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Control of Artificial Respiration by Adaptive Pole-Placement Method

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SUMMARY

Most organic functions are described by complex dynamics of unknown and/or ambiguous subsystems characterized by their nonlinearity, chronic change and individual difference. Nevertheless, a respiratory regulation system among these subsystems is described by a bilinear mathematical model whose state variables are alveolar and average mixed venous CO_2-concentrations, and whose inputs are the ventilation rate of alveolus and metabolic rate converted into CO_2-volume. However, its nonlinear dynamic characteristics depend on time-varying parameters, in particular, on the blood flow rate which varies on a large scale incidental to metabolic rate change.

In this paper, an automatic control system of artificial respiration is discussed on the basis of the adaptive pole-placement method using a linear mathematical model where the ventilation rate and alveolar CO_2-concentration are regarded as a controlling input and a controlled output, respectively. The feature of the proposed method is that desirable characteristics given beforehand by medical doctors can be realized automatically even with regard to individual difference and chronic change of characteristics seen distinctively in an organism.

Here, to confirm the robustness of the proposed control system, a simulation experiment is given with some metabolic rate change as an input change regarding its contribution to the output as an effect of disturbance from an environment. Then the proposed method is applied to clinical experiments using a respirator controlled by outside signals. This respirator has been developed to meet the aim of the present study, resulting in good performance of dynamic characteristics of alveolar CO_2-concentration on healthy subjects.

Key words: Adaptive pole-placement; artificial respiration; control system.

1. Introduction

Recently, there has been an increase in the number of patients of advanced age who suffer from pulmonary disorders incidental to the rapid change of our society. Hence, artificial respiration is foreseen to become more and more important because it is one of the most effective means for the treatment of hydrogen-ion concentration of arterial blood in the case of acute respiratory insufficiency. However, it requires some medical experience and skills to provide patients appropriate care, which places increased psychological and/or physical burdens on medical staffs. Therefore, there is a clinical demand for an artificial respiration control system to realize automatically desired characteristics, in which only an air mask is provided to a patient without demand of any other assistance and no special medical knowledge.

To meet such a demand, many studies of auto-

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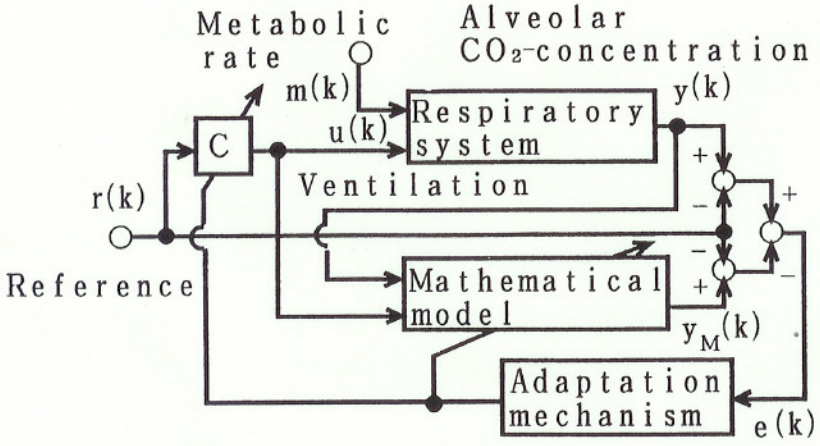

Fig. 1. Control system of artificial respirator by model reference adaptive control.

matic control methods for artificial respiration have been reported [1-8], among which some linear [3, 7] and nonlinear [6] model reference adaptive control methods have been proposed. These methods provide an appropriate controlling input with simultaneous parameter estimation of a respiratory system incidental to the change of the state of patients. However, the stability of a controller is always problematic and thus it is not appropriate to provide a safe and valid artificial control of respiration by model reference adaptive control methods.

In the present study, a control system of artificial respiration is synthesized using an adaptive pole-placement method with its robustness [10] examined by a simulation experiment. Thus, ventilation and alveolar CO_2-concentration are chosen as a controlling input and a controlled output of a respiratory regulation system, respectively. These are measured noninvasively and their relations sufficiently represent the dynamic characteristics of the system. Hence, there is very little harmful influence on patients in its clinical application.

