MFAC and Parameter Optimization for a Class of Models in HVAC

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Abstract That the aging equipment, nonlinearity, and other external factors combine to make one-order plus time-delay process model be uncertain in Heating, Ventilation, and Air Conditioning (HVAC) makes the initial control parameters ineffective. Aiming at one-order plus time-delay process model with uncertainty in HVAC, the Model-Free Adaptive Control (MFAC) is introduced in studying the control characters. The changes on the overshoot and settling time are simulated and compared with PID, which shows that MFAC has good stability and anti-interference and is insensitive to the change of time-delay. Therefore, it is proved that MFAC is suitable for solving the problem of control failure caused by changing time-delay. However, there are no good methods for the parameters setting of MFAC, which makes it difficult to find the optimal controller parameters. Aiming at the condition, the simplex method is used to optimize the controller parameters and the first-order inertia plus time-delay model is regarded as the controlled object in this paper. The simulation results show that the MFAC parameters optimized by the simplex method have good control results.

Keywords Model-free adaptive control · Uncertainty · Anti-interference · Simplex · Optimization

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1 Introduction

One-order plus time-delay process model is the common mathematical model in Heating, Ventilation & Air Conditioning (HVAC) control systems. For example, the pressure difference control model, the temperature difference control model, the air supply temperature control model and fan static pressure control model in a central air conditioner are one-order plus time-delay process models. If the mathematical model of one-order plus time-delay is accurate, there are some good control methods dealing with the time-delay. For example, when the time-delay is small and accurate, PID and derived PID algorithms can get good control results. When the time-delay is longer and accurate, Dalin algorithm and Smith predictive control algorithm are very suitable. However, in practice, there are many uncertainties of mathematical models in many systems and the model is difficult to establish, which results in the partial failure of control algorithm. For example, Smith predictive control relies heavily on the precise mathematical model. When the estimated model and the actual object do not match, the control quality will deteriorate significantly or even diverge, and it is also very sensitive to external disturbances [1].

Aiming at the uncertainty, some results had been reported and some general conclusions had been got [2]. However, because the mathematical models of the controlled systems are diverse and different models have different parameters and structures, the specific effects on the performance of the Model-Free Adaptive Control (MFAC) are not still very clear. For example, there are no results on MFAC dealing with the uncertainty of the one-order plus time-delay process model caused by the aging equipment, nonlinearity, and other external factors in Heating Ventilation Air Conditioning (HVAC). In order to explore the adaptability of the MFAC dealing with the uncertainty of the one-order plus time-delay process model, the control performance is studied by the simulation when the model parameters change, such as the time-delay, process gain, and system time constant. This study result is helpful to refine the application scope of MFAC and choose control methods for one-order plus time-delay delay systems with uncertainty.

Based on the above study, how to optimize the MFAC controller parameters is studied. Although MFAC is an effective, widely applicable and advanced control strategy that does not rely on the mathematical model of objects, its controller parameters are not easy to optimize, which sometimes affects the control performance of MFAC. Therefore, how to set and optimize the parameters of the MFAC controller is an important issue. Hou refers to the parameters tuning method of PID controller and proposes four methods of tuning the controller parameters of MFAC: parameters tuning method based on the Z-N empirical equation, Cohen-Coon parameters tuning method, parameters tuning method based on Z-N Critical Proportional band and parameters tuning method based on system performance index [3]. These methods have played a positive role in the promotion of MFAC. However, the choice of the initial value of MFAC controller has a great influence on its control performance.

If the initial value changes, the control effect will also change. It leads to the difficulty during tuning the controller parameters of MFAC. Therefore, in this research work, it attempts to use the simplex optimization algorithm to automatically optimize parameters for different initial values of the MFAC controller parameters.

2 The Model-Free Adaptive Control

MFAC uses a novel concept pseudo partial derivative (PPD) (or pseudo-gradient or pseudo-Jacobi matrix) and an equivalent dynamic linearization data model at current operation point. The optimal controller is designed in the light of the estimation of the PPD online, which only makes use of the output and input data of the controlled plant [4–7].

The MFAC has the following advantages. (1) It only employs the input and output data of the controlled system. This shows that we are able to design the controller independently and we are able to build a universal controller. (2) Any training process and any external testing signals are not needed in the MFAC mechanism. This shows that the MFAC is low cost and less expensive. (3) It is simple and can be easily employed and carried out, and it has strong robustness and the minimum computational burden [4–7].

