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Multi-parameter decoupling and slope tracking control strategy of a large-scale high altitude environment simulation test cabin

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Liquid nitrogen;
Mathematical model;
Vacuum

Abstract A large-scale high altitude environment simulation test cabin was developed to accurately control temperatures and pressures encountered at high altitudes. The system was developed to provide slope-tracking dynamic control of the temperature–pressure two-parameter and overcome the control difficulties inherent to a large inertia lag link with a complex control system which is composed of turbine refrigeration device, vacuum device and liquid nitrogen cooling device. The system includes multi-parameter decoupling of the cabin itself to avoid equipment damage of air refrigeration turbine caused by improper operation. Based on analysis of the dynamic characteristics and modeling for variations in temperature, pressure and rotation speed, an intelligent controller was implemented that includes decoupling and fuzzy arithmetic combined with an expert PID controller to control test parameters by decoupling and slope tracking control strategy. The control system employed centralized management in an open industrial ethernet architecture with an industrial computer at the core. The simulation and field debugging and running results show that this method can solve the problems of a poor anti-interference performance typical for a conventional PID and overshooting that can readily damage equipment. The steady-state characteristics meet the system requirements.

1. Introduction

A multi-parameter large-scale high altitude environment simulation test cabin can simulate multiple parameters of aircraft flying at high altitudes. It has important significance to develop the linear passenger aircraft and large military transport aircraft.[1–3] With the improvement of the aircraft environmental control system test requirements, aimed at saving effective cost, environmental cabin is designed to achieve low temperature, low pressure and temperature shock test in the same

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chamber. A multi-parameter large-scale high altitude environment simulation test cabin is shown in Fig. 1. The system consists of a refrigeration system, a vacuum system, an environmental cabin and an observation and control system. The cabin can be used for ground simulation tests of equipment that subject to temperatures and pressures of high altitude. Fig. 2 shows a flowchart describing test procedures with the cabin. The system is operated as described below. When there is no requirement for a given cooling rate, the air refrigeration turbine can be used as a cooling device, based on the cabin temperature control requirements, by opening the control turbine inlet with pneumatic valve QF1. Opening QF1 could not only change the cooled turbine inlet pressure and the corresponding cooling turbine expansion ratio and adjust the temperature drop passing the turbine, but also change the flow in the cooling turbine. Therefore opening QF1 could effectively adjust the amount of the refrigerant in the refrigeration turbine and control the cabin temperature. By adjusting the cold air inlet tube pneumatic valve QF2, the flow of cold air going to the turbine outlet and the back of the environmental cabin is controlled, which means the cabin temperature may be controlled. When there is a requirement for rapid cooling and depressurization, liquid nitrogen should be primarily used for refrigeration. Adjust the inlet tube pneumatic valve QF6, which connects liquid nitrogen tank and environment cabin. This will control the cabin cooling rate. At the same time, the cooling air made by turbine is accessed directly into an orifice plate and there is radiation cooling under a low pressure environment. It is needed to ensure the turbine speed via controls QF2 and QF3. Therefore the temperature control of the environmental cabin is actually a control of the pneumatic control valve. The simulation of the environmental cabin's low pressure is achieved by a vacuum pump working continuously while controlling the exhaust valve QF4 and the fill valve QF5, as shown in Fig. 2. The advantage of this method is that tests could quickly realize a variety of pressures as may be required to mimic various altitudes. However, there is a multi-parameter control coupling in the large-scale multi-parameter high altitude environment simulation and a large inertial lag link, especially when it is simulating high-altitude environment. The system thus needs slope tracking control to overcome the control difficulties of meeting control precision requirements, when it is cooling and depressurizing.

Fig. 1 Large multi-parameter environmental simulation test cabin.

In the system control aspect of environment simulation equipment, Dong et al. proposed use of a double PID controller to control the environmental chamber temperature,[4] while Yuan and Li proposed to use a PI controller to control the pressure.[5] Pang et al. proposed the use of a fuzzy PID controller to control the electric heater in the central air-conditioning system.[6,7] Zhao and Song designed a fuzzy PID controller to control the temperature and the pressure of the cabin separately,[8,9] however they did not give the way to control them at the same time. To solve the difficulty in tracking and controlling the slope of the curve in a multi-parameter large-scale high altitude simulation chamber test equipment, the refrigeration equipment needs to be safe in service.[2] This paper proposes a decoupling and slope tracking control strategy, and a fuzzy control strategy combined with an expert PID judge is used to slope track and automatically control the temperature and pressure parameters. Fuzzy algorithms have the advantages of being simple, flexible, easy adjustment with a small amount of calculation, practical, rapidity, strong stability, high robustness, and the ability to achieve high control accuracy.[10–12] The introduction of expert judgment can reduce the problems associated with the turbine rate, bring the refrigeration system to a stable state as soon as possible and improve the efficiency of the experiment. Using this method will solve the multi-parameter slope curve control problem of cooling while depressurizing and have better control accuracy, thereby ensuring the normal operation of large-scale multi-parameter environmental simulation tests.

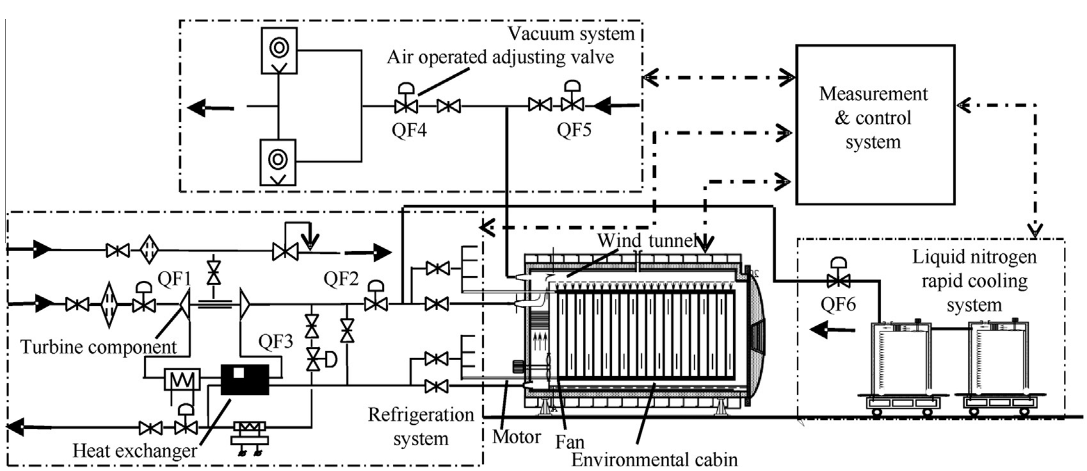

Fig. 2 Flowchart of large multi-parameter environmental simulation test cabin.

