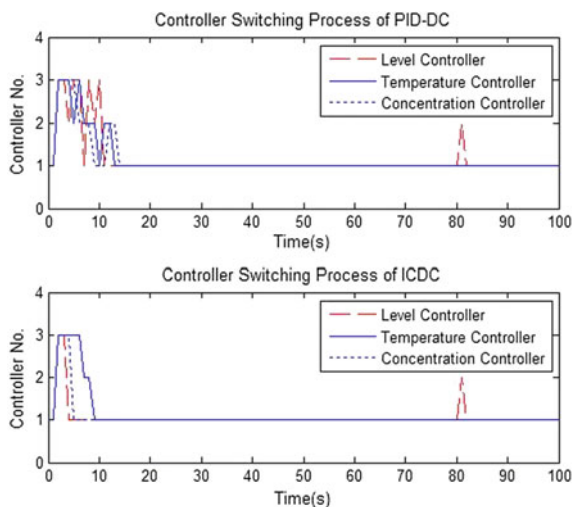
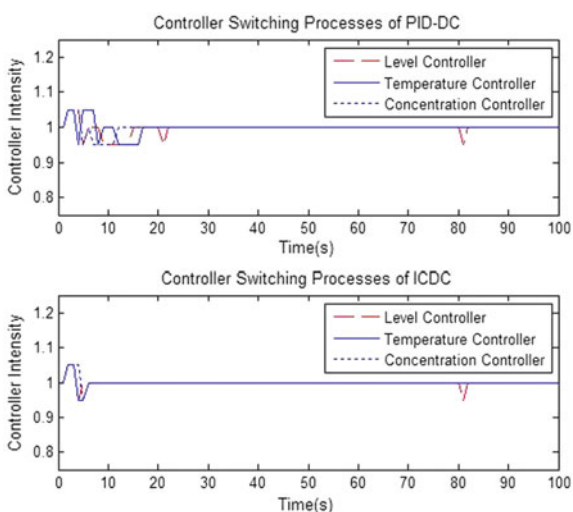


Fig. 2.21 Switching processes of incremental parameters



References

1. Ding, Y.S., Liu, B., Ren, L.H.: Intelligent decoupling control system inspired from modulation of the growth hormone in neuroendocrine system. *Dynam. Cont. Dis. Ser. B.* **14** (5), 679–693 (2007)
2. Ding, Y.S., Liu, B.: An intelligent bi-cooperative decoupling control approach based on modulation mechanism of internal environment in body. *IEEE. T. Contr. Syst. T.* **19**(3), 692–698 (2011)