Following discrete-time SISO nonlinear systems is considered:

$$y(k+1) = f(y(k), y(k-1), \ldots, y\big(k-n_y\big), u(k), u(k-1), \ldots, u(k-n_u) \quad (1)$$

where n_y, n_u are the orders of output $y(k)$ and input $u(k)$, respectively, $f(\cdots)$ is a nonlinear function.

Rewrite Eq. (1) as:

$$y(k+1) - y(k) = \phi(k)[u(k) - u(k-1)] \quad (2)$$

where $\phi(k)$ is the PPD of controlled plant [4].

Aiming at the controlled system as Eq. (2), based on the MFAC, the control law can be given as follows [4]

$$u(k) = u(k-1) + \frac{\rho}{\lambda + \left|\hat{\phi}(k)\right|^2}\hat{\phi}(k)\big[y^* - y(k)\big] \quad (3)$$

where ρ is the control parameter, y^* is the desired output value of the system, λ is a proper constant, $\hat{\phi}(k)$ is the following PPD estimation of $\phi(k)$. $\hat{\phi}(k)$ can be calculated by Eq. (4).

$$\hat{\phi}(k) = \hat{\phi}(k-1) + \frac{\rho}{\mu + \Delta u(k-1)^2}\Delta u(k-1)\Big[\Delta y(k) - \hat{\phi}(k-1)\Delta u(k-1)\Big] \tag{4}$$

where $\hat{\phi}(k) = \hat{\phi}(1)$, if $\left|\hat{\phi}(k)\right| \le \varepsilon$, or $|\Delta u(k-1)| \le \varepsilon$. $\Delta u(k-1) = u(k-1) - u(k-2)$, η is the parameter which is added to increase flexibility of the algorithm, μ is a proper constant, $\Delta y(k) = y(k) - y(k-1)$, ε is a sufficiently small positive number.

3 Simulation Studies on Controlling Object with Uncertainty

3.1 Simulation Object and Parameter Settings

The static pressure model of central air conditioning is shown in Eq. (5).

$$G(s) = \frac{y(s)}{u(s)} = \frac{K}{Ts+1}e^{-\tau s} \tag{5}$$

where u is the input frequency of fan, y is the duct static pressure, K is the process gain, T is the system time constant, τ is the time-delay.

Due to the uncertainty resulting from the aging equipment, nonlinearity and other external factors, the parameters of Eq. (5) maybe change. The static pressure model built by identification during a certain period is shown in Eq. (6) [8]. Based on the results of reference [8], the final scope of changing parameters, K, T and τ are limited to be [3, 6], [4, 8], and [2, 10], respectively.

$$G(s) = \frac{4.20}{6.21s+1}e^{-4.87s} \tag{6}$$

In order to compare the control effects of the traditional PID and MFAC in the case of different changes of different parameters, the change of K, T, and τ is divided into three categories. The specific changes in the model parameters are shown in the first 3 columns of Table 1. The initial values of the controller parameters of PID and MFAC are assigned as the following. $k_P = 0.1842$, $k_I = 0.023$, $k_D = 0.2218$. $\mu = 1.55$, $\lambda = 1.65$, $\eta = 0.009$, $\rho = 0.14$.

Simulation studies were carried out with the PID and MFAC control strategies, respectively, in the case of parameter changes. The simulation results are shown in Table 1. Due to the limitation of paper length, four kinds of simulation results are shown here. The simulation results with the original parameters of the model are shown in Fig. 1. The simulations with a single parameter change of process gain K, time constant T and time-delay τ, respectively, are shown in Figs. 2, 3 and 4.