2. Model of a multi-parameter cabin control system

2.1. Temperature model

Low temperature control in the environmental cabin is actually carried out by controlling the opening of the cold-air adjusting valve QF2 to change the cold-air flow entering the cabin. From conservation of energy, the following lumped parameter model can be established to describe the change law of temperature in the cabin:

$$\sum_{i=1}^{n} M_i C_i \frac{dT}{dt} = Q_{in} - Q_{out} - Q_x - Q_w - Q_e \quad (1)$$

where Q_{in} and Q_{out} are the cold-air quantities entering and leaving the cabin, respectively; Q_x is the air heat leak power; Q_w and Q_e are cold quantities absorbed by the bulkhead and samples, respectively.

It is assumed that the air heat leak power is directly proportional to the temperature difference between the inside and outside of the cabin, so Q_x can be formulated as follows:

$$Q_x = k_h (T_c - T_0) \quad (2)$$

where k_h is the heat leak coefficient and T_c and T_0 are the temperatures inside and outside the cabin, respectively.

Q_w is the power of convective heat transfer through the bulkhead to the cabin air. The heat transfer equation is formulated as follows:

$$Q_w = W_{in} C (T_w - T_c) \left[\exp\left(-\frac{(hA)_w}{W_{in} C} \right) - 1 \right] \quad (3)$$

where W_{in} is the cold-air mass flow entering the cabin, $(hA)_w$ the product of the bulkhead heat transfer coefficient and area, T_w the bulkhead temperature, and C the constant pressure specific heat coefficient.

Q_e is the cold-air quantity absorbed by the samples in the way of the air convection in the cabin, which can be formulated as follows:

$$Q_e = (hA)_e (T_e - T_c) \quad (4)$$

where $(hA)_e$ is the product of the sample heat transfer coefficient and area and T_e the sample temperature.

Q_{out} is the cold-air quantity leaving the cabin, which has the following formulation:

$$Q_{out} = \frac{W_{out} C (T_0 - T_c)}{3600} \quad (5)$$

where W_{out} is the cold-air mass flow entering the cabin, which can be calculated by the following expression in accordance with resistance equation:

$$W_{out} = \sqrt{\frac{2(P_c - P_o)}{f\rho}} \quad (6)$$

Thus, it follows that:

$$Q_{out} = \sqrt{\frac{2(P_c - P_o)}{f\rho}} \cdot \frac{C(T_0 - T_c)}{3600} \quad (7)$$

where P_c and P_o are the pressure of the cabin and the pressure of environment which is outside of cabin. The parameters f and ρ are the resistance coefficient and air density, respectively.

Q_{in} is the cold-air quantity entering the cabin, has the following formulation:

$$Q_{in} = \frac{W_{in} C (T_1 - T_c)}{3600} \quad (8)$$

where T_1 is the cold-air temperature.

2.2. Pressure model

The cabin pressure depends on the air capacity. According to conservation of mass, it follows that:

$$\frac{dW_g}{dt} = W_{in} + W_x - W_{out} \quad (9)$$

where W_g and W_x are the air mass flow inside the cabin and the air leakage mass flow of the cabin. Substituting the ideal gas law ($PV = RT_0$) into the above equation, it follows that:

$$\frac{dP_c}{dt} = \frac{RT_c}{V} (W_{in} + W_x - W_{out}) \quad (10)$$

Fig. 2 shows that the low pressure environment simulation in the cabin is obtained by controlling the pumping valve QF4 and air supply valve QF5. At the same time the valve QF2 which is connected with cabin should be closed to reduce the quality of air entering the cabin. Assuming the vacuum system is sufficiently large and W_{in} can equal zero, to maintenance a low pressure environment in the cabin, the way to control pressure is to control the supply air flow from QF5. The lumped parameter equation is then

$$\frac{dP_c}{dt} = \frac{RT_c}{V_c} (W_x - W_{out}) \quad (11)$$

The conversion relationship between the ability of the vacuum system and W_{out} depends on the altitude H simulated by environment simulation test cabin corresponding to the air density, which can be formulated as follows:

$$\rho_H = 1.225 \left(1 - \frac{H}{44300} \right)^{4.256} \quad (12)$$

where ρ_H is the air density.

2.3. Actuator model

2.3.1. The air-operated adjusting valve model

The relationship between W_{in} and the control variable l, i.e., the valve opening and flow, can be obtained from the flow characteristics of the adjusting valve as follows[8]:

$$\frac{W_{in}}{W_{max}} = f\left(\frac{l}{l_{max}} \right) \quad (13)$$

Denote $R_L = W_{max}/W_{min}$, where R_L is the regulation ratio, and l/l_{max} are the ratios of flows and trips, respectively, with the valve having either some or full opening. Most valves used in air conditioning have logarithmic flow or percentage flow characteristics. The mathematical expression is shown as follows:

$$\frac{W_{in}}{W_{max}} = R_L^{\left(\frac{l}{l_{max}} - 1\right)} \quad (14)$$

It can be seen from the above expression that the valve curve is nonlinear.

