Chapter 24
Modeling and Feedback Control of Electro-Active Polymer Actuators

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Abstract Electro-active polymers (EAPs) are functional polymeric materials which respond to electrical stimuli with shape change. Since EAPs can be activated by the electric field, driving equipments and implementation of control are easily achievable. However, a modeling and a feedback control are needed for practical applications such as a positioning control or a force control with high speed and high precision. In this chapter, we will show the basics of modeling and feedback control methods for ionic polymer-metal composites (IPMCs) from a viewpoint of control engineering. First, general modeling and actuation methods are briefly explained. Then, feedback control methods for output force or deformation are illustrated such as a PID controller, a feed-forward and feedback controller based on an identified model, a servo controller, and a robust PID controller considering uncertainty of the actuator.

Keywords Electro-active polymer • Feedback control • Ionic polymer-metal composite • Modeling

24.1 Introduction

Electro-active polymers (EAPs) [1, 2] are functional polymeric materials which respond to electrical stimuli with shape change. EAPs have potential capabilities as soft actuators, and are sometimes called artificial muscles due to their biotic smooth

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motions. Since EAPs can be activated by the electric field, driving equipments and implementation of control are easily achievable.

There are many types of EAP materials, generally classified into three categories, as a dielectric type, a conductive polymer type and an ionic polymer type. Although dielectric type EAPs need to high-voltage for actuation, the conductive type and the ionic polymer type EAPs can be activated by low-voltage in several volts. We focus on the ionic polymer-metal composite (IPMC) [3], which is one of the ionic polymer type EAP. Ionic polymer actuators can be activated easily. If you just activate the actuator, only an electric battery and a switch are needed. If you do not require accuracy of movements, a model of the actuator may not be needed. Here, the term "model" is a mathematical expression of a target system, i.e. a mathematical equation or data to characterize dynamics of the actuator system. The dynamic characteristics of ionic polymer actuators vary depending on environmental conditions. Therefore, it is considered that a feedback control is needed for practical applications. In such case, an analysis and a design based on the model are effective. The control based on the model is needed to realize a positioning control or a force control with high speed and high precision.

In this chapter, we will show the basics of modeling and feedback control methods for ionic polymer actuators from a viewpoint of control engineering. Although various studies for control have been conducted in recent years, simple and fundamental control approaches are introduced in this chapter. First, general modeling and actuation methods are explained. Then, feedback control methods for output force or deformation are illustrated such as a PID controller, a feed-forward and feedback controller based on an identified model, a servo controller, and a robust PID controller considering uncertainty of the actuator.

24.2 Modeling and Actuation Methods for Electro-Active Polymer Actuators

24.2.1 Modeling Methods

To control actuators with satisfactory accuracy, modeling of actuators is important. The modeling means to construct numerical models which characterize behaviors of the actuator. In this chapter, numerical models indicate transfer functions or differential equations [4, 5]. In control engineering, there are two main types of modeling methods as a white-box modeling and a black-box modeling.

The white-box modeling is also called first principle modeling or physics modeling, and to derive detailed models based on the physical principles. Various researches of the white-box modeling for ionic type EAPs were conducted [6–12]. However, there are demerits that the white box model is commonly complex and it is hard to use directly for analysis and design of control systems.

On the other hand, the black-box modeling is to treat the system as a black-box without consideration of physical principles, and to derive models based on the input–output data obtained from experiments. Various researches of the black-box modeling for ionic type EAPs were also reported [13–19]. The black-box modeling is also called system identifications. It is useful as the control-oriented modeling method, and can be applied to any kinds of EAPs. However, system identifications need to be conducted for each actuator sample because of no consideration of the physical parameters.

There exists an intermediate method called gray-box modeling, which has advantages of white-box and black-box methods. The gray-box modeling is the method based on the partial phenomenological model considering the physical principles and estimations of unknown parameters from experimental data. This methods lead to simplification of mathematical explanations. There are many researches on the gray-box modeling for ionic polymer actuators [20–23].

24.2.2 Actuation Method

Ionic polymer actuators bend in response to electrical field. The deformation arises from the internal stress generated according to the movement of ions. Basically, it is possible to drive these actuators with a driving circuit similar to that for the electromagnetic motor. General driving methods such as voltage control, current control and PWM control are applicable.