3. Ding, Y.S., Liang, X., Hao, K.R., Wang, H.P.: An intelligent cooperative decoupling controller for coagulation bath in polyacrylonitrile carbon fiber production. *IEEE. T. Contr. Syst. T.* **21**(2), 467–479 (2013)
4. Zheng, J.C., Guo, G.X., Wang, Y.Y: Feedforward decoupling control design for dual-actuator system in hard disk drives. *IEEE. T. Mag.* **40**(4), 2080–2082 (2004)
5. Wu, X.J., Jiang, J.G., Dai, P., Zuo, D.S.: Full digital control and application of high power synchronous motor drive with dual stator winding fed by cycloconverter. Paper present at the 5th International Conference on Power Electronics and Drive Systems (PEDS). **2**, 1194–1199 (2003)
6. Hauksdottir, A.S., Ierapetritou, M.: Simultaneous decoupling and pole placement without canceling invariant zeros, pp. 25–27. Paper present at the Amer. Contr. Conf. Conf. Arlington, USA (2001)
7. Deng, Z.L., Huang, X.R.: Multivariable decoupling pole assignment self-tuning feedforward controller. Paper present at IEE. P.—Contr. Theor. Ap. **138**, 85–88 (1991)
8. Lin, M.C., Mon, Y.J.: Decoupling control by hierarchical fuzzy sliding-mode controller. *IEEE. T. Contr. Syst. T.* **13**(4), 593–598 (2005)
9. Song, Z., Sukthankar, P., Chen, Y.Q., Gu, J.: Progressive fuzzy fusion control of two coupled inverted pendulum. Paper present at IEEE International Symposium on Computational Intelligence in Robotics and Automation (CIRA). **3**, 1457–1462 (2003)
10. Liu, H.B., Li, S.Y., Chai, T.Y.: Intelligent decoupling control of power plant main steam pressure and power output. *Int. J. Elec. Power.* **25**, 809–819 (2003)
11. Saravanan, S., Kher, S.: Fuzzy control of multivariable process by modified error decoupling. *Isa. T.* **41**(4), 437–444 (2002)
12. Lin, S.T.: Tsai, H.C: Impedance control with on-line neural network compensator for dual-arm robots. *J. Intell. Robot. Syst.* **18**(1), 87–104 (1997)
13. Ma, Z., Jutan, A.: Control of a pressure tank system using a decoupling control algorithm with a neural network adaptive scheme. *IEE. P.—Contr. Theor. Ap.* **150**(4), 389–400 (2003)
14. Shu, H.L., Guo, X.C.: Decoupling control of multivariable time-varying systems based on PID neural network. Paper present at the 5th Asian Control Conference (ACC), Melbourne, Australia. 20–23 (2004)
15. Warwick, K., Zhu, Q.M., Ma, Z.: A hyperstable neural network for the modeling and control of nonlinear systems. *Sadhana.* **25**(2), 169–180 (2000)
16. Zhang, J., Chung, H.S.H., Lo, W.L., et al.: Implementation of a decoupled optimization technique for design of switching regulators using genetic algorithms. *IEEE. T. Power. Electr.* **16**(6), 752–763 (2001)
17. Hazzab, A., Bousserhane, I.K., Kamli, M.: Design of a fuzzy sliding mode controller by genetic algorithms for induction machine speed control. *Int. J. Emerg. Electr. Power Syst.* **1** (2), 1–17 (2004)
18. Hou, Y.B.: A decoupling control method with improving genetic algorithm. Paper present at 2002 International Conference on Machine Learning and Cybernetics (ICMLC). **4**, 2112–2115 (2002)
19. Quan, Y., Yang, J.: Optimal decoupling control system using kernel method. *J. Syst. Eng. Electron.* **15**(3), 364–370 (2004)
20. Farhy, L.S., Straume, M., Johnson, M.L., Kovatchev, B., Veldhuis, J.D.: A construct of interactive feedback control of the GH axis in the male. *Am. J. Physiol. - Reg. I.* **281**(1), 38–51 (2001)
21. Keenan, D.M., Licinio, J., Veldhuis, J.D.: A feedback-controlled ensemble model of the stress-responsive hypothalamo-pituitary-adrenal axis. *P. Natl. Acad. Sci.* **98**(7), 4028–4033 (2001)
22. S. Mitra, S., Hayashi, Y.: Bioinformatics with soft computing. *IEEE. T. Syst. Man. Cy. C.* **36** (5), 616–635 (2006)
23. Fu, Y., Chai, T.Y.: Intelligent decoupling control of nonlinear multivariable systems and its application to a wind tunnel system. *IEEE.T. Contr. Syst. T.* **17**(6), 1376–1384 (2009)