2.3.2. The refrigeration turbine model

The simulation model is implemented in MATLAB-Simulink on the basis of a positive compressor turbine air refrigeration program in an environmental cabin. The mathematical model of the turbine expansion system needs to be built. The simulation model includes a first-order inertial element, which can be formulated as follows[13–15]:

$$Q_t = C_v\left[T_{ti}\left(1-\frac{1}{\pi_t^{0.286}}\right)\eta_t - (T_{hi}-T_c)(1-\eta_h)\right] \tag{15}$$

$$T_{ti} = (T_{hi}-T_c)\eta_h \tag{16}$$

where Q_t is the specific refrigerating effect, T_{ti} the turbine inlet temperature, π_t the expansion ratio of the expender; η_t and η_h are the efficiencies of the expander and heat transfer efficiency respectively; T_{hi} is the imported temperature of heat exchanger and C_v represents the specific volume of the air.

3. Design of control system

The control system of a large multi-parameter environmental simulation testing cabin is composed of two parts: hardware and software. The hardware adopts the core structure of an industry computer based on the industrial Ethernet[16–18] as shown in Fig. 3 and includes a master control computer, a test and measurement computer, a switch, industrial Ethernet IEEE802.3, fiber shielded wire, DO, DI, A/D, D/A, a temperature sensor, a pressure sensor, and a flow sensor.

The software adopts a thread and mission management operation platform based on Windows XP. The object-oriented and modular method[19–21] is used in the design of software. Fig. 3 shows the main module of the master control computer including the multi-thread and mission manager module, the real-time control and calculation module, real-time data save, real-time data charge, real-time data display, and the hardware manager. In addition, databases such as an information database and a result database have been included.

The control of temperature and pressure is shown in Fig. 4. The automatic control of the entire low temperature experiment, controlled by the computer, can be divided into the following 4 steps.

Step 1. Automatic turbine start.

The opening of the air-operated adjusting valve QF1 at the turbine entrance is controlled, which should be opened slowly. The turbine revolution speed should be controlled within the permissible maximum to prevent equipment damage.

Step 2. Automatic temperature decrease.

The revolution speed is controlled in the control setting range. After the cabin temperature slowly decreases to the control setting range, the insulation process begins.

Step 3. Automatic insulation control.

A constant cabin temperature is maintained. In addition, the control error of the cabin temperature should conform to GB or the military standard.

Step 4. Automatic turbine stop.

The opening of the adjusting valve QF1 at the turbine entrance is controlled, which should be closed slowly. The adjusting valve QF2 should be closed after the turbine is stopped.

Based on the above control processes, the controller can be designed shown in Fig. 4. $E(S)$ is the set parameter of the system and $V(S)$ is the actual control parameter value .The design includes the fuzzy controller, an expert PID controller and the mode-selective switch. The processes of the automatic start and temperature decrease of the turbine can be carried out by the fuzzy controller and the expert PID controller. During the insulation process, the control of the temperature in the cabin can be realized mainly by the expert PID controller. Higher control accuracy can be achieved as a result of the introduction of the integration item.[22]

When the revolution speed is considered as the controlled object, its deviation e and deviation change rate e_c, applied as the control inputs, can be obtained by comparing the revolution speed n measured by the revolution speed sensor with the setting revolution speed n_0. The choice between the expert PID control and fuzzy control is made based on the setting value, that is, the fuzzy control is adopted when e is greater than the setting value, otherwise the expert PID control is adopted.

4. Controller

4.1. Expert-fuzzy PID controller

By measuring and then calculating the actual measuring value and setting value, we get error e and error change rate $\triangle e$ as control input variable, which can be observed from control configuration for the turbine refrigeration system shown in Fig. 4. Using expert control or fuzzy PID control is decided by the final state of switch. That means, when error is greater than the switch setting, fuzzy PID control method will be used; when error is less than the setting value, the switch is set using expert control method.

Expert controller can work to maintain the same output of controller to keep control variable, when the measured value reaches the precision range of experimental requirements. So it could avoid the occurrence of concussion in the range of setting value permissible error and quickly reach the experimental requirements. Expert controller is mainly made up of expert judgment and mainly shown as if-then sentence in program.[23–26]

Fuzzy PID controller is based on conventional PID regulator using fuzzy theory to build function relationship between the proportional, integral, differential coefficients k_p, k_i, k_d with error absolute value $|E|$ and error change rate absolute value $|\Delta E|$, according to the method of online self-tuning parameters k_p, k_i, k_d by different $|E|$ and $|\Delta E|$. The general type of conventional PID regulator control method can be expressed as follows:

$$U(k) = k_p e(k) + k_i\sum e(k) + k_d \Delta e(k) \tag{17}$$

where $k = 0, 1, \ldots, n$; $e(k)$ and $\triangle e(k)$ are error and error change rate respectively.

The design of expert-fuzzy self-adaption PID controller could be designed with 5 steps as follows.

Step 1. Fuzziness.

To realize coarse tuning and fine tuning of fuzzy control method, the actual domain of discourse of error $e(k)$ and error change rate $e(k)$ can be translated into a greater exact domain

