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Hybrid qualitative and quantitative control method

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Abstract: Quantitative control with accurate mathematical model has high precision and its performance is restricted by parameters varying while qualitative control often has both strong robustness and low precision. Combining the merits of both, an algorithm of hybrid qualitative and quantitative control (HQQC) was proposed without accurate math model. Bond graph model without causality stroke was firstly built in the algorithm, the qualitative representations were analyzed and illustrated with improved bond graph theory. Then control equation of HQQC was deduced from simplifying qualitative representations. Comparing with PID, simulation results demonstrate the robustness and transient performance of the algorithm, especially when the plant is time-vary and nonlinear.

Key words: bond graph; qualitative control; quantitative control
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一种定性和定量信息混合控制法

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摘要: 基于精确数学模型的定量控制,虽精度高,但控制质量受限于对象参数的变化;定性控制具有较强的鲁棒性,但精确性稍差.结合两者优点,本文提出了一种无需对象精确数学模型的定性、定量信息混合控制新算法.该算法首先建立无因果划的键图模型,使用改进的键图理论,分析并给出键图模型中知识的定性表达方程,并对该定性表达方程进行适当的化简导出控制方程.对比PID控制的仿真结果证实:该算法具有较好的鲁棒性和动态性能,尤其在对象参数时变和含有非线性环节时.

关键词: 键图; 定性控制; 定量控制

1 Introduction

Two classical control algorithms are used in practice. One is the conventional quantitative control to synthesize accurate math model for high precision. Its precision will drop in the variable parameters and nonlinear process. The other is the qualitative control of strong robustness, which often fail to achieve both the robustness and the precision for its knowledge qualitative representation. So it is necessary to combine qualitative control and quantitative control. Such an algorithm of hybrid qualitative and quantitative control (HQQC) is based on improved bond graph theory in the paper. In HQQC, plant model with no causality stroke is formulated through system structure instead of accurate mathematic parameters and an improved knowledge qualitative representation equation mapped model is developed. After analyzing and simplifying qualitative equation, control equation is deduced. Further it is a virtue that accurate quantitative information of plant can be added to the control equation to overcome lower precision. Good characters of HQQC, such as strong robust, high precision and simple control equation for design, are verified through simulations. This method gives a new approach to control the variable and nonlinear plant.

2 HQQC algorithm

2.1 Bond graph model without causal stroke

The bond graph technique[1], used for modeling dynamic systems, is an information diagram with power variable pairs of effort (e) and flow (f). The bond graph modeling is suitable to any complex plant. The following discussion employs a separately excited DC motor with a resilient load to illustrate the bond graph model and improved qualitative equation. Fig.1 shows the system bond model of no causal stroke. R_1 is the armature resistance and I_1 is the inductance of the motor, I_2 is the rotor inertia of motor, C_1 is spring, I_3 is the inertia of the load and R_2 is the friction of the load.

2.2 Knowledge representations in improved bond graph theory: qualitative equations

Different conventional bond graph theories[2] and causality aren't employed to guide the state equation formulation. An improved bond graph theory of no causal stroke is developed to obtain simpler qualitative equations with canceling integral and deferential function.

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Table 1 shows input-output qualitative equation of primitive elements[3]. From Fig. 1 and Table 1, primitive qualitative equations of the DC motor system are obtained as equations (1) ~ (16):