Figure 24.1 shows an example of a control system. To drive the actuator, the input signal, generated in the computer, is applied to the actuator through the driving circuit such as a power amplifier. Furthermore, to construct a control system, suitable sensors are needed for measuring the state of the actuator. The information from the sensor is sent to the computer, and the input signal is calculated based on appropriate control algorithm.

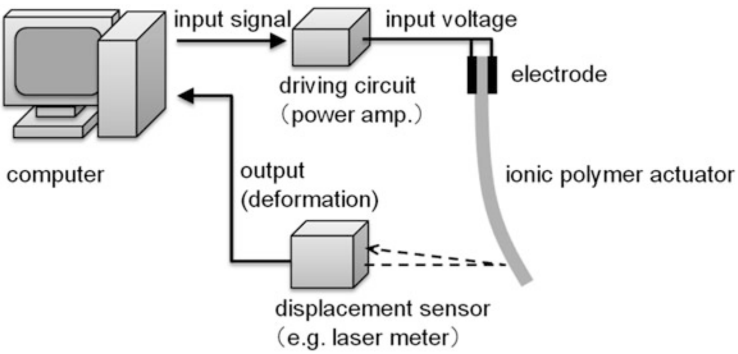


Fig. 24.1 Configuration example of control systems

24.2.3 Control Research for Ionic Polymer Actuators

There are various researches on controls of EAP actuators. In this section, we briefly introduce the control researches on IPMC actuators. As we shall demonstrate in the next section, fundamental control algorithms have been applied to regulate the deformation and/or the output force.

The simplest and powerful control method is a PID (proportional-integral-derivative) control [24, 25]. In fact, the PID control can be implemented easily and realized the sufficient performance with a certain range. On the assumption that dynamics of the IPMC is represented by linear time-invariant systems, typical control algorithms such as a state feedback control with a linear quadratic regulator (LQR) [14, 15], a lead-lag compensator [26], a feed-forward compensator [16, 27, 28] were applied. These model-based controls lead to improve the transient and stationary responses.

From another viewpoint, characteristics of IPMCs vary by environmental changes or iterative activation, the control performance may degrade or even the system may become unstable. Therefore, robust control approaches were applied [18, 29]. The robust controls aim to keep the stabilities and/or performances even with the existence of modeling errors, uncertainties, or parameter variations of the system. As defining the bounds of uncertainties, the robust controller guarantees the control performance as long as the modeling error is within the bounds. As another approach, adaptive controls were also applied to deal with the uncertainties and time-varying behaviors [30–32]. The basic idea of the adaptive control is on-line parameter estimations, and estimated parameters are used on the control system.

24.3 Deformation Control

In this section, deformation control methods of IPMC actuators are explained. There are many algorithms for control, and fundamental control methods are explained [33].

24.3.1 PID Control

A PID control is one of the most simple and practical feedback control method, and widely applied in industry. The control input is calculated based on an error which is the difference between a measured output signal and a desired value. To vanish the error, the control input is determined by weighted sum of proportional, integral and derivative values of the error.

Defining the measured deformation as $y(t)$, the desired value as $y_r(t)$, the error is set as $e(t) = y_r(t) - y(t)$. The input signal of the PID controller is defined by

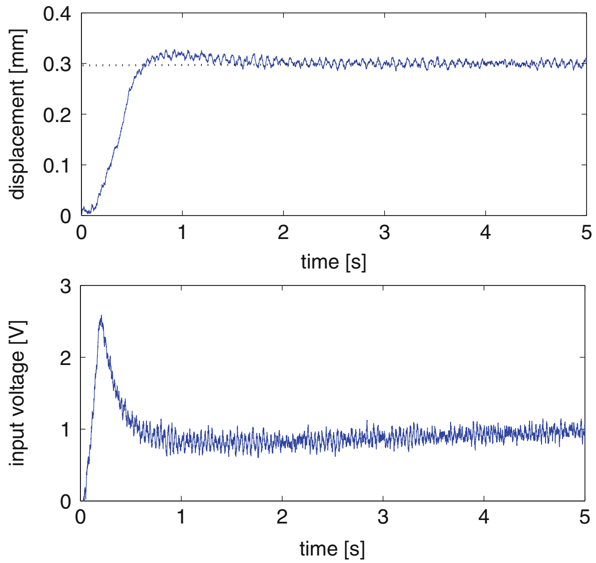


Fig. 24.2 Experimental result of PID control

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)\, d\tau + K_d \dot{e}(t) \tag{24.1}$$

where K_p, K_i, K_d are tuning parameters, which are the proportional gain, the integral gain, the derivative gain, respectively.