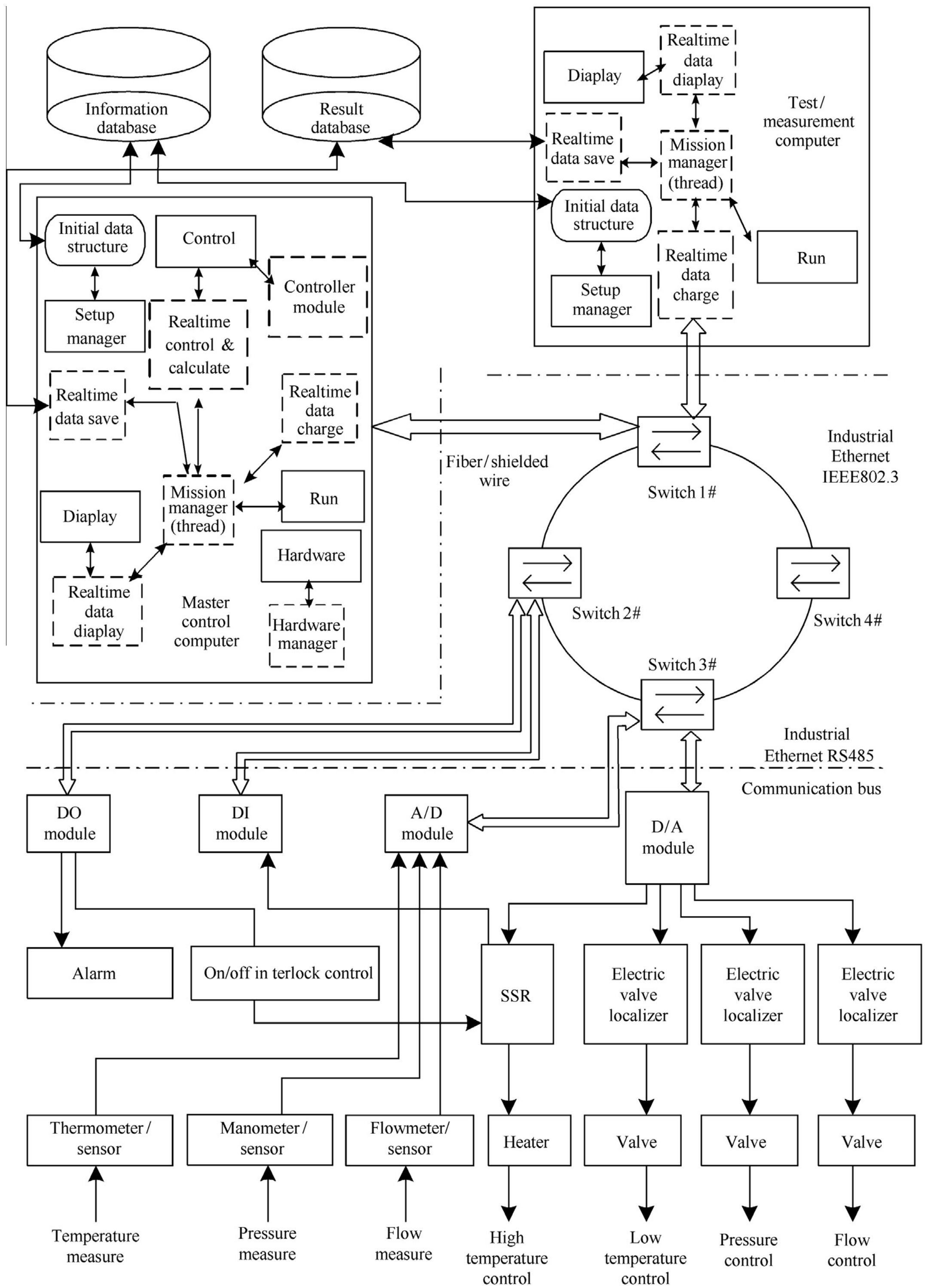

Fig. 3 Industrial Ethernet control system.

of discourse [−60, 60], in which 60 is the maximum of temperature change and can be expressed as follows:

$$|e| = \begin{cases} \ln\left(\frac{|e(k)|}{3}\right) & |e(k)| > 3 \\ 0 & -3 \leqslant e(k) \leqslant 3 \end{cases} \tag{18}$$

$$|\Delta e| = \begin{cases} \ln\left(\frac{|\Delta e(k)|}{3}\right) & |e(k)| > 3 \\ 0 & -3 \leqslant e(k) \leqslant 3 \end{cases} \tag{19}$$

Then the change of $|e|$ and $|\Delta e|$ can be obtained, and the dynamic range was greatly compressed and plugged into two fuzzy variables E and $\triangle E$, both of which contains a fuzzy

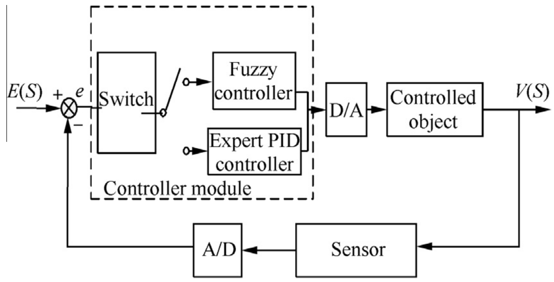

Fig. 4 Control configuration for turbine refrigeration system.

set {NB, NM, NS, Z, PS, PM, PB}. NB represents negative big, NM represents negative, NS represents negative small, Z represents zero, PS represents positive small, PM represents the median, and PB represents positive big.

The membership function of linguistic variables E and ΔE could use desirable linear function or nonlinear function according to the actual situation, and their membership function curve is shown in Fig. 5, and fuzzy PID input, output, rules diagram are shown in Fig. 6.

Step 2. Establishing rules of inference.

Establishing the relevant k_p, k_i, k_d fuzzy inference rule of control system in Tables 1–3 as follow.

Step 3. Fuzzy inference and defuzzification.

According to system sampling E and ΔE, the controller parameters can be calculated by Eq. (20). Every part relationship of rule antecedent is "and", so AND operation can be selected.

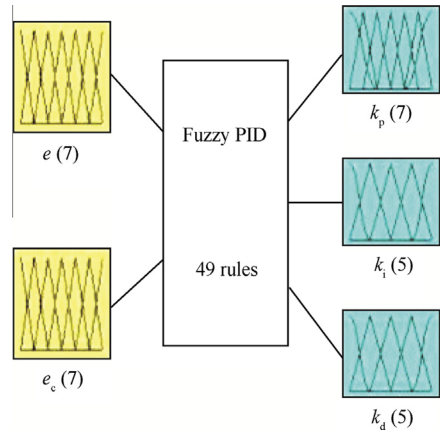

Fig. 6 Fuzzy PID input, output, rules relational graph.

Table 1 k_p fuzzy inference ruler graph.