$$E_1(nT) = E_2(nT) + E_3(nT) + E_4(nT), \quad (1)$$
$$F_1(nT) = F_2(nT) = F_3(nT) = F_4(nT), \quad (2)$$
$$E_2(nT) = R_1 \times F_2(nT), \quad (3)$$
$$E_3(nT) = I_1 \times (F_3(nT - F_3((n-1)T)), \quad (4)$$
$$E_4(nT) = F_5(nT), \quad (5)$$
$$F_4(nT) = E_5(nT), \quad (6)$$
$$E_5(nT) = E_6(nT) + E_7(nT), \quad (7)$$
$$F_5(nT) = F_6(nT) = F_7(nT), \quad (8)$$
$$E_6(nT) = I_2 \times (F_6(nT) - F_6((n-1)T)), \quad (9)$$
$$E_7(nT) = E_8(nT) = E_9(nT), \quad (10)$$
$$F_7(nT) = F_8(nT) + F_9(nT), \quad (11)$$
$$F_8(nT) = C_1 \times (E_8(nT) - E_8((n-1)T)), \quad (12)$$
$$E_9(nT) = E_{10}(nT) + E_{11}(nT), \quad (13)$$
$$F_9(nT) = F_{10}(nT) = F_{11}(nT), \quad (14)$$
$$E_{10}(nT) = I_3 \times (F_{10}(nT) - F_{10}((n-1)T)), \quad (15)$$
$$E_{11}(nT) = R_2 \times F_{11}(nT). \quad (16)$$

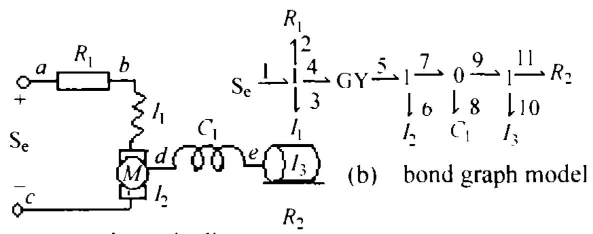

Fig. 1 A separately excited DC motor with resilient load

Table 1 Primitive element of improved bond graph and their qualitative representations

element	symbol	qualitative representation
inertial	⇀I	$E(nT) = I \times (F(nT) - F((n-1)T)$
capacitance	⇀C	$F(nT) = C \times (E(nT) - E((n-1)T)$
resistance	⇀R	$E(t) = R \times F(t)$
transformer	⇀TF⇀	$E_{in} = E_{out}, F_{in} = F_{out}$
gyrator	⇀GY⇀	$E_{in} = F_{out}, F_{in} = E_{out}$
serial junction	⇀1 ⋮ n	$E_{in1} = E_{out1} + \cdots + E_{outn}$ $F_{in1} = F_{out1} = \cdots = F_{outn}$
parallel junction	⇀0 ⋮ n	$E_{in1} = E_{out1} = \cdots = E_{outn}$ $F_{in1} = F_{out1} + \cdots + F_{outn}$

2.3 Creation of control equation

A feedback control system with the above plant is shown in Fig.2. E_R is output error and E_C is output error derivative. The control objective is to regulate voltage E_1 to keep load speed F_{10}. The control equation of HQQC algorithm is deduced by simplifying the qualitative equation (1) ~ (16).

2.3.1 control equation without quantitative information

① The value of R, I and C parameters is defined as I when their values are not given.

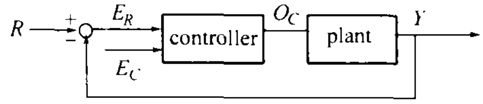

Fig. 2 Feedback control system

Following the above rule, equations (3), (4), (9), (12), (15), (16) are changed. For example equation (3) becomes $E_2(nT) = F_2(nT)$.

② Identify the input and output variables of controller. Then replace the variables with the smallest subscript variables according to the equation relationships.

After analyzing, $F_9(nT)$ is input E_R of controller, $F_9(nT) - F_9((n-1)T)$ is another input E_C of controller. E_1 is output of controller. From equations (2), (8), (10) and (14), F_2, F_3 and F_4 are replaced by F_1; F_6 and F_7 are replaced by F_5; E_8 and E_9 are replaced by E_7; F_{10} and F_{11} are replaced by F_9 respectively.

③ Cancel all the equations without "plus + " operators.

Following the above three rules, the previous qualitative equation can be simplified as

$$E_1(nT) = F_1(nT) + F_1(nT) - F_1((n-1)T) + E_4(nT),$$
$$F_1(nT) = E_4(nT) - E_4((n-1)T) + E_7(nT),$$
$$E_4(nT) = E_7(nT) - E_7((n-1)T) + F_9(nT),$$
$$E_7(nT) = F_9(nT) - F_9((n-1)T) + F_9(nT).$$

④ Simplify the above qualitative equation by retaining variables of controller inputs and outputs.