Table 1 The model parameters and simulation results

Model parameters	Parameters change	PID control		MFAC	
		Settling time/s	Overshoot/%	Settling time/s	Overshoot/%
$K = 4.20$, $T = 6.21$, $\tau = 4.87$	Primitive parameters	37	0	163	0
$K = 6$, $T = 6.21$, $\tau = 4.87$	One parameter changes	48	8.25	151	2.51
$K = 3$, $T = 6.21$,$\tau = 4.87$		62	0	258	0%
$K = 4.20$, $T = 8$,$\tau = 4.87$		54	3.30	205	0.99
$K = 4.20$, $T = 4$, $\tau = 4.87$		54	0	178	0
$K = 4.20$, $T = 6.21$, $\tau = 10$		105	39.96	206	2.04
$K = 4.20$, $T = 6.21$, $\tau = 2$		55	0	183	0

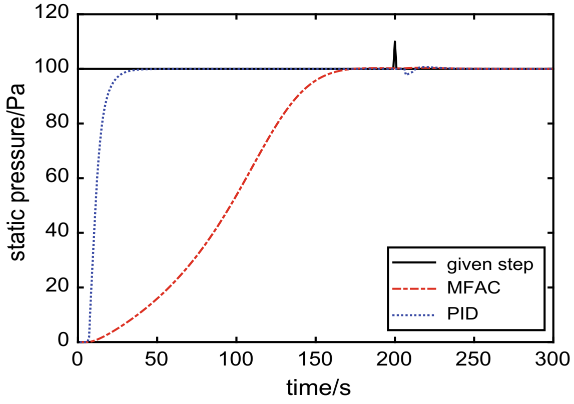

Fig. 1 The simulation based on primitive parameters

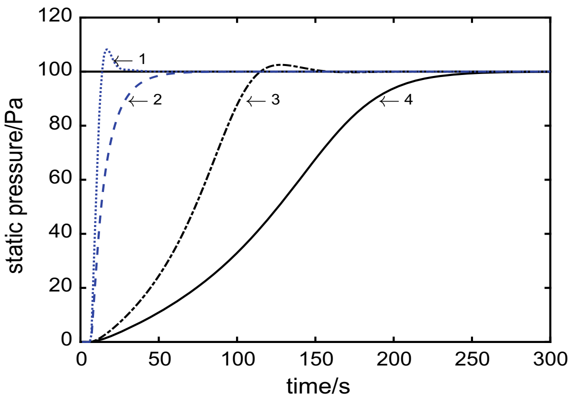

Fig. 2 The simulation based on changed parameter K. 1—PID: $K = 6$, $T = 6.21$, $\tau = 4.87$; 2—PID: $K = 3$, $T = 6.21$, $\tau = 4.87$, 3—MFAC: $K = 6$, $T = 6.21$, $\tau = 4.87$; 4—MFAC: $K = 3$, $T = 6.21$, $\tau = 4.87$

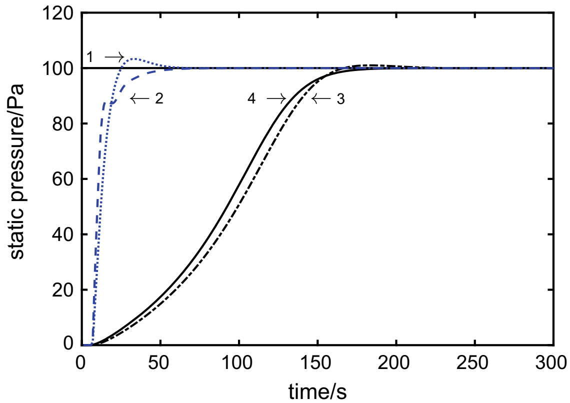

Fig. 3 The simulation based on changed parameter T. 1—PID: $K = 4.2$, $T = 8$, $\tau = 4.87$; 2—PID: $K = 4.2$, $T = 4$, $\tau = 4.87$, 3—MFAC: $K = 4.2$, $T = 8$, $\tau = 4.87$; 4—MFAC: $K = 4.2$, $T = 4$, $\tau = 4.87$

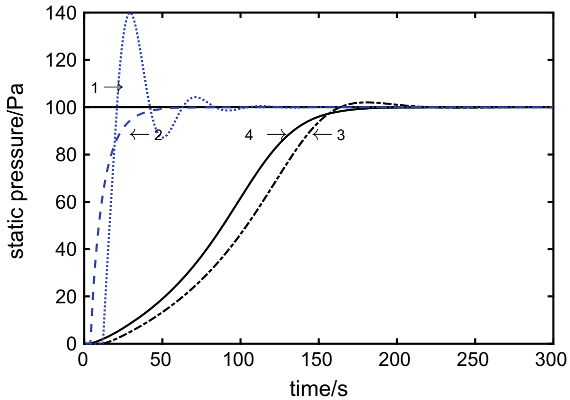

Fig. 4 The simulation based on changed parameter τ. 1—PID: $K = 4.2$, $T = 6.21$, $\tau = 10$; 2—PID: $K = 4.2$, $T = 6.21$, $\tau = 2$, 3—MFAC: $K = 4.2$, $T = 6.21$, $\tau = 10$; 4—MFAC: $K = 4$, $T = 6.21$, $\tau = 2$