E	ΔE						
	NB	NM	NS	ZO	PS	PM	PB
NB	PB	PB	PM	PM	PS	ZO	ZO
NM	PB	PB	PM	PS	PS	ZO	NS
NS	PM	PM	PM	PS	ZO	NS	NS
ZO	PM	PM	PS	ZO	NS	NM	NM
PS	PS	PS	ZO	NS	NS	NM	NM
PM	PS	ZO	NS	NM	NM	NM	NB
PB	ZO	ZO	NM	NM	NM	NB	NB

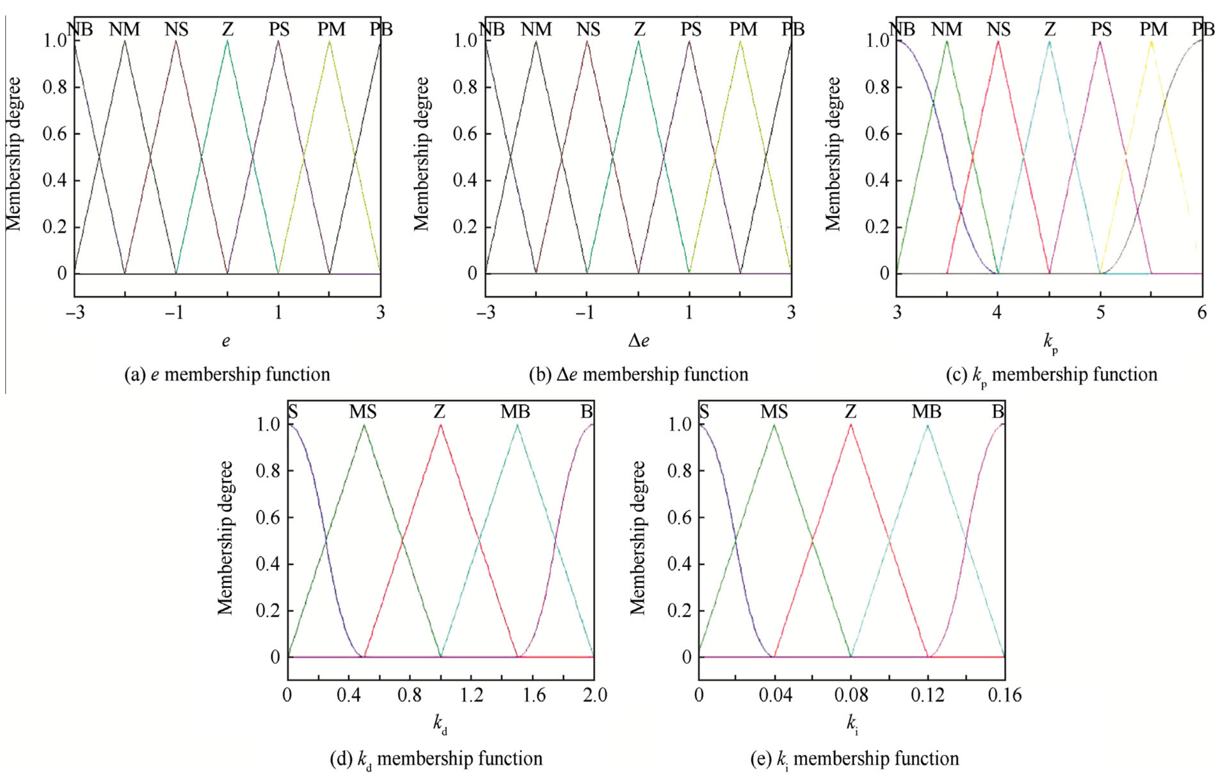

Fig. 5 Membership function curves.

Table 2 k_i fuzzy inference ruler graph.

E	ΔE						
	NB	NM	NS	ZO	PS	PM	PB
NB	NB	NB	NM	NM	NS	ZO	ZO
NM	NB	NB	NM	NS	NS	ZO	ZO
NS	NB	NM	NS	NS	ZO	PS	PS
ZO	NM	NM	NS	ZO	PS	PM	PM
PS	NM	NS	ZO	PS	PS	PM	PB
PM	ZO	ZO	PS	PS	PM	PB	PB
PB	ZO	Zo	PS	PM	PM	PB	NB

Table 3 k_d fuzzy inference ruler graph.

E	ΔE						
	NB	NM	NS	ZO	PS	PM	PB
NB	PS	NS	NB	NB	NB	NM	PS
NM	PS	NS	NB	NM	NM	NS	ZO
NS	ZO	NS	NM	NM	NS	NS	ZO
ZO	Zo	NS	NS	NS	NS	NS	ZO
PS	ZO	ZO	Zo	zO	Zo	ZO	ZO
PM	PB	NS	PS	PS	PS	PS	PB
PB	PB	PM	PM	PM	PS	PS	NB

$$\begin{cases} k_p = \dfrac{\sum_{j=1}^{9}\mu_j(E,\Delta E)k_{pj}}{\sum_{j=1}^{9}\mu_j(E,\Delta E)} \\ k_i = \dfrac{\sum_{j=1}^{9}\mu_j(E,\Delta E)k_{ij}}{\sum_{j=1}^{9}\mu_j(E,\Delta E)} \\ k_d = \dfrac{\sum_{j=1}^{9}\mu_j(E,\Delta E)k_{dj}}{\sum_{j=1}^{9}\mu_j(E,\Delta E)} \end{cases} \tag{20}$$

Step 4. Obtaining of parameter.

When error $|E|$ is big, to let the system have better quickly tracking performance, no matter how the error variation trend changes, bigger k_p and smaller k_d should be selected. At the same time, to avoid bigger overshoot of system response, the integral action should be limited and selected a smaller k_i. When error $|E|$ is medium big, to let the system have smaller overshoot, k_p should be smaller. And meanwhile to ensure the response speed of system, k_i and k_d should be medium. The value of k_d have great influence on the system response. When error $|E|$ is smaller, to ensure system have better steady-state performance, k_p and k_i should be bigger. Meanwhile to avoid system occur oscillation nearby the set value and consider the performance of anti-jamming of system, when $|\Delta E|$ is smaller, k_d should be selected bigger. When $|\Delta E|$ is bigger, k_d should be selected smaller. The parameters of fuzzy self-adaption PID controller are k_p, k_i, k_d shown in Eq. (17) and are k_{pj}, k_{ij}, k_{dj} ($j = 1, 2, \ldots, 9$) weighted in Eq. (20), thus realizing online self-adaption of the three parameters.