Using a newly developed respirator controlled by signals from a computer, healthy young student volunteers participated in simulation experiments to clarify the feature of the proposed method, and which resulted also in good control performance of alveolar CO_2-concentration. The superiority of this method to a model reference adaptive control method is confirmed by comparison in clinical experiments.

2. Theory and Method

2.1. Control system of artificial respiration

A respiratory regulation system is basically a nonlinear time-varying system [12]. Hence, a single-input and single-output system is taken into account whose ventilation and alveolar CO_2-concentration are chosen as controlling input and a controlled output, respectively. A model reference adaptive control system determines the controlling input estimating system parameters of an appropriate linear mathematical model.

As illustrated in Fig. 1, the parameters of a mathematical model are improved by an adaptation mechanism so that an error actually output from the mathematical model converges asymptotically to zero. This adaptive method is most useful from the viewpoint that the output error of a mathematical model from a time-varying controlled system has a tendency to decrease with continual improvement of its parameters. Thus, a respiratory system can be controlled as a time-invariant linear system in a certain time interval, even when system parameters including blood flow rate change largely according to the metabolic rate change.

A stable controller, however, cannot always be synthesized by a model reference linear adaptive con-

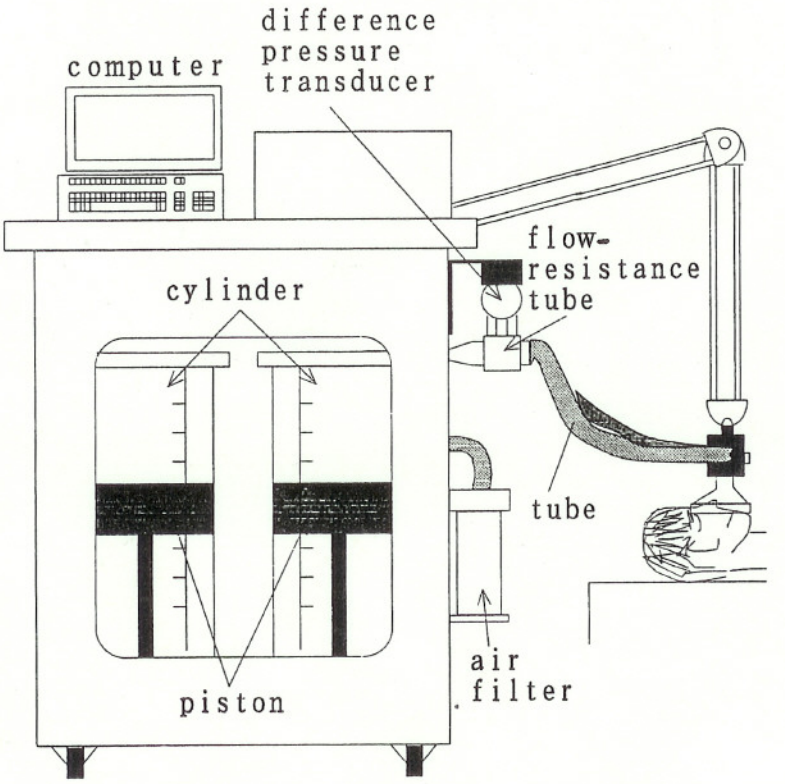

Fig. 2. An outline of respirator.

trol method. This is because a discrete-time system obtained from a stable continuous-system* may have unstable zeros depending on the choice of a sampling interval and/or its mathematical model [9]. In addition, nonlinear model reference adaptive control systems remain unstable except for some special cases [6]. Thus, clinically, it is not easy to provide a patient safe control of artificial respiration by model reference adaptive control methods. To overcome such difficulties, and adaptive pole-placement method with a linear mathematical model is adopted because of its distinctive superiority in robustness [10].

In this section, the feature of a respirator developed for the control of artificial respiration is discussed first and then some mathematical descriptions are given for the synthesis of a control system based on an adaptive pole-placement.

2.1.1. Respirator for automatic control of respiration

The respirator we developed is applied to the relevant automatic control of respiration [11]. This respirator can be controlled not only by a manual operation but also by outside signals. The characteristic feature of the respirator is that its operational mode can be set by controlling signals from a computer.

As illustrated in Fig. 2, the respirator has two cylindrical pumps whose movements are controlled independently. One of the cylinders is for sending air to a patient (inspiratory mode) and the other for sucking expiratory air from a patient (expiratory mode).