Figure 24.2 shows the experimental result. As shown in the Fig. 24.1, a strip of IPMC is fixed in a cantilever, and the displacement at a point near the tip is measured and controlled. In this experiment, the desired value was set as 0.3 mm, and PI control was applied. The displacement and the input voltage are shown in the Fig. 24.2. It is observed that smooth transient response and convergence to the desired value were realized. The response characteristics and stability can be adjusted by feedback gains.

24.3.2 2DOF Control Based on the Identified Model

Next, a tracking controller based on an identified model is explained, which is a 2-dof controller and has a feed-forward loop and a feedback loop. The identified model is used in feed-forward loop. Figure 24.3 shows the block diagram of the control system. P(s) is the model of the actuator system. Feed-forward part of the controller consists of the inverse system of actuator's dynamics P^{-1}(s) and a low-pass filter L(s). K(s) is a feedback part, and the feedback acts in the variation between the output and the reference signal which is a desired value filtered by the low-pass filter L(s).

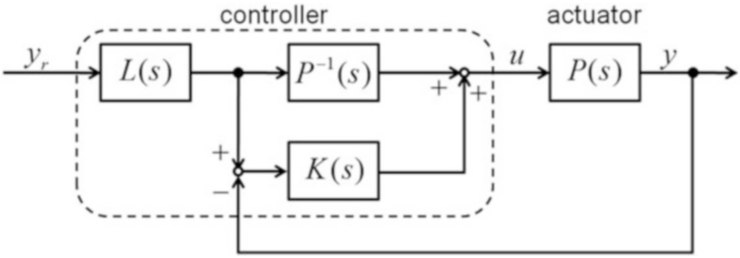
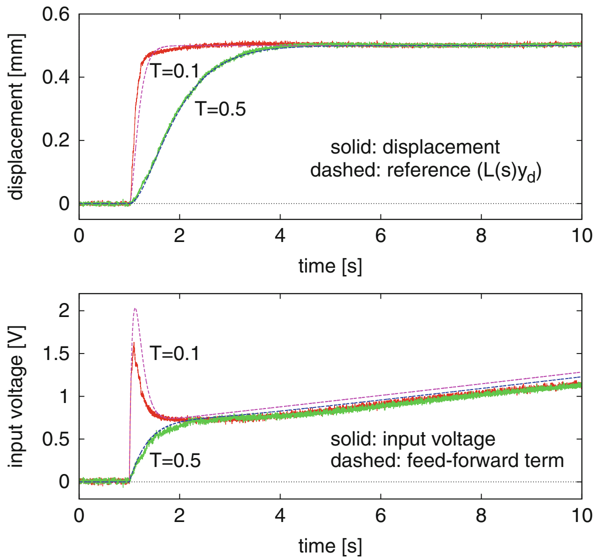


Fig. 24.3 Block diagram of the 2DOF control system

Fig. 24.4 Experimental result of 2DOF control



The feed-forward controller plays a role in shaping of desired response and improvement of controlled performance. The feedback controller plays a role in reducing of influence of disturbance or modeling errors.

Figure 24.4 shows the experimental result. The actuator model was identified from the experimental data of step response as the third-order transfer function:

$$P(s) = \frac{b_1 s + b_0}{s^3 + a_2 s^2 + a_1 s + a_0}. \tag{24.2}$$

The low-pass filter in the controller is set as second-order system:

$$L(s) = \frac{1}{(Ts+1)^2} \tag{24.3}$$

where T is a constant. In the feedback part, PI controller is applied, where feedback gain was set as $K_p = 5$ and $K_i = 3$.

From the results of Fig. 24.4, it is observed that each displacement fits with the reference signals and converges to the desired values. The input voltages consist chiefly of feed-forward inputs. Therefore, the identified model of the actuator is confirmed to be valid.