24. Liang, J., Wang, Z., Liu, Y., Liu, X.: Robust synchronization of an array of coupled stochastic discrete-time delayed neural networks. *IEEE. T. Neural. Networ.* **19**(11), 1910–1921 (2008)
25. Chunghtai, S.S., Wang, H.: A high-integrity multivariable robust control with application to a process rig. *IEEE. T. Contr. Syst. T.* **15**(4), 775–785 (2007)
26. Liu, B., Ding, Y.S.: A novel intelligent controller inspired from the regulation mechanism of testosterone. *J. Shanghai Jiaotong University* (in press)
27. Liu, B., Ren, L.H., Ding, Y.S.: A novel intelligent controller based on modulation of neuroendocrine system. *International Symposium on Neural Networks*, vol.3, 119–124. Springer, Berlin Heidelberg (2005)
28. Dan, G., Lall, S.B.: Neuroendocrine modulation of immune system. *Indian. J. Pharmacol.* **30**, 129–140 (1998)
29. Timmis, J., Neal, M.: Artificial homeostasis: integrating biologically inspired computing. [http://www.cs.kent.ac.uk/pubs/2003/1586/content.pdf\(2004\)](http://www.cs.kent.ac.uk/pubs/2003/1586/content.pdf(2004)). Access (2004)
30. Keenan, D.M., Licinio, J., Veldhuis, J.D.: A feedback-controlled ensemble model of the stress-responsive hypothalamo-pituitary-adrenal axis. *P. Natl. Acad. Sci. USA* **98**, 4028–4033 (2001)
31. Farhy, L.S., Straume, M., Johnson, M.L., et al.: A construct of interactive control of the GH axis in the male. *Am. J. Physiol. Reg. I.* **281**(1), 38–51 (2001)
32. Farhy, L.S.: Modeling of oscillations of endocrine networks with feedback. *Method. Enzymol.* **384**, 54–81 (2004)
33. Lee, M., Park, S.: Process control using a neural network combined with the conventional PID controllers. *T. Contr. Automat. Syst. Eng.* **2**(3), 196–200 (2000)
34. Loquasto, F., and Seborg, D.E.: Model predictive controller monitoring based on pattern classification and PCA. Paper present at Amer. Contr. Conf. Conf. **3**, 1968–1973 (2003)
35. Ackermann, U.: Regulation of arterial blood pressure. *Surgery.* **22**(5), 120a–120f (2004)
36. Campbell, I.: Body temperature and its regulation. *Anaesth. Intens. Care. Med.* **9**(6), 259–263 (2008)
37. Fanga, B., Kelkara, A.G., Joshib, S.M., Pota, H.R.: Modelling, system identification, and control of acoustic-structure dynamics in 3-Denclosures. *Control. Eng. Pract.* **12**, 989–1004 (2004)
38. Wang, S., Chen, Z.H., Ma, W.J., Ma, Q.S.: Influence of heat treatment on physical chemical properties of PAN-based carbon fiber. *Ceram. Int.* **32**(3), 291–295 (2006)
39. Sedghi, A., Farsani, R.E., Shokufar, A.: The effect of commercial polyacrylonitrile fibers characterizations on the produced carbon fibers properties. *J. Mater. Process. Tech.* **198**(1–3), 60–67 (2008)
40. Tan, L.J., Chen, H.F., Pan, D., Pan, N.: Investigating the spin ability in the dry-jet wet spinning of PAN precursor fiber. *J. Appl. Polym. Sci.* **110**, 1997–2000 (2008)
41. Ismail, F., Rahman, M.A., Mustafa, A., Matsuura, T.: The effect of processing conditions on a polyacrylonitrile fiber produced using a solvent-free coagulation process. *Mater. Sci. Eng., A* **485**(1–2), 251–257 (2008)
42. Nain, S., Sitti, M., Jacobson, A., Kowalewski, T., Amon, C.: Dry spinning based spinneret based tunable engineered parameters (STEP) technique for controlled and aligned deposition of polymeric nanofibers. *Macromol. Rapid. Comm.* **30**, 1406–1412 (2009)
43. Stoker, M., White, A.S.: Mechatronic cine-film copying using transputer control. *Mechatronics* **10**(7), 773–807 (2000)
44. Karaman, M., Batur, C.: Draw resonance control for polymer fiber spinning process. Paper present at Amer. Contr. Conf. Conf., 2155–2159, (1998)
45. Carrol, J.R., Givens, M.P.: Design elements of the modern spinning control system. Paper present at Textile, Fiber & Film Industry Technical Conference, IEEE, 1–12 (1994)
46. Ghosh, A., Das, S.K.: Open-loop decoupling of MIMO plants. *IEEE. T. Automat. Contr.* **54** (8), 1977–1981 (2009)
47. Wu, M., Yan, J., She, J.H., Cao, W.H.: Intelligent decoupling control of gas collection process of multiple asymmetric coke ovens. *IEEE. T. Ind. Electron.* **56**(7), 2782–2792 (2009)

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