So the simplified result is

$$E_1(nT) = 13F_9(nT) - 22F_9((n-1)T) + 16F_9((n-2)T) - 6F_9((n-3)T) + F_9((n-4)T).$$

And control equation is

$$E_1(nT) = O_C = 13E_R(nT) - 6E_R((n-1)T) - 16E_C((n-1)T) - 6E_R((n-3)T) + E_R((n-4)T). \quad (17)$$

2.3.2 Control equation merging quantitative value of parameters

Considering the effect of armature resistance of the motor R_1, the quantitative value of parameter R_1 (assumed $R_1 = 0.5$) can be inserted into the control equation for high precision. So the control equation becomes an algorithm of hybrid qualitative and quantitative control (HQQC).

Keeping other steps of process 2.3.1, only equation (3) is $E_2(nT) = R_1 \times F_2(nT)$, the simplified result is

$$E_2(nT) = (5R_1 + 8)F_9(nT) - (7R_1 + 15)F_9((n-1)T) + (4R_1 + 12)F_9((n-2)T) - (R_1 + 5)F_9((n-3)T) + F_9((n-4)T).$$

The controller's control equation becomes

$$E_1(nT) = O_C = 10.5E_R(nT) - 4.5E_R((n-1)T) - 14E_C((n-1)T) -$$

$$5.5E_R((n-3)T) + F_9((n-4)T). \quad (18)$$

In comparison to equation (17), coefficients of E_R and E_C in equation (18) have changed. So the transient responses vary between equation (17) and (18). Due to merging quantitative value, a good control performance can be obtained by control equation (18).

In the practical process, O_C in equation (17) or (18) becomes $\Delta U(nT)$ to avoid steady error. The real output of controller (HQQC) is defined as $U(n) = U((n-1)T) + \Delta U(nT)$.

3 Simulation results

Because many high-order processes can be approximated to second-order plant in practice, a two couple water tank is employed to demonstrate the effectiveness of the HQQC.

Figure 3 is the bond graph model of no causal stroke for two couple water tank. The control task is that water tank C_2 achieves the set point. E_1 is controller output. E_{15} is error, and F_{15} is error change. Control equation (19) is directly given. Where 25 primitive equations of water tank are omitted and quantitative values have been insert into equation (19).

$$O_C(nT) = 2.9E_R(nT) - 2.165E_R((n-1)T) + 2.5E_R((n-2)T) - 0.015E_R((n-3)T) + 1.74E_C((n-1)T) - 0.835E_C((n-1)T) + 0.1E_C((n-2)T) + 0.005E_C((n-3)T). \quad (19)$$

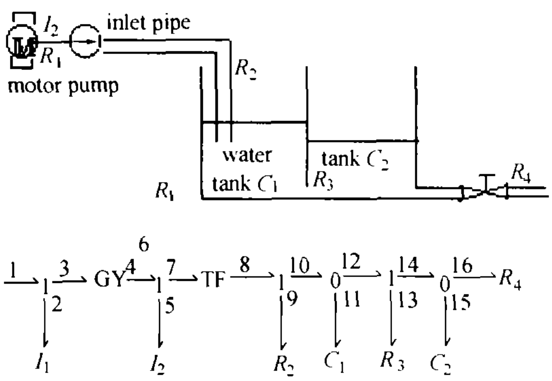

Fig. 3 Two couple water tank bond graph model

Experiments are carried out to check the transient performance of HQQC, robustness for nonlinear and time-varying plant, and to track performance for set point disturbance. Fig.4, Fig.5, Fig.6 and Fig.7 show the simulation result with comparison to PID tuned by $Z-N$, where set point is 8. By these curves, it can be found that equation (19) (HQQC) has better performance than PID control, especially for robustness. The main cause of the above better performance is that HQQC algorithm naturally belongs to qualitative control, which requires less precise model information.