24.3.3 Servo Control

A servo control is applied for tracking to desired signals or stabilizing systems under the conditions of persisting disturbances. In this section, a controller design method based on state space models in modern control theory is explained.

The model of the actuator is assumed to be represented as a linear time-invariant system. Consider the system of the actuator defined by

$$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx \end{aligned} \tag{24.4}$$

where y is the output signal (displacement), u is the input signal (input voltage) and x is the state of the system. A, B. and C are constant matrixes, and the system is assumed to be controllable and observable. The system given by the transfer function can be represented in state space.

Let us consider the servo system problem for tracking to a constant reference signal. Defining a new input signal as $\dot{u} = v$, and an augmented system can be defined by

$$\begin{aligned} \begin{bmatrix} \dot{x} \\ \dot{u} \end{bmatrix} &= \begin{bmatrix} A & B \\ 0 & 0 \end{bmatrix} \begin{bmatrix} x \\ u \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \end{bmatrix} v \\ y &= \begin{bmatrix} C & 0 \end{bmatrix} \begin{bmatrix} x \\ u \end{bmatrix}. \end{aligned} \tag{24.5}$$

The feedback controller to the augmented system (24.5) can be designed by appropriate feedback methods such as pole placement or optimal control methods. Defining the feedback gain matrix for the augmented system as F, then the matrix F is separated to the following:

$$\begin{bmatrix} F_1 & F_2 \end{bmatrix} = FZ^{-1}, \ Z = \begin{bmatrix} A & B \\ C & 0 \end{bmatrix}. \tag{24.6}$$

Finally, the feedback controller to the system (24.4) is calculated by

$$u = -F_1 x + F_2 \int_0^t e(\tau) d\tau \tag{24.7}$$

where the error between the reference signal and the output signal, $e(t) = y_r(t) - y(t)$

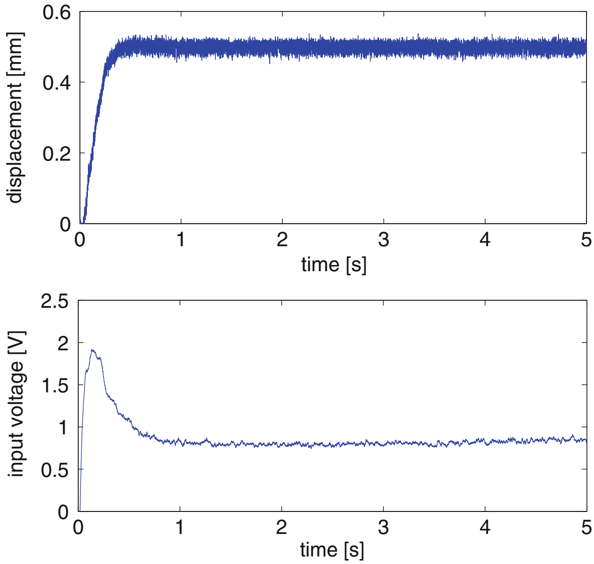


Fig. 24.5 Experimental result of servo control

Figure 24.5 shows the experimental results of the servo control. In this experiment, the reference signal was set to the constant value as 0.5 mm. It is observed that the displacement converged to the reference signal, and tracking control was realized.

24.4 Force Control

IPMC actuators are kinds of bending type EAP actuators. A force control is considered to be useful from the viewpoint of utilizing the flexibility of IPMCs. However, characteristics of IPMCs vary by environment such as humidity or by iterative activation, the control performance may degrade or even the system may become unstable. Therefore, applications of robust control methods are awaited in order to cope with the uncertainty or the variation of the system. The term "robust" means the characteristics that control systems keep the stabilities and/or performances even with the existence of the uncertainties or the variations of the system. In this section, a simple transfer function model and a robust PID tuning method for force control are introduced [34].

24.4.1 Modeling Method for Force Control

For force control of IPMC actuators, a simple time-invariant model is derived with considering IPMC dynamics which consist of an electrical system and an electromechanical system.