Step 5. Adding expert judgment.

When the measured value is close to the size of the set value, and the error of accuracy and the mode selection switch is set to expert control state, the output of the controller maintains constant. That means $u(k) = u(k-1)$; it allows measured value to stabilize. When the measured value exceeds the steady error accuracy range and then it is switched to adaptive PID controller state.

Step 6. Table of control rules.

The fuzzy control rules, described by "IF—THEN" statements, can be transformed into the following form by the experiment analysis and simulation adjustments:

R_{ij} : if e is A_i and e_c is B_j, then u is C_{ij}

where $i = 1, 2, \ldots, 6$; $j = 1, 2, \ldots, 5$. The inference results of the corresponding control rules to the fuzzy inputs and outputs are shown in Fig. 7.

4.2. Expert-parameter compensation decoupling control

As the test parameters' coupling degree is different judging from the results of the simultaneous low temperature and depressurizing environment simulation test, two control methods can be used to control.

(1) When the degree of parameter coupling is relatively low.

We directly use a double PID to realize multivariable control, as shown in Fig. 8. A double PID control system diagram consists of a double loop PID controller, where the control algorithm is:

$$u_1(k) = k_{p1}e_1(k) + \frac{k_{d1}}{T_s}(e_1(k) - e_1(k-1)) + k_{i1}\sum_{i=1}^{k} e_1(i)T_s \tag{21}$$

$$u_2(k) = k_{p2}e_2(k) + \frac{k_{d2}}{T_s}(e_2(k) - e_2(k-1)) + k_{i2}\sum_{i=1}^{k} e_2(i)T_s \tag{22}$$

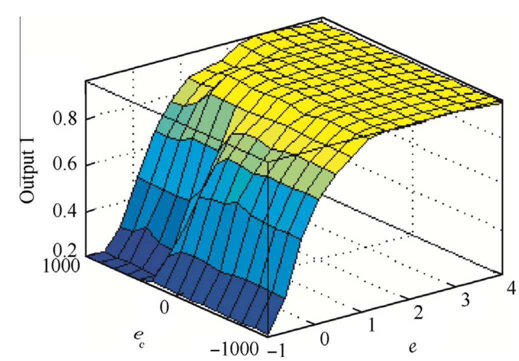

Fig. 7 Three-dimensional chart of the inference of fuzzy control rules.

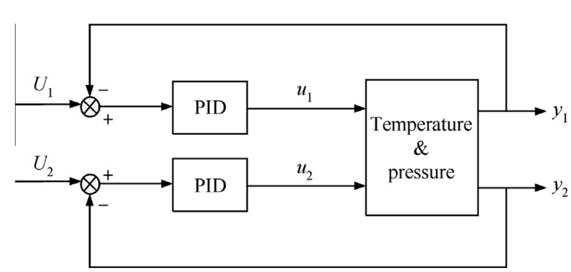

Fig. 8 Double PID control system.

where T_s is the sampling time, and e is error which is calculated by:

$$e(k) = U(k) - y(k) \tag{23}$$

Replace the PID controller into various kinds of intelligent controller, as shown in Fig. 9. This forms a double variant expert control system that can provide expert judgment.

(2) When degree of parameter coupling is relatively high.

As the influence of coupling between pressure and temperature becomes significant, we introduce a compensation coefficient λ to quantitatively describe the pressure and temperature coupling situation. In a specific design process, in which we design system parameters using a single input, single output (SISO) approach, the control parameter coupling equation is:

$$\begin{bmatrix} \Delta l'_P(k) \\ \Delta l'_T(k) \end{bmatrix} = \begin{bmatrix} \lambda_{11} & \lambda_{12} \\ \lambda_{21} & \lambda_{22} \end{bmatrix} \begin{bmatrix} \Delta l_P(k) \\ \Delta l_T(k) \end{bmatrix} \tag{24}$$

and in Eq. (24):

$$\begin{cases} \lambda_{11} = \varphi_1(l_P, l_T) \\ \lambda_{12} = \psi_1(l_P, l_T) \\ \lambda_{21} = \varphi_2(l_P, l_T) \\ \lambda_{22} = \psi_2(l_P, l_T) \end{cases} \tag{25}$$

where $\Delta l'_p(k)$ is the compensated pressure variable quantity, $\Delta l_p(k)$ the compensated pressure-regulating valve practical variable quantity with the actual control being the degree of regulating valve displacement, $\Delta l'_T(k)$ the compensated temperature variable quantity, $\Delta l_T(k)$ the k moment compensated liquid nitrogen regulating valve variable and an actual function of the displacement; λ_{ij} is the compensation coefficient (i, j = 1, 2), and φ_1, φ_2, ψ_1, ψ_2 are corresponding functional relations. Unfolding the above-mentioned equation, we could get:

$$\begin{cases} \Delta l'_P(k) = \lambda_{11}\Delta l_P(k) + \lambda_{12}\Delta l_T(k) \\ \Delta l'_T(k) = \lambda_{21}\Delta l_P(k) + \lambda_{22}\Delta l_T(k) \end{cases} \tag{26}$$

It can be seen from Eq. (26) that the pressure variable and temperature variable have relationships with the open degree of the pressure regulating valve and the liquid nitrogen regulating valve. According to control theory and test analysis, adjusting the pressure regulating valve has a greater effect than liquid nitrogen regulating valve does; similarly, to adjust temperature, the liquid nitrogen regulating valve has a great effect than pressure regulating valve does. So,

$$\lambda_{11} >> \lambda_{12},\ \lambda_{22} >> \lambda_{21}$$

Therefore, in the control procedure, $\Delta l_T(k)$ could be regarded as a disturbance action of pressure $\Delta l'_p(k)$ control, and $\Delta l_p(k)$ could be regarded as a disturbance action of flow

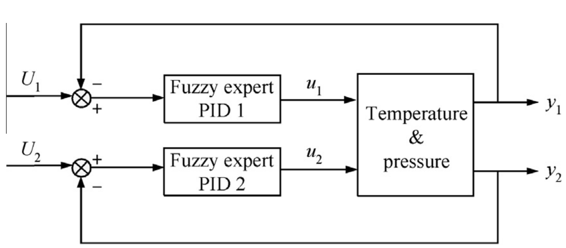

Fig. 9 Double loops fuzzy expert PID control system.