In every respiratory period, a computer for controlling can set operational modes of a respirator such as ventilation [ml/stroke], ventilation frequency [1/min]

*Continuous-time system and discrete-time system [14]: In general, most phenomena usually encountered result from a chronically continuous system (continuous-time system). On the other hand, a discrete-time system is the one giving phenomena which reveal themselves intermittently or are regarded as intermittent.

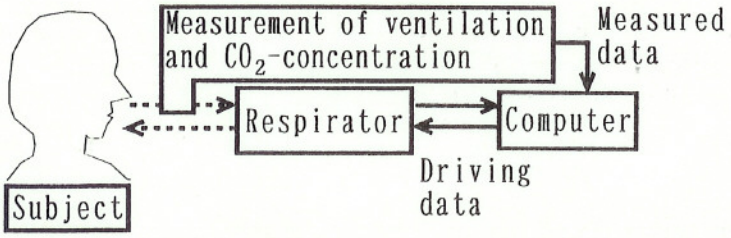

Fig. 3. An outline of control system of artificial respiration.

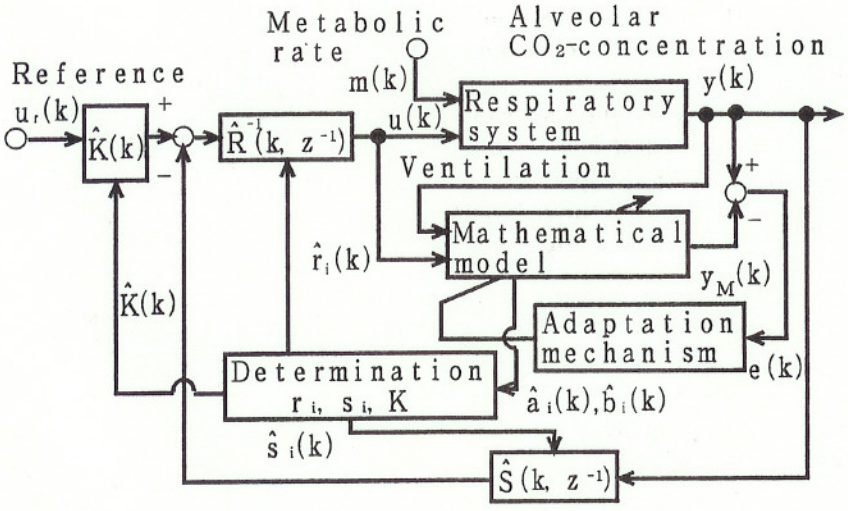

Fig. 4. Control system of artificial respiration by adaptive pole placement method.

and cycle percent ratio [%]. In particular, the cycle percent can be set by the changing ratio inspiratory and expiratory duration, and the pause of a respirator. The ventilation can also be realized according to the respiratory pattern and rhythm of a patient, thereby changing the piston movements of the respirator by software. The independent operations of inspiration and expiration ensure patients an easy and appropriate respiration because air can be expired in a preparatory time of the next inspiration in the same amount as the previously inspired air. The intermixture of inspiratory and expiratory air is avoided by a valve mounted on an air mask which is synchronized with respiration so that alveolar CO_2-concentration can be measured accurately in every respiratory cycle. This valve makes it possible to supply an accurate amount of ventilation which yields a high-quality performance of digital control of alveolar CO_2-concentration.

2.1.2. Configuration of hardware control system of respiration

Using the previously mentioned respirator, a control system of artificial respiration is designed as illustrated in Fig. 3, in which the data processing and control procedure of respiration are explained, thus clarifying their signal flows. The ventilation amount is obtained by an integrator (NIHON KOHDEN; AQ-601G) from the air-flow velocity measured by a flow resistance tube, difference pressure transducer and amplifier (NIHON KOHDEN; TV-112T, TP-602T, AR-601G). The concentrations of carbon dioxide and oxygen of expired endtidal gas are measured in every sampling interval T by a gas analyzer (NEC SAN-EI; Respina 1H26) for controlling and monitoring the experimental process.

To monitor an experimental state for the safety of patients, saturation of arterial blood and pulse rate are measured by using the pulse oximeter (NIHON KOHDEN, OLV-1200).