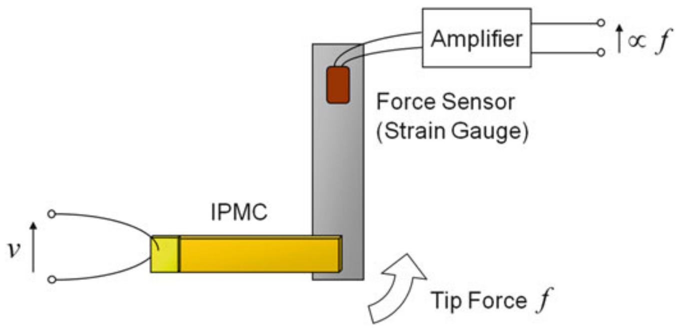


Fig. 24.6 Schematic view of the blocked force measurement

In this section, we consider a condition that a blocked force generated at the tip of a beam-shaped IPMC actuator is measured. Figure 24.6 shows a schematic view of the blocked force measurement using a strain gauge. In the figure, v [V] and f [N] are the applied voltage and the generated tip force of the IPMC, respectively. Being applied voltage, the IPMC bends to generate force on a force sensor. The force sensor is a thin steel cantilever bonded strain gauges. Because the tip force is proportional to the sufficiently small strain, the force can be estimated from the measured strain.

The dynamics from the applied voltage v to the measured force f are considered to be divided into subsystems of electrical part, electro-mechanical part and sensing part.

Electrical impedances of IPMCs are capacitive. The capacitive impedance corresponds to electric double layers between the polymers and the electrodes of IPMCs [21, 22]. A resistive element also appears in the impedance model due to the ion conductivity of the polymer. Using the electric double layer capacitance, C_d, and the membrane resistance, R_m, we model the electrical admittance as a first-order linear approximation. Let G_e(s) be a transfer function from the voltage v to the current i:

$$G_e(s) = \frac{C_d s}{T_e s + 1} \tag{24.8}$$

where $T_e = R_m C_d$ is a time constant of the electrical (admittance) system.

Next, we model the electro-mechanical part, $G_{\mathrm{em}}(s) = F(s)/I(s)$, which is the system from the input current to the output force. We consider two components in the model. The first term is proportional to the current i, and the second term is proportional to the charge. The current-proportional term is modeled as a first order transfer function. This term slowly converges to zero if the current is zero, therefore it can represent stress relaxation. The stress relaxation is a phenomenon that the bending stress gradually converges to zero even under constant voltage because of the diffusion of water (or solvent) in the polymer [6, 7]. The second charge-

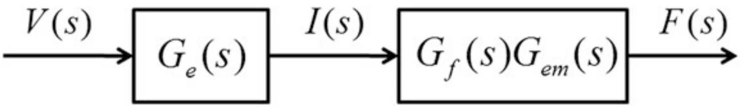


Fig. 24.7 Block diagram of the dynamics of IPMC

proportional term keeps steady stress [9] under constant voltage, and it is modeled as an integration of the current. Let G_{em}(s) be a transfer function from i to f. Taking the components into G_{em}(s), we have

$$G_{em}(s) = \frac{K_r}{T_{em}s + 1} + \frac{K_s}{s} \tag{24.9}$$

where T_{em} is a time constant of stress relaxation, and K_r, K_s are constants.

Because the force is measured by a strain-gauge based force sensor, the model of the sensor should be considered. Typical amplifiers for strain gauges have low pass filters; therefore the dynamics of the force sensor can be approximated by a first order system. Let G_f(s) be a transfer function of the sensor:

$$G_f(s) = \frac{1}{T_f s + 1} \tag{24.10}$$

where T_f is a time constant of the sensor.

Figure 24.7 shows a block diagram of the proposed model. The first block, G_e, is the transfer function of the electrical model. The second block, $G_f G_{em}$, shows a transfer function of the electro-mechanical model and the sensor model. Let G(s) be a transfer function from v to f. From Eqs. (24.8), (24.9) and (24.10), we obtain

$$G(s) = G_f(s)G_{em}(s)G_e(s) = \frac{(K_r + K_s T_{em})C_d s + K_s C_d}{(T_f s + 1)(T_{em}s + 1)(T_e s + 1)}. \tag{24.11}$$

The obtained transfer function G(s) of Eq. (24.11) shows that the numerator is first order and the denominator is third order. In consideration of an application to feedback control, we treat the model as a black-box. Therefore, the coefficients of the transfer function G(s) can be simplified as:

$$G(s) = \frac{s + b_0}{a_3 s^3 + a_2 s^2 + a_1 s + a_0}, \tag{24.12}$$

where the coefficients a_i ($i = 0$, 1, 2, 3) and b_0 can be obtained from Eq. (24.11) dividing both the numerator and the denominator by $(K_r + K_s T_{em})C_d$.