Since HQQC algorithm in the paper is qualitative control, bond graph model can be deeply simplified. Motor inertia and pump inertia in Fig. 3 have little effect on system output. Canceling these elements and showing bond graph model in Fig. 8, control equation mapped the case becomes equation (20):

$$O_c(nT) = 3E_R(nT) - 2E_R((n-1)T) + 2E_C(nT) - E_C((n-1)T). \quad (20)$$

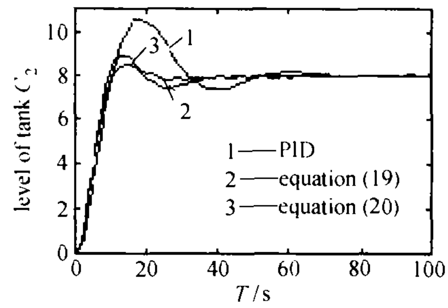

Fig. 4 Response of two tank's time constants $T_1 = 5$, $T_2 = 8$

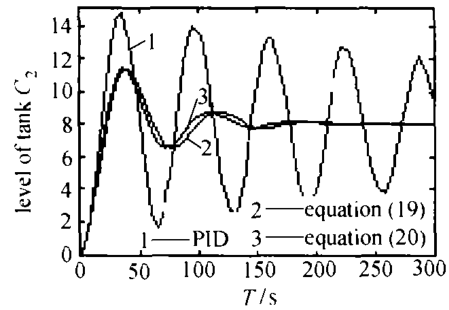

Fig. 5 Response of two tank's time constants $T_1 = 5$, $T_2 = 8$

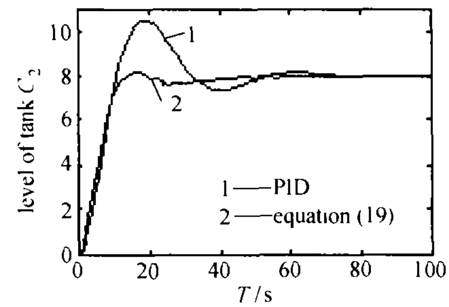

Fig. 6 Response of two tank's time constants $T_1 = 5$, $T_2 = 8$ and $[-1 \quad +1]$ dead zone contained

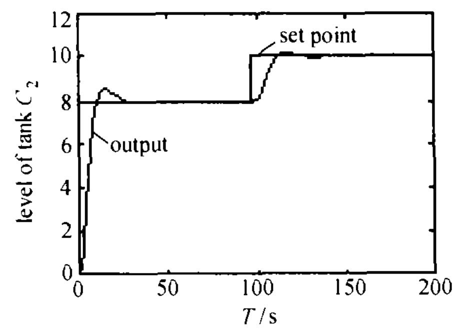

Fig. 7 Track performance by equation (19), two tank's time constants $T_1 = 5$, $T_2 = 8$

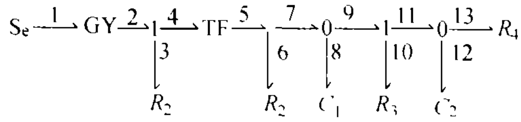

Fig. 8 After omitting I_1, I_2, bond grap model of two couple water tank

Simulation results by equation (20) are shown as curve (3) in Fig. 4 and Fig. 5. Compared with curve (2), the performance changes are very small. However, the control algorithm is simpler. On the other hand, the example also proves that algorithm can control time-varying plant.

4 Conclusion

A hybrid qualitative and quantitative control algorithm (HQQC) based on improved bond graph theory is proposed in this paper. By simplifying qualitative equation, the control algorithm can be deduced. Inserting quantitative value of important parameter into the control algorithm can get higher control precision. Simulation results prove that the algorithm has better performance than PID control; for example, it has strong robust, good transient response and track performance. It gives a bright promise to control plant with variable parameters, nonlinear and strong disturbance. Future work on the approach is added to error scale factor SF_e, error change scale factor SF_{ec} and output scale factor SF_u to control equation so that an adaptive control algorithm can be constructed.

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