2.2. Synthesis of control system of artificial respiration by adaptive pole-placement

Since zeros of a controlled system are cancelled by poles of a controller in a model reference adaptive control method, it is not applicable to the control of a nonminimum phase system.* As previously described, even if a controlled system is stable in continuous time, zeros of its discretized system are not always located in a stable domain. This is because it becomes a nonminimum phase system depending on the choice of sampling interval and/or a mathematical model. In such a case, a control by an adaptive pole-placement method is useful and effective. In this way, the control system of an artificial respiration is synthesized according to Fig. 4 [10].

2.2.1. Adaptation algorithm

In the present study, a respiratory regulation system is assumed to be represented by the following linear system with input $u(k)$ and output $y(k)$.

$$A(z^{-1})y(k)=B(z^{-1})u(k) \tag{1}$$

where

$$A(z^{-1})=1+\sum_{i=1}^{n_a}a_iz^{-i} \quad \text{and} \quad B(z^{-1})=\sum_{i=d}^{n_b}b_iz^{-i}$$

This system yields the following mathematical model for parameter estimation:

$$y_M(k)=-\sum_{i=1}^{n_a}\hat{a}_i(k)y(k-i)+\sum_{i=d}^{n_b}\hat{b}_i(k)u(k-i) \tag{2}$$
$$=\hat{\theta}^T(k)\zeta(k)$$

*If the transfer function of a system does not have any pole (root when its denominator polynomial is equated to zero) and any zero (root when its nominator polynomial is equated to zero) in the unstable domain of the complex plane, it is called a minimum phase system; otherwise it is called a nonminimum phase system.

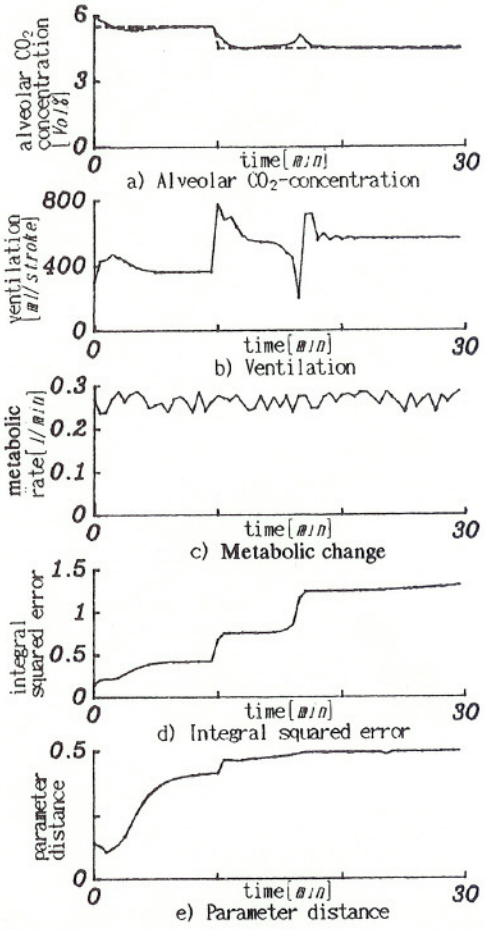

Fig. 5. Responses of respiratory control system by adaptive pole placement method (simulation experiment).

where

$$\hat{\theta}^T(k)=[-\hat{a}_1(k)\cdots-\hat{a}_{n_a}(k)\hat{b}_d(k)\cdots\hat{b}_{n_b}(k)]$$
$$\zeta^T=[y(k-1)\cdots y(k-n_a)u(k-d)\cdots u(k-n_b)] \tag{3}$$

$\hat{\theta}(k)$ and $\zeta(k)$ are state variable and estimated parameter vectors, respectively, at time k_τ (hereafter, k with parenthesis implies time k_τ); $y(k)$ is a deviation of alveolar CO_2-concentration [vol%] from equilibrium state given by constant ventilation; $u(k)$ is a change in ventilation [ml/min] from the one giving equilibrium alveolar CO_2-concentration; $y_M(k)$ ia an output from a mathematical model [Vol%] for the input $u(k)$; $\hat{a}_i(k)(1 \leqq i \leqq n_a)$ and $\hat{b}_i(k)(d \leqq i \leqq n_b)$ are unknown parameters with a dead time ($d \geqq 1$) at time k_τ.