In Eqs. (24.11) and (24.12), assuming $K_r + K_s T_{em} >> K_s$, we approximate as $b_0 \approx 0$. Thus the model for force control is given by

$$G(s) = \frac{s}{a_3 s^3 + a_2 s^2 + a_1 s + a_0}. \tag{24.13}$$

Note that the model of Eq. (24.13) is effective in the case that the dynamics of stress relaxation is dominant.

24.4.2 Robust PID Force Control [34]

The parameters of the transfer function varies so much by environmental changes, therefore it is desirable to construct a robust control system even with the uncertainties of the model. We first show a representation of the parametric uncertainty and a closed loop transfer function with a PID controller. The coefficients of the transfer function in Eq. (24.12) are set as $\theta = [\,a_0 \quad a_1 \quad a_2 \quad a_3\,]$. Assuming $a_3 > 0$, and the parameter θ is a member of a set of parameter Θ defined as

$$\Theta = \{\theta \mid \alpha_i \le a_i \le \beta_i \quad (i = 0, 1, 2, 3)\} \tag{24.14}$$

where α_i and β_i are the lower and upper bounds of a_i. The input signal of a PID controller is given by

$$v(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \dot{e}(t) \tag{24.15}$$

where $e(t) = f_r(t) - f(t)$, and f_r is the reference of force. From Eqs. (24.13) and (24.15), the closed loop transfer function from the reference f_r to the actual force f is obtained as

$$\frac{F(s)}{F_r(s)} = \frac{K_d s^2 + K_p s + K_i}{a_3 s^3 + (a_2 + K_d) s^2 + \left(a_1 + K_p\right) s + (a_0 + K_i)}. \tag{24.16}$$

To a step reference input, the steady state error that equals $(Ki/(a0 + K_i) - 1)\ F_r$ appears, however it is negligible because we can design $a_0 << K_i$.

The closed loop transfer function of Eq. (24.16) has parametric uncertainties as in Eq. (24.15) and the characteristic equation of the closed loop system is a member of a set of polynomial, which is referred as an interval polynomial family. The characteristic equation of the closed loop system of Eq. (24.16) is given by

$$K(s, \theta) \quad = \quad a_3 s^3 + (a_2 + K_d) s^2 + \left(a_1 + K_p\right) s + (a_0 + K_i). \tag{24.17}$$

In this case, the interval polynomial, denoted by $K(s, \Theta)$, is defined as

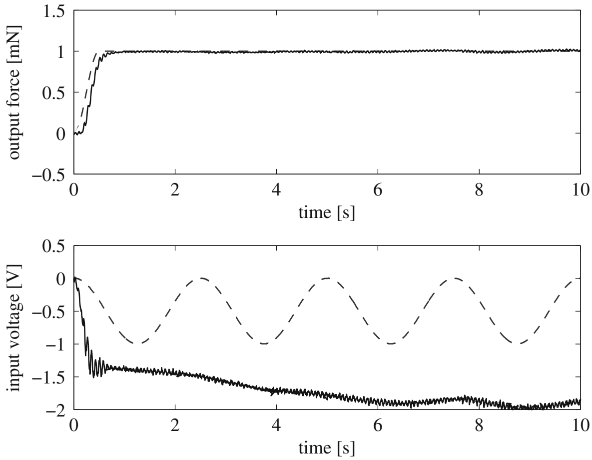


Fig. 24.8 Experimental results of robust PID force control

$$\begin{aligned} K(s,\Theta) &= \{K(s,\theta) \mid \theta \in \Theta\} \\ &= [\alpha_3 \quad \beta_3]s^3 + [\alpha_2 + K_d \quad \beta_2 + K_d]s^2 + [\alpha_1 + K_p \quad \beta_1 + K_p]s \\ &\quad + [\alpha_0 + K_i \quad \beta_0 + K_i]. \end{aligned} \tag{24.18}$$

The control objective is that the system is robust stable for the parametric uncertainties of Eq. (24.14). Therefore, the control system design problem is to find PID gains K_p, K_i, K_d such that the interval polynomial of Eq. (24.18) is robust stable polynomial family.