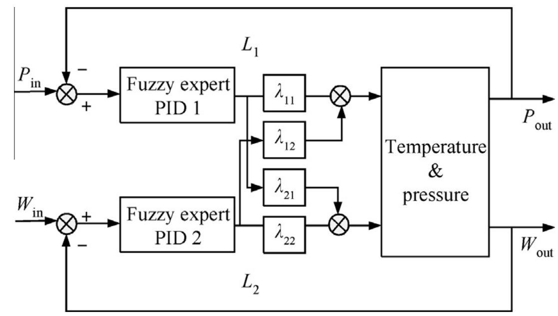

Fig. 10 Schematic diagram of fuzzy expert parameter compensation decoupling.

rate $\Delta l'_T(k)$ control, based on single variable control and adding a revise decoupling compensation term d. This allows for a constantly revised decoupling coefficient to have the system in an optimal decoupling status. To realize compensation decoupling control, the key question is how to confirm the compensation factors λ_{12} and λ_{21}.

Discretize Eq. (26) and we get

$$\begin{cases} \Delta l'_P(n) = \lambda_{11}\Delta l_P(n) + \lambda_{12}\Delta l_T(n) \\ \Delta l'_T(n) = \lambda_{21}\Delta l_P(n) + \lambda_{22}\Delta l_T(n) \end{cases} \tag{27}$$

Rewrite the first equation in n, and $n-1$ moment, then:

$$\begin{cases} \Delta l'_P(n) = \lambda_{11}\Delta l_P(n) + \lambda_{12}\Delta l_T(n) \\ \Delta l'_T(n-1) = \lambda_{21}\Delta l_P(n-1) + \lambda_{22}\Delta l_T(n-1) \end{cases} \tag{28}$$

Simultaneously solve the equations and remove λ_1, λ_2 to get compensation coefficients λ_{12} andλ_{22}:

$$\lambda_{12} = \frac{\Delta l'_P(n)\Delta l_P(n-1) - \Delta l'_P(n-1)\Delta l_P(n)}{\Delta l_T(n)\Delta l_P(n-1) - \Delta l_P(n)\Delta l_T(n-1)} \tag{29}$$

$$\lambda_{21} = \frac{\Delta l'_T(n)\Delta l_T(n-1) - \Delta l'_T(n-1)\Delta l_T(n)}{\Delta l_P(n)\Delta l_T(n-1) - \Delta l_T(n)\Delta l_P(n-1)} \tag{30}$$

The theory of Fuzzy expert parameter compensation decoupling of a control system is shown in Fig. 10.

Test requirements often need overpressure protection and amplitude limiting protection, so we consider using the fuzzy expert PID controller for single input, single output control, with λ_{11} and λ_{22} being the scale factors for valve protection and current control, and λ_{12} and λ_{21} being decoupling compensation coefficients. The control signal is converted and amplified to become a 4–20 mA current signal and to realize the control of the pressure regulating valve and the liquid nitrogen regulating valve. Compensation decoupling could basically remove the decoupling among parameters with a simple algorithm. Because coefficient compensation is in real-time, the system could realize real-time decoupling control.

5. Simulation

The simulation model is established in accordance with the design scheme of a multi-parameter environmental simulation testing cabin. The simulation model of the control system is built on the MATLAB-Simulink platform following the principles shown in Fig. 4, where in the simulation model of the environmental simulation testing cabin can be established in

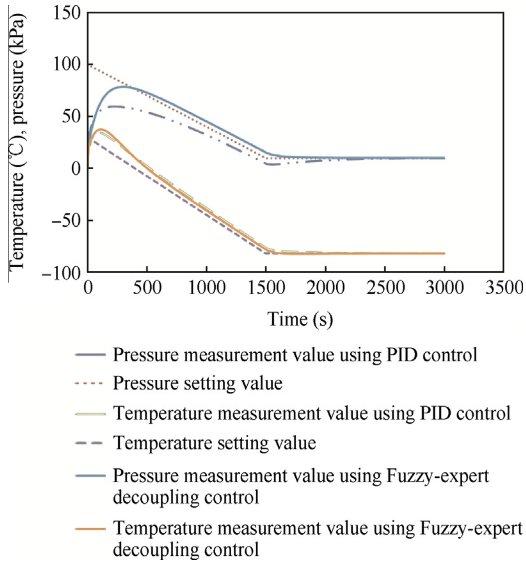

Fig. 11 Depressurization and cooling slope control curves using classic PID control and fuzzy expert decoupling control.

accordance with the mathematical model with Eqs. (1)–(16). The low pressure simulation model of the environmental simulation testing cabin can be established in accordance with the mathematical model with Eq. (10).

According to the refrigeration requirements, the temperature decreases from room temperature of 300 K(27 °C) to 191 K(−82 °C), after coming into the deviation range of ±1 °C, the temperature is fixed for 15 min. At the same time, the pressure decreases from the standard atmosphere pressure at 101.3–10 kPa. A classic PID control method is adopted, with the results using a classic PID control method and the fuzzy expert decoupling control method shown in Fig. 11. It can be seen from Fig. 11 that the effect of the fuzzy expert decoupling control method strategy is better than that of classic PID control. The fuzzy expert method can effectively suppress overshoot and improve the pumping rate. The expert control method can effectively suppress overshoot and improve the cooling rate. The transition times of the fuzzy expert method and classic PID methods are 200 s and 500 s, respectively. Furthermore, the fuzzy expert method can achieve a higher temperature control precision. During the simulation process, the normalization method is used to reduce the simulation time and CPU efforts.