Parameters of a mathematical model are regulated so that error $e(k)$ given by the following equation converges asymptotically to zero:

$$e(k)=y(k)-y_M(k) \tag{4}$$

The constant-trace algorithm [13] is adopted for parameter regulation law, which is available for a time-variant and/or nonlinear system as follows:

$$\hat{\theta}(k)=\hat{\theta}(k-1)+\Gamma(k-1)\zeta(k)\varepsilon(k) \tag{5}$$

where

$$\Gamma(k)=\Gamma'(k-1)-\left\{\frac{\Gamma(k-1)\zeta(k)\zeta^T(k)\Gamma(k-1)}{1+\zeta^T(k)\Gamma(k-1)\zeta(k)}\right\},$$

$$\Gamma(k)=\Gamma'(k)/\lambda(k),$$

$$\lambda(k)=\frac{\mathrm{tr}\Gamma'(k)}{\mathrm{tr}\Gamma(0)},\quad \mathrm{tr}\Gamma(0)>0 \quad \text{and}$$

$$\varepsilon(k)=\frac{y(k)-\hat{\theta}^T(k-1)\zeta(k)}{1+\zeta^T(k)\Gamma(k-1)\zeta(k)}$$

2.2.2. Method of adaptive pole-placement

The aim of the design of the present control system is to synthesize the ventilation change $u(k)$ as a controlling input adaptively so that alveolar CO_2-concentration $y(k)$ asymptotically satisfies the following relation for its desired value given by a bounded reference input $u_r(k)$:

$$C(z^{-1})y(k)=KB(z^{-1})u_r(k) \tag{6}$$

Here, $C(z^{-1})$ is a polynomial that provides desirable poles beforehand as determined by a designer. Thus a closed-loop system seen from a reference input $u_r(k)$ to an output $y(k)$ becomes stable, where K is a gain to make a steady-state error zero. They are described respectively, as

$$C(z^{-1})=1+c_1z^{-1}+\cdots+c_{n_c}z^{-n_c} \quad \text{and}$$
$$K = C(2)/B(2) \tag{7}$$

Thus, a controlling input $u(k)$ is determined by Eq. (8) as

$$R(z^{-1})u(k)=Ku_r(k)-S(z^{-1})y(k) \tag{8}$$

where

$$R(z^{-1})=1+r_1z^{-1}+\cdots+r_{n_r}z^{-n_r} \quad \text{and}$$
$$S(z^{-1})=s_0+s_1z^{-1}+\cdots+s_{n_s}z^{-n_s} \tag{9}$$

Equation (2) yields

$$(A(z^{-1})R(z^{-1})+B(z^{-1})S(z^{-1}))y(k)=KB(z^{-1})u_r(k) \tag{10}$$

which gives the following equation taking into account Eq. (6):

$$C(z^{-1})=A(z^{-1})R(z^{-1})+B(z^{-1})S(z^{-1}) \tag{11}$$

Polynomials $R(z^{-1})$ and $S(z^{-1})$ are determined so that they may satisfy Eq. (11). Here, parameters of a controlled system a_i and b_i are unknown. Therefore, parameters of $R(z^{-1})$ and $S(z^{-1})$ are determined using their estimated parameters denoted by $\hat{a}_i(k)$ and $\hat{b}_i(k)$.

3. Application of Pole-Placement Method To Artificial Respiration

3.1. Simulation experiment of artificial control respiration

In accordance with the illustration in Fig. 4, a simulation experiment is performed using a mathematical model described by Eq. (2), introducing a well-known bilinear model [6, 12] of a respiratory regulation system (cf. Appendix A). Here, the metabolic rate is changed within ±10 percent from an equilibrium state according to the change of a uniformly distributed pseudorandom number. The metabolic rate change has some effect on parameters of a respiratory regulation system including blood flow rate [2, 12] (cf. Appendix B), and, as a result, causes a change of system characteristics. This is considered to contribute to the disturbance to the output.

Figure 5 shows an experimental result obtained from a simulation control of respiration in 30 min with a sampling interval T = 30 s, where the lengths of memories of autoregressive and moving average parts are chosen as $n_a = n_b = 2$ with a dead time $d = 1$ and initial gain matrix chosen as $\Gamma(0) = I$ (unit matrix).