According to Kharitonov's theorem, for the third order system, any members of the interval polynomial of Eq. (24.17) are stable if and only if the following polynomial is stable [35].

$$K_2(s) = \beta_3 s^3 + (\alpha_2 + K_d)s^2 + \left(\alpha_1 + K_p\right)s + (\beta_0 + K_i) \tag{24.19}$$

As the result, if we design the PID gains K_p, K_i, K_d to make $K_2(s)$ stable, the closed loop system of Eq. (24.16) is stable for any parametric uncertainties of Eq. (24.14).

In a practical application, the controller design of the proposed method is conducted through the following steps:

1. Estimate the bound of the parameters, α_i and β_i (i = 0, 1, 2, 3) of Eqs. (24.13) and (24.14) by carrying out several identification experiments.
2. Determine the PID gain to make $K_2(s)$ of Eq. (24.19) stable by appropriate methods such as a pole placement.

Experimental result of the robust PID force control is shown in the Fig. 24.8. In this experiment, two IPMC samples were used for control and disturbance generation. Identification experiment was repeated five times to obtain the bound of parameters. And then, the PID gains were chosen by the pole placement, and the control experiment was conducted.

Figure 24.8 shows the case with a disturbance. The upper graph of Fig. 24.8 plots the output force; the solid line is the controlled force f, and the dashed line is the desired force f_r. The controlled force f is well kept to the desired force during the experiment. The lower graph of Fig. 24.8 plots the input voltage; the solid line is the control voltage, and the dashed line is the disturbance input. It is observed that the desired force can be kept even if the disturbance acts. For details of verification experiments, please see the reference [34].

24.5 Conclusion

In this chapter, the basics of modeling and feedback control methods for ionic polymer actuators are explained. As the PID controller is a simple feedback method, widely used in practical applications, and it is also effective on the control of polymer actuators. The characteristics of ionic polymer actuators vary by environmental conditions, therefore robust controllers are useful. The modeling of the dynamics of the actuator is significantly important for analysis and control design.

The methods explained in this chapter are simple and fundamental approaches, however, various researches for controls of polymer actuators have been conducted to develop application systems of polymer actuators on practical levels. In order to apply the polymer actuator to practical robotic and mechatronics systems, there exist many problems such as limitation of output force or durability; however, mutual evolutions of improvements on the actuator technology and the design of the control system are important for further applications.

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References

1. Bar-Cohen Y (ed) (2004) Electroactive polymer (EAP) actuators as artificial muscles: reality, potential, and challenges, 2nd edn. SPIE Press, San Diego
2. Kim KJ, Tadokoro S (eds) (2007) Electroactive polymers for robotic applications: artificial muscles and sensors. Springer, London
3. Oguro K, Kawami Y, Takenaka H (1992) Bending of an ion-conducting polymer film-electrode composite by an electric stimulus at low voltage. J Micromach Soc 5:27–30 (in Japanese)
4. Ljung L, Glad T (1994) Modeling of dynamic systems. Prentice Hall, Englewood Cliffs
5. Goodwin GC, Payne RL (1997) Dynamic system identification: experiment design and data analysis. Academic, New York