3.2 Analysis of Simulation Results

For the original model, the results of control simulation in this study show that the overshoots of both methods are 0%. The settling time is 37 s by PID control, and it is 163 s by MFAC control. For anti-interference capability, when a perturbation amplitude of 10 is added in input at $t = 200$ s, the output fluctuates by PID control, its size is -2.26 and the settling time of this disturbance is 17 s and the output by MFAC control has a smaller fluctuation with a size of 0.39, and the settling time for this disturbance is 15 s. This indicates that when MFAC is adopted, the system has good anti-interference performance, good stability, and short recovery time.

Based on the above analysis, the following conclusions can be obvious. (1) The anti-interference performance of MFAC is better than that of PID. That is to say, if the system is disturbed, the system controlled by MFAC method has good immunity, stability and short recovery time. (2) From the effect of settling time and overshoot, For MFAC, the change of process gain K has a great influence on the settling time. The change of inertia time constant T and time-delay τ has little effect on the settling time, and the change of three parameters has little effect on the overshoot. For PID control, the change of process gain K and time-delay has a greater impact on overshoot and settling time, and the inertia time constant T has a great effect on overshoot and has little effect on the settling time.

It is obvious that the one-order plus time-delay process model with uncertainties in HVAC systems, especially with high anti-interference requirements, large delays and uncertain delays, the control performance of MFAC is superior to that of PID.

4 MFAC Parameter Optimization

So far, there are no very simple and useful methods for tuning and optimizing the controller parameters, λ, ρ, η, and μ, of MFAC. In addition, the initial values of controller parameters dramatically affect the control results. Therefore, it is hard to obtain the optimal controller parameters. In order to obtain the optimal controller parameters, the optimization theory is introduced to this paper. For multivariate optimization, there are some methods, conjugate gradient method, steepest descent method, random optimization method, and simplex method, to be chosen. In general, the random optimization method is suitable for optimizing many parameters. Conjugate gradient method and steepest descent method will take long time to optimizing parameters because of calculating the gradient of objective function in each step. The simplex method uses the comparison of the objective function values of different parameter points to determine the optimal direction, and does not require gradient information. It is more suitable for occasions where there are not many variables to be optimized [9]. Therefore, the basic simplex method is chosen to auto-optimize the controller parameters of MFAC for any given initial values.

4.1 The Basic Idea of the Simplex Method

Simplex is an optimization technique that does not require complex mathematical and statistical tools. It does not need to calculate the gradient of the objective function. There are four basic steps: expansion, contraction, compression, and discarding, during the optimizing process. The basic idea of simplex is described as follows. Take $(n + 1)$ points in the n-dimensional space to form the initial simplex, compare the values of the objective function at the $(n + 1)$ point, discard the worst point that is the point with the largest function value, and replace it with the new point to form a new simplex. By iterating, the value of the function at its vertex gradually decreases, and the vertex gradually approaches the minimum point of the objective function. If it is required to solve the maximum or minimum point of function, the values of function at several points can be obtained and compared, and the changing trend of the function can be determined based on their size relationship, which can decide the reference direction of the search. The minimum or maximum value will be found according to the reference direction of the search [10].