Let a polynomial be given as

$$C(z^{-1})=1 \tag{12}$$

which determines poles of the system as viewed from a reference input to a controlled output. The orders of polynomials $R(z^{-1})$ and $S(z^{-1})$ are chosen as $n_r = n_s = 1$.

Figure 5 shows that alveolar CO_2-concentration

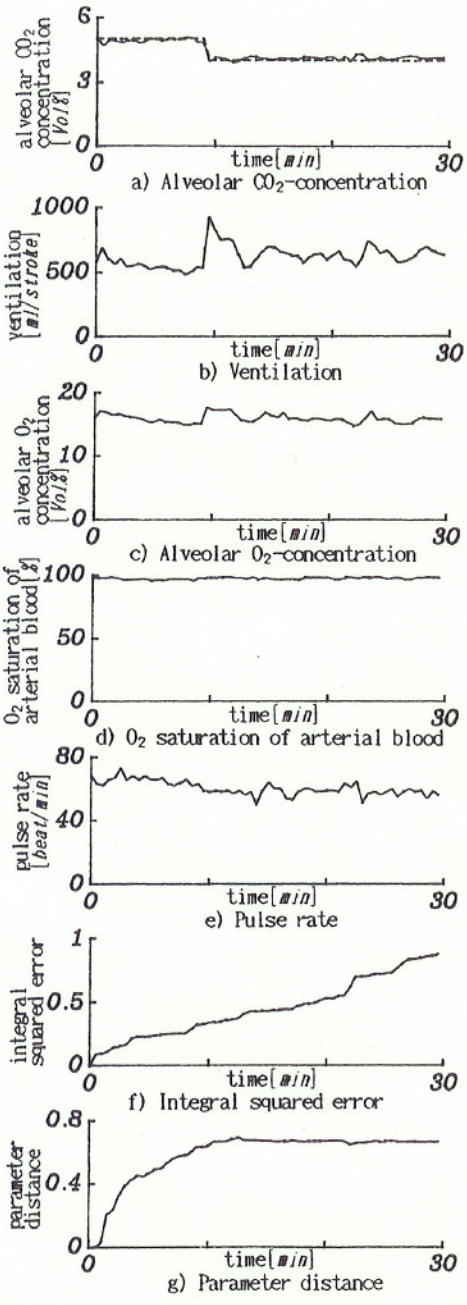

Fig. 6. Results of experiment by adaptive pole placement method.

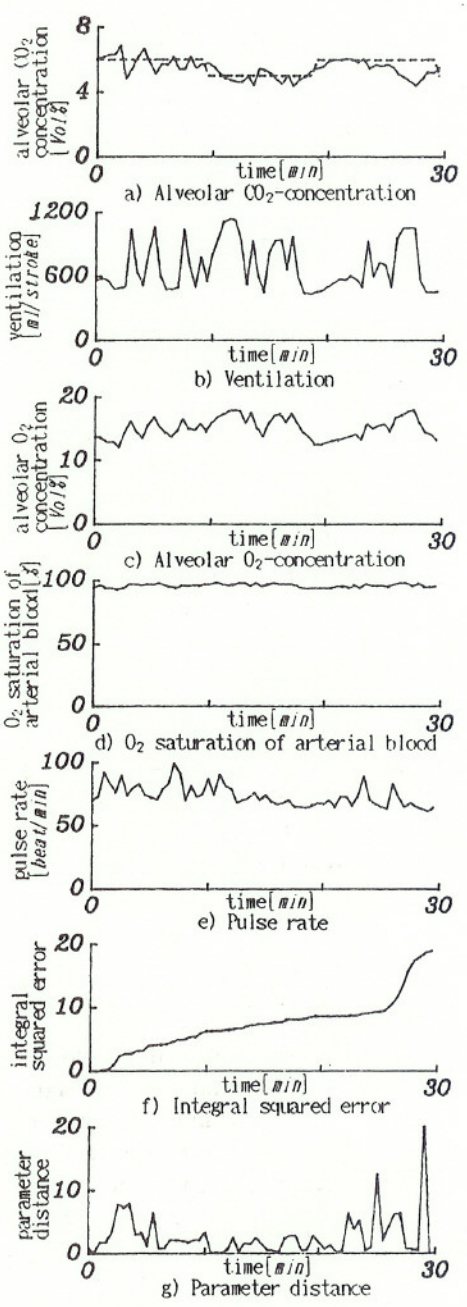

Fig. 7. Results of experiment by model reference adaptive control.

follows up a desired value in 5 min from the start of the control. Although a controlled output once deviated from the desired value at about 15 min, it follows up again a desired value sufficiently rapidly since the adaptation mechanism works well according to the parameter change of a respiratory regulation system caused by metabolic rate change.