6. Asaka K, Oguro K (2000) Bending of polyelectrolyte membrane platinum composites by electric stimuli part II. Response kinetics. J Electroanal Chem 480:186–198
7. Yamaue T, Mukai H et al (2005) Electrostress diffusion coupling model for polyelectrolyte gels. Macromolecules 38:1349–1356
8. de Gennes PG, Okumura K et al (2000) Mechanoelectric effects in ionic gels. Europhys Lett 50 (4):513–518
9. Nemat-Nasser S, Li JY (2000) Electromechanical response of ionic polymer-metal composites. J Appl Phys 87(7):3321–3331
10. Tadokoro S, Yamagami S et al (2000) Modeling of Nafion-Pt composite actuators (ICPF) by ionic motion. In: Proceedings of the SPIE, vol 3987, pp 262–272
11. Toi Y, Kang SS (2005) Finite element analysis of two-dimensional electrochemical–mechanical response of ionic conducting polymer–metal composite beams. Comput Struct 83(31–32):2573–2583
12. Wallmersperger T, Leo DJ, Kothera CS (2007) Transport modeling in ionomeric polymer transducers and its relationship to electromechanical coupling. J Appl Phys 101:024912
13. Kanno R, Kurita A et al (1994) Characteristics and modeling of ICPF actuator. In: Proceedings of the Japan–USA symposium on flexible automation. Kobe, Japan, pp 691–698
14. Mallavarapu K, Leo D (2001) Feedback control of the bending response of ionic polymer actuators. J Intell Mater Syst Struct 12:143–155
15. Yamakita M, Kamamichi N et al (2004) Development of an artificial muscle linear actuator using ionic polymer-metal composites. Adv Robot 18(4):383–399
16. Chen Z, Tan X, Shahinpoor M (2005) Quasi-static positioning of ionic polymer-metal composite (IPMC) actuators. Proceedings of the IEEE/ASME international conference on advanced intelligent mechatronics. Monterey, USA, pp 60–65
17. Kothera C, Leo D (2005) Bandwidth characterization in the micropositioning of ionic polymer actuators. J Intell Mater Syst Struct 16(1):3–13
18. Kang S, Shin J et al (2007) Robust control of ionic polymer-metal composites. Smart Mater Struct 16:2457–2463
19. Yamakita M, Sera A et al (2008) Integrated design of an ionic polymer–metal composite actuator/sensor. Adv Robot 22:913–928
20. Kanno R, Tadokoro S et al (1996) Linear approximate dynamic model of ICPF (ionic conducting polymer gel film) actuator. Proceedings of the international conference on robotics and automation. Minneapolis, USA, pp 219–225
21. Bao X, Bar-Cohen Y, Lih S (2002) Measurements and macro models of ionomeric polymer-metal composites. In: Proceedings of the SPIE, vol 4695. San Diego, USA, pp 220–227
22. Newbury KM, Leo DJ (2003) Linear electromechanical model of ionic polymer transducers – part I: model development. J Intell Mater Syst Struct 14:333–342
23. Chen Z, Tan X (2008) A scalable dynamic model of ionic polymer metal composite actuators. In: Proceedings of the SPIE, vol 6927. San Diego, USA, p 69270I
24. Richardson R, Levesley M et al (2003) Control of ionic polymer metal composites. IEEE/ASME Trans Mechatron 8(2):245–253
25. Yun K, Kim WJ (2006) Microscale position control of an electroactive polymer using an anti-windup scheme. Smart Mater Struct 15(4):924–930
26. Bhat N, Kim WJ (2004) Precision force and position control of an ionic polymer metal composite. IMechE J Syst Control Eng 218(6):421–432
27. Shan YF, Leang KK (2009) Frequency-weighted feedforward control for dynamic compensation in ionic polymer–metal composite actuators. Smart Mater Struct 18:125016
28. Fleming MJ, Kim KJ, Leang KK (2012) Mitigating IPMC back relaxation through feedforward and feedback control of patterned electrodes. Smart Mater Struct 21:085002
29. Lin HH, Fang BK et al (2009) Control of ionic polymer–metal composites for active catheter systems via linear parameter-varying approach. J Intell Mater Syst Struct 20(3):273–282
30. Brufau-Penella J, Tsiakmakis K et al (2008) Model reference adaptive control for an ionic polymer metal composite in underwater applications. Smart Mater Struct 17:045020

31. Lavu BC, Schoen MP, Mahajan A (2005) Adaptive intelligent control of ionic polymer–metal composites. Smart Mater Struct 14:466–474
32. Fang BK, Lin CK, Ju MS (2011) Adaptive control of ionic polymer–metal composite in air and under water using a modified direct self-tuning regulator embedded with integral action. Smart Mater Struct 20:105016
33. Ogata K (2009) Modern control engineering, 5th edn. Prentice Hall, New York
34. Sano S, Takagi K et al (2010) Robust PID force control of IPMC actuators. In: Proceedings of the SPIE, vol 7642. San Diego, USA, p 76421U
35. Barmish BR (1994) New tools for robustness of linear systems. Macmillan Publishing Company, New York