4.2 Simplex Parameter Optimization Design Based on Simulink

Selection of Objective Function. The control performance must be measured and determined according to the performance index, and the performance index usually adopts the objective function. In practice, the function of the deviation between the reference input and the actual system response is used as the objective function. It also called the error objective function. The objective function mainly includes the integration of the error square, the integral of the time and the square of the error, the integral of the absolute value of the error, the integration of the time and the absolute error. The integral function of time and squared error is used as the objective function in this paper. It is shown as Eq. (7).

$$J_{ITSE} = \int_0^{\infty} te^2(t)dt \tag{7}$$

Programming

Main Program Design. The main program of the MFAC parameter optimization design based on the simplex method is shown as follows:

```
global rou;
global lambda;
global eta;
global miu;
```

```
global i;
i=1;
m0=[0.005 1 0.001 1]
[m,n,o,p]=fminsearch('optm',m0)
```

In the program, the four controller parameters, λ, ρ, η, and μ denoted as lambda, rou, eta, and miu, respectively, of MFAC are defined as global variables. i is a loop variable. The vector m0 is the initial value of λ, ρ, η and μ. The fminsearch function is used in the main program. It is a function for solving unconstrained nonlinear programming, and it uses a simplex algorithm. It works as the following:

$$[\mathrm{x,fval,exitflag,output}]=\mathrm{fminsearch(fun,x0,options)}$$

In the function, fun is the objective function, x0 is the starting point for optimizing search. Options are option parameters for setting optimization. x is the return value of the optimization parameter. fval is the return function value at the optimal point x. exitflag is the termination flag of the return algorithm. Output is a return data structure of optimization algorithm information.

The Optimization Module Based on Simulink. The optimization program based on Simulink is shown in Fig. 5.

The objective function is an integral function of the time and error squared product constructed. The fcn2 function module is error squared and the clock module is the time. Subsystem is the package module of MFAC [11, 12].

4.3 Simulation on Optimizing the Controller Parameters of MFAC

Considering that one characteristic of model-free adaptive control is insensitivity to time-delay, the mathematical model of the simulation object still uses the previous fan static pressure model. It is shown as Eq. (6). This model is a one-order plus

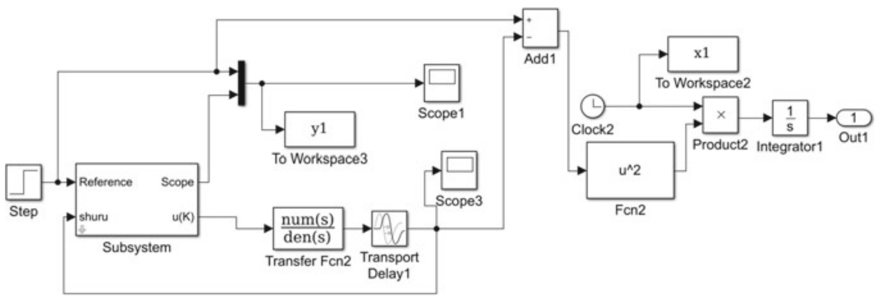

Fig. 5 The optimizing parameter based on Simulink

Table 2 The parameters of MFAC and control result

	Initial value		Optimal value	
ρ	0.15	0.5	0.2236	0.5935
λ	2.2	4	1.3956	3.7836
η	0.11	0.1	0.1183	0.1069
μ	2	4	1.3106	3.6486
Overshoot/%	0	0	5.02	4.79
Settling time/s	500	120	70	40

time-delay process model. Because of $f = \tau/T = 4.87/6.21 = 0.784 > 0.5$, the model has a large delay.

In order to verify the parameter optimization effect of MFAC based on the simplex method, 2 groups of initial parameters were given at random and the optimizations are realized. The initial values and optimal values of the parameters and the control effects are shown in Table 2. The settling time is calculated based on the relative error that is 5%.

The simulation results with 2 groups of initial parameters and 2 groups of optimized parameters are shown in Figs. 6 and 7.

The simulation of parameters optimization shows that the optimization results with the simplex method are affected by the initial values of the parameters and that the optimization results maybe change when the excitation signals change. In general, based on the simulation of one-order plus time-delay process model with the simplex method, the following conclusion can be concluded. (1) As long as the reasonable initial controller parameters of MFAC are given, the optimized parameters can be found based on the simplex method. (2) The constraint range of parameter values, $\rho, \eta \in (0, 2)$, is given in Ref. [2], which ensures that any system that satisfies the