Figure 5(d) shows that the estimated parameter distance (calculated as Euclidean distance from the origin concerning parameters of a mathematical model) settles in a constant value of about 10 min after the change in reference input. Therefore, the proposed method is considered sufficiently applicable to the clinical control of a respiratory regulation system.

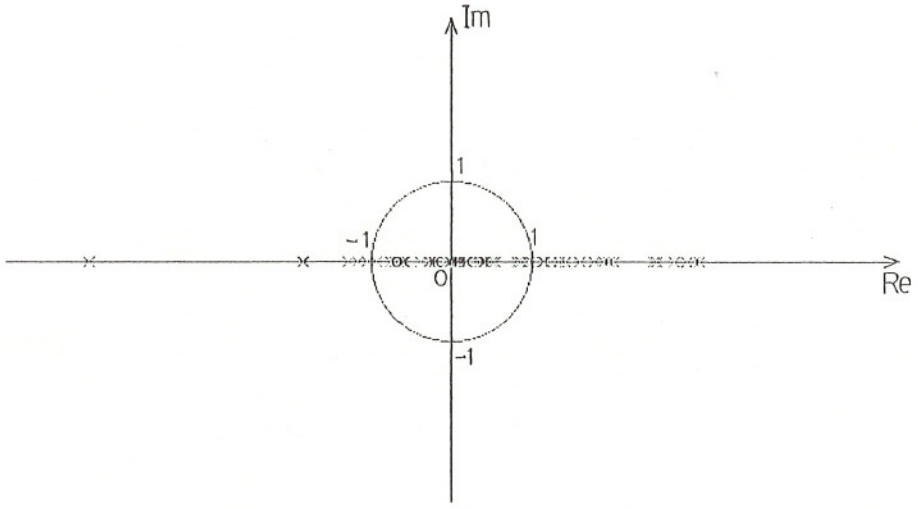

Fig. 8. Zero-distribution of mathematical model used for model reference adaptive control.

3.2. Clinical experiment of artificial respiration

Artificial respiration is performed on 10 healthy subjects in 30 min using a control system described in section 2. Here, 30 s are chosen as sampling interval T, an initial gain matrix is set $\Gamma(0) = I$ and an asymptotic stable polynomial is given by $C(z^{-1}) = 1$ as in the case of the simulation experiment. A step-like function decreases at 10 min from the start of the control experiment by 1.0 percent from an average alveolar CO_2-concentration given for an individual subject before the experiment. The memory lengths of autoregressive and moving average parts of a mathematical model are given as $n_a = n_b = 2$ with a dead time $d = 1$.

The memory lengths of polynomials $R(z^{-1})$ and $S(z^{-1})$ for the assignment of appropriate poles are chosen as $n_r = n_s = 1$. An example of a control experiment is illustrated in Fig. 6. A model reference adaptive control method is introduced using the same linear mathematical model as in the case of the present adaptive pole-placement method for the comparison of control performances of the two methods. The experimental result is shown in Fig. 7, where a reference output $r(k)$ (desired value) has a step-like change by 1.0 percent at 10 min and a step-like change again to the original value at 20 min from the start of the experiment.

There appears a good inclination of alveolar CO_2-concentration to follow up a controlled value in a model reference adaptive control. However, the control performance is not good enough. More particularly, a controlled output is far away from the desired value after 25 min from the start of the experiment, i.e., a clinically unstable state is observed from dynamics of alveolar CO_2-concentration caused by frequent change in ventilation.

Figure 8 shows positions of zeros of each mathematical model estimated at every sampling time during the overall experimental procedure. The figure shows also that zeros of an estimated mathematical model frequently move in and out of a unit circle on a complex z-plane in the course of the adaptation process. Zeros appear more frequently outside the unit circle 20 min after the start time of the experiment, which results in the unstable state of the control system.