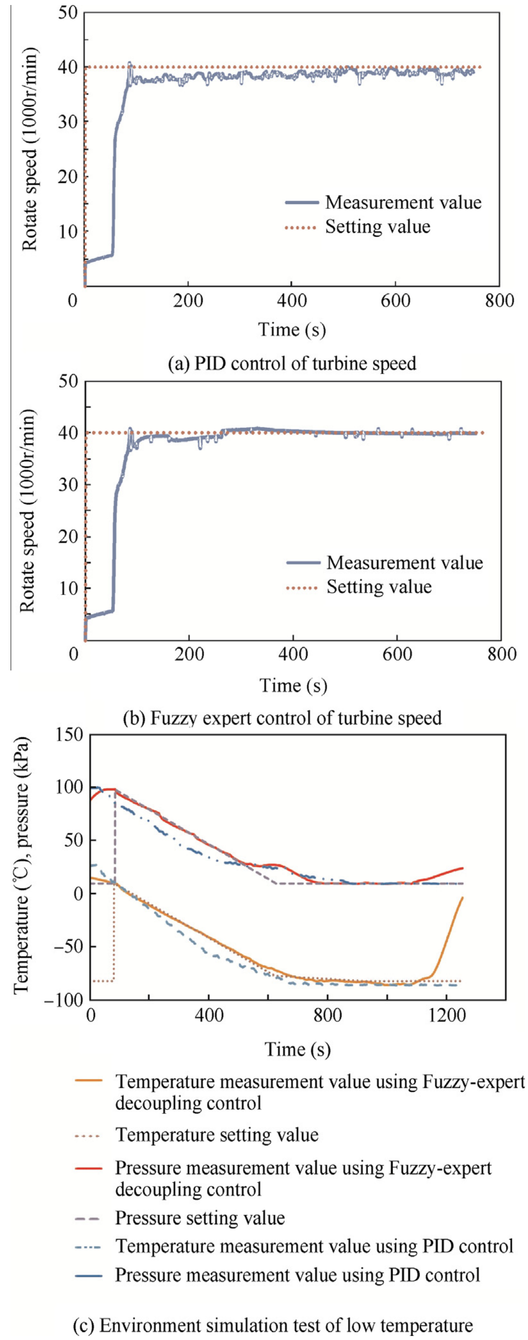

Fig. 12 Actual measurement curves while depressurization in cabin using PID control and fuzzy expert decoupling control.

6. Experimental results

A large-scale high altitude environment simulation cabin debugging test was carried out using an open Industrial Ethernet architecture, and a fuzzy expert control algorithm is used to control test parameters, and then we acquire a similar simulation study control result of cooling to 191 K(−82 °C) and decreasing pressure to 10 kPa. Actual measurement data of the cabin turbine refrigeration system's debugging test are shown in Fig. 12.

Fig. 12(a) shows the PID control measurement curve of turbine speed, while Fig. 12(b) presents a fuzzy expert control measurement curve of turbine speed which is about 40000 r/min. As can be seen from the figures, the regulating process of a classic PID control method is longer, with a large oscillation speed and a longer transition time, which has the possibility of damage of air refrigeration turbine. If the system state is changed, the control performance will be greatly affected. By contrast, the fuzzy expert control regulation is quick with a short stabilization time and smaller steady state error, so its control performance is better than the classic PID control system. Fig. 12(c) is the actual measurement plot of the environment simulation test of low temperature while depressurizing the cabin using liquid nitrogen refrigeration cold plate radiation refrigeration, a 4 °C/min cooling slope tracking and 9 kPa/min depressurization slope tracking at the same time. The figures also shows actual measurement curve plot of depressurization and cooling slope control obtained by the classic PID control method and the proposed fuzzy expert decoupling control method. The control curve plot shows a better control effect and multi-parameter curve traceability of fuzzy expert decoupling control. Especially in the depressurization and cooling process, the fuzzy expert control method has better control effect as to following the setting curve, and the classic PID control method has bigger errors than it. The transition times of the fuzzy expert method is also less than classic PID method. So experimental results prove that the fuzzy expert method is better than classic PID method in low temperature, low pressure and temperature shock test.

7. Conclusions

It is difficult to control the multi-parameter environmental simulation testing cabin for its large scale. And it is also not easy to control temperature and pressure at the same time to realize the multi-parameter comprehensive dynamic quick and accurate environment simulation of achieving low temperature, low pressure and temperature shock test in the same chamber. To solve these problems, the fuzzy expert control method is adopted in this paper based on the analysis of the dynamic-state characteristics and modeling the parameter change to realize the decoupling and slope Tracking Control. It is found that fuzzy expert control could overcome difficulties that turbine speed control cannot proceed with a PID setting, ensuring that the turbine would not exceed a maximum speed and would be controlled in the stable range during both the cooling process and the heat preservation process in the environment simulation Cabin. In addition, by using a decoupling control method combined with fuzzy expert control, we control the liquid nitrogen refrigeration in combination with turbine cold air in cold plate radiation refrigeration. This system obtains cooling slope tracking and a depressurization slope at the same time, so the accuracy of this control method is better than classic PID control method. It can be seen from the simulation and actual experiments that the lumped parameter proposed in this paper is correct and the fuzzy-control method is superior to the classical PID control method. The fuzzy-control method has the advantages of no-overshoot, fast response, high steady-state precision and effective control. The simulation analysis and experimental results show that this method provides a valuable experience in simulating an all-weather environmental temperature and pressure at ground level with no coupling.

In the future, many new control methods including artificial neural networking can be applied to a multi-parameter simulation cabin control system. The fuzzy control method can be used to improve the PID method by the PID method parameters' automatically self-tuning. Furthermore, the control method can be simulated on the platform with the lumped parameter model given in this article. It is also useful to apply the industrial Ethernet control system to a large multi-parameter simulation cabin. This control method and scheme can provide decoupling and fast simulation for aircraft environment simulation test in the future. The simulated flight conditions will be more real and will make contributions to the improvement of the reliability testing of aircraft products.

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