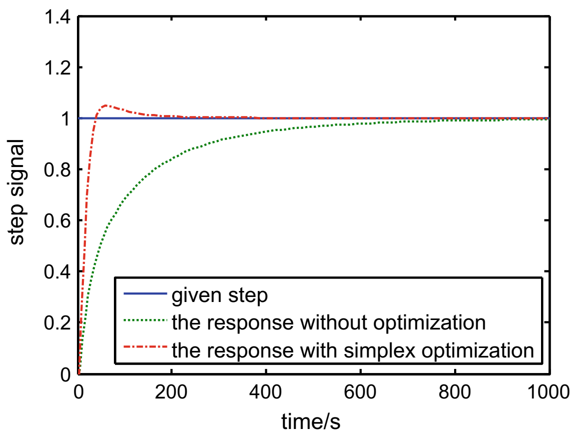

Fig. 6 The simulation result with the first set of parameters

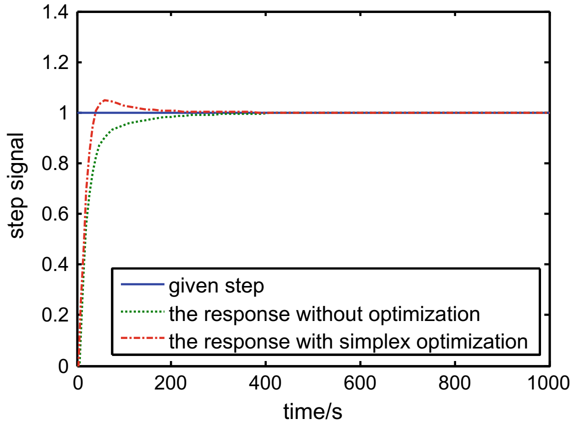

Fig. 7 The simulation result with the second set of parameters

constraints can achieve bounded parameter estimation error and the convergence of output error. The value of ρ and η can change according to the controlled system.

5 Conclusions

The performance of MFAC is studied based on the one-order inertial plus time-delay model with uncertainties in an HVAC system. The results show that MFAC has good stability and anti-interference performance and that MFAC is insensitive to delay variation. At the same time, aiming at the blindness of setting controller parameters of MFAC, the simplex method is used to optimize MFAC controller parameters. The simulation results show that the initial values of MFAC controller parameters are different and the optimized values are different, but the control results with the same optimized parameters are good.

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References

1. Sanz, R., García, P., Albertos, P.: A generalized smith predictor for unstable time-delay SISO systems. ISA Trans. **72**(1), 197–204 (2018)
2. Hou, Z.S., Jin, S.T.: A novel data-driven control approach for a class of discrete-time nonlinear systems. IEEE Trans. Control. Syst. Technol. **19**(6), 1549–1558 (2011)
3. Hou, Z.S., Zhu, Y.M.: Model based control and MFAC, which is better in simulation? IFAC Proc. Vol. **46**(13), 82–87 (2013)

4. Hou, Z.S., Xu, J.X.: On data-driven control theory: the state of the art and perspective. Acta Autom. Sin. **35**(6), 650–667 (2009)
5. Han, Z.G.: An integrated approach to modeling and adaptive control. Acta Autom. Sin. **30**(3), 380–389 (2006)
6. Hou, Z.S., Gao, H.J.: Data-driven control and learning systems. IEEE Trans. Industr. Electron. **64**(5), 4070–4075 (2017)
7. Hou, Z.S., Chi, R.H.: An overview of dynamic-linearization-based data-driven control and applications. IEEE Trans. Ind. Electron. **64**(5), 4076–4090 (2017)
8. Yang, S.Z., Ren, Q.C.: Robust control based on fan model uncertainty. Meas. & Control. Technol. **32**(10), 69–74 (2013). (in Chinese)
9. Kudinov, Y.I., Kolesnikov, V.A., Pashchenko, F.F.: Optimization of fuzzy PID controller's parameters. Procedia Comput. Sci. **103**, 618–622 (2017)
10. Aekarin, S., Wudhichai, A.: Particle swam optimization based optimal PID parameters for air heater temperature control system. Procedia Comput. Sci. **86**, 108–111 (2016)
11. Li, C.Q., Liu, G.S.: Development & simulation of MFA control module based on Matlab-Simulink. Control. Eng. China **15**(9), 61–63 (2008). (in Chinese)
12. Liu, X.Q., Wang, Y., Mu, S.Y.: Design of optimal parameters for PID controller Based on Simplex Search. Comput. Simul. **21**(11), 191–194 (2005). (in Chinese)