On the other hand, the result from the control experiment by the adaptive pole-placement method shows that alveolar CO_2-concentration follows up sufficiently well a desired value as shown in Fig. 6. The illustration shows that a controlling input does not change so much in amplitude and does not force a subject into irrational respiration.

Endtidal O_2-concentration of expired air, fluctuations in O_2 saturation of arterial blood and pulse rate indicate a normal range of the physiological state, which ensures the safety of a subject in the control process of artificial respiration. However, a parameter distance varies largely from the start to the end of the

experiment based on a model reference adaptive control method.

On the other hand, it settles to an almost constant value after the step-like change in reference input as seen in the case of the simulation experiment when the clinical experiment is based on an adaptive pole-placement method. Almost the same tendency has been observed with other subjects, as previously mentioned. Furthermore, a model reference adaptive control method has not been made to coincide with such a phenomenon as a cough during an experiment, which often results in large parameter change of a mathematical model. However, a pole-placement method has been confirmed to coincide with it during the experimental procedure.

4. Conclusions

In this study, simulation and clinical experiments are performed based on a linear adaptive pole-placement method taking into account a time varying and nonlinear regulatory system of respiration as a controlled system. A control system of artificial respiration based on adaptive pole-placement method has been confirmed by assignment of poles to appropriate positions, even when a control is not possible by a model reference adaptive control method. This is obviously and clearly seen from monitoring data of the state of subjects for their safety.

The proposed pole-placement method is concluded to be more safe and more reliable in a clinical application in comparison with conventional methods. It is also desirable clinically because a stable control system can be synthesized using a simple mathematical input-output relation of ventilation and alveolar CO_2-concentration which are both readily and noninvasively measured and never becomes a burden to patients.

In the present study, a pole which gives desirable dynamic characteristics has been assigned to the origin of a complex z-plane. However, it is seen that control is not always desirable when poles are assigned to other positions of the plane. Therefore, a placement of poles is important for the determination of the control performance of the control system. Thus, the quantitative comprehension of the relation of a pole-placement to a controlled system remains as an important study in the future. Also, the determination of the structure of a mathematical model remains a problem to be solved for the synthesis of a desirable control system.

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APPENDIX

Appendix A [6, 12]

It is well known that substantial characteristics of the respiratory regulation system are represented by

$$dx/dt = Ax + uN_1x + Bu$$

where

$$A=\begin{bmatrix}-(Q\alpha+u_0)/V_1 & Q/V_1\\ Q\alpha/V_2 & -Q/V_2\end{bmatrix},\quad N_1=\begin{bmatrix}-1/V_1 & 0\\ 0 & 0\end{bmatrix}$$

$$B=\begin{bmatrix}(F^i(CO_2)-x_0)/V_1 & 0\\ 0 & 1/V_2\end{bmatrix}$$

$$x_0 = F^i(CO_2) + m_0/u_0,\ y_0 = \alpha x_0/Q_0 + \beta$$

Constants for simulation experiments are given as follows:

$F^i(CO_2) = 3.95 \times 10^{-2}$ [Vol%]: inspiratory CO_2-concentration;

V_1 = 2.6[1]: volume of alveoli;

V_2 = 40[1]: equivalent volume of body tissue;

Q_0 = 5.5[1/min]: equilibrium blood flow rate;

x_0 = 5.89[Vol%]: equilibrium state of alveolar CO_2-concentration;

y_0 =54.6[Vol%]: equilibrium state of average venous CO_2-concentration;

u_0 = 4.5[1/min]: ventilation rate which gives equilibrium state;

m_0 = 0.2632[1/min]: metabolic rate of body tissue converted into CO_2-volume which gives equilibrium state;

α = 3.30, β = 32[vol%]: constants determined by air pressure and the operating range of CO_2-dissociation curve.

Deviation from constant values x_0, y_0, u_0, m_0 are denoted by variables x, y, u, m, respectively. Vector state and input variables are given by $x^T = [x, y]$ and $u^T = [u, m]$, respectively.

Appendix B [2, 12]

Blood flow rate is assumed to have a dynamics given by the following linear differential equation corresponding to metabolic rate change:

$$dQ/dt = a_qQ + b_qm$$

where system constants are given as a_q = -0.3[1/min], and Q is blood flow rate change from its equilibrium value Q_0 given Appendix A.

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