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Fractional-Order PID and Active Disturbance Rejection Compound Control for Vacuum Induction Furnace

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Abstract. This paper proposes a compound control strategy which is generated by the combination of fractional-order proportional-integral-derivative (FOPID) and the active disturbance rejection control (ADRC) to improve temperature control accuracy for melting period of vacuum induction furnace. The method of ADRC does not rely on the accurate mathematical model of the controlled system. Due to the exist of the extended state observer, the ADRC can compensate the influence of the system on the output in a larger range, which is very suitable for the temperature control system of vacuum induction furnace with uncertainty. The method of FOPID control can improve the control quality of the system with the addition of two free variables. The robustness and capacity of resisting disturbance of the proposed method was verified by the simulation results.

Keywords. Fractional order PID, active disturbance rejection control, temperature control.

1. Introduction

Vacuum induction melting technology is a kind of induction heating technology with high heating efficiency, high speed and low consumption. It is developed and optimized on the basis of ordinary induction furnace. With the development of aerospace industry, nuclear energy and other industries, sophisticated industrial equipment has higher requirements for material performance and smelting machinery. In view of the high performance and high precision requirements of the process refining process, a large number of scholars have found through theoretical discussion and practical research that the special smelting technology of high-precision materials in vacuum environment can meet the performance requirements of the equipment to a certain extent. Alloys made in vacuum are widely used in cutting-edge technologies such as biotechnology (prosthetic implants) and aviation (turbine blades) [1].

Meanwhile, there are few researches on the melting temperature of vacuum induction furnace. The classic temperature control method in the vacuum furnace is PID control. The temperature in the vacuum induction furnace is measured by a

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thermocouple. When the measured temperature deviates from the set temperature, the heating input is adjusted to minimize the deviation. This is a typical feedback control process [2,3]. However, with the improvement of alloy quality requirements by advanced technology, more accurate control methods should be used to control the temperature in the vacuum induction furnace during melting period. Aiming at the uncertainty of temperature variation in the melting stage of vacuum induction furnace, a compound control strategy based on FOPID and ADRC is proposed in this paper. In paper [3], fractional-order PID and active disturbance rejection controller (FOPID-ADRC) is applied to the speed regulation system of the nonlinear double-mass servo drive system, and it is proved that the compound controller has good robustness. In paper [4], the fractional calculus is introduced into ADRC, where the extended state observer (ESO) and the nonlinear state error feedback (NLSEF) are replaced by Fractional-order extended state observer and PID controller respectively. Robustness analysis shows that FADRC is also appropriate for incommensurate fractional-order system. In paper [5], the FOPID-ADRRC is applied to the supersonic aircraft, the simulation results prove that the designed controller has good adaptability and robustness in dealing with the uncertainty and external disturbance. However, the proposed method greatly improves the complexity of the algorithm, which is not conducive to practical engineering.

The structure of the present work is as follow: The first section describes the process principle of vacuum induction furnace; In the second section, the design of fractional-order ADRC is introduced; The third section is the simulation experiment of FOPID-ADRC. The dynamic performance and robustness of the FOPID-ADRC are analyzed; The forth section is the conclusion.

2. Technical Principle of Vacuum Induction Furnace

Vacuum induction furnace is an important equipment in vacuum smelting technology, mainly used for smelting precision alloy, electromagnetic materials and high temperature alloy. Induction heating technology refers to the use of the principle of electromagnetic induction heating to melt metal under vacuum conditions. The current in the vacuum induction furnace passes through the electromagnetic coil around the metal at a certain frequency, and the induced electromotive force generated thereby causes eddy currents inside the metal charge, thus generating a large amount of heat to heat the metal [6]. Because the whole process occurs in a vacuum environment, it is conducive to the removal of gas impurities in the metal. Through the control of vacuum environment and induction heating, the smelting temperature can be adjusted and the alloy metal can be added in time to achieve the purpose of refining. Due to the characteristics of induction smelting technology, liquid metal materials can be automatically stirred by the interaction of electromagnetic force inside the crucible to make the composition more uniform, which is also a major advantage of induction smelting technology [7].

The preparation of high purity alloy in vacuum induction furnace is divided into four stages: charging, melting, refining and pouring. The melting temperature has an important effect on the quality of the alloy. The temperature in the vacuum induction furnace is controlled by input frequency. In the process of vacuum smelting, the input frequency must be controlled accurately and stably to ensure the quality of the products. High temperature will lead to metal burning and splashing, which will cause the chemical composition segregation of the smelted products, and low temperatures cause metal to clump. Therefore, it is very important to control the temperature change in a small range during the melting stage of vacuum induction furnace. Meanwhile, the temperature in the vacuum induction furnace will be affected by the metal melting process, resulting in heat loss in three forms: heat conduction, heat convection and heat radiation [8,10]. The main heat loss is caused by thermal radiation, including the incident radiation heat flow inside the furnace wall and the net radiation heat flow outside the furnace wall [2]. In practice, the shape of meniscus is constantly changing and the free surface of meniscus will directly affect the distribution of electromagnetic field. When the shape of the meniscus changes, the Joule heat in the charge changes as well [1].

3. Design of Fopid-Adrc

3.1. Fopid Control

Oustaloup proposed the fractional-order controller on the basis of the classical PID[8-10]. It is demonstrated that the performance of FOPID controller is better than traditional PID. Podlubny proposed the FOPID controller as a generalized form of the standard PID controller [11]. In addition to the K_p, K_i, K_d of the traditional PID controller, the FOPID controller also has two free variables λ, μ, which realizes the control from point to surface [12]. Therefore, FOPID has a larger adjustable range and better control quality than traditional PID [13]. The Riemann-Liouville definition of first derivative fractional calculus is[14]:

$$D^1 f(t) = \frac{df(t)}{dt} = \lim_{h \to 0} \frac{f(t) - f(t-h)}{h} \tag{1}$$

It can be seen that the fractional derivative is great importance for long-term conditions. However, the integral derivative is only applicable to the current moment. The characteristic of the fractional derivative makes the system respond slowly and sensitive to disturbance [15].

The Laplace transform of Riemann-Liouville definition of fractional calculus is equal to:

$$L\{{}_0D_t^{\alpha} f(t)\} = s^{\alpha} F(s) - \sum_{k=0}^{n-1} s^k [{}_0D_t^{\alpha\text{-}k-1} f(t)]_{t=0} \tag{2}$$

Under zero initial conditions, the summation term in Equation. (2) is zero.

The differential equation of FOPID can be expressed as:

$$u_{FOPID}(t) = K_p c(t) + K_i D_t^{-\lambda} c(t) + K_d D_t^{\mu} c(t) \tag{3}$$

where *u(t)* is controller output, *c(t)* is controller output, λ and μ is any real number greater than zero, K_p, K_i and K_d is proportional gain, integral coefficient and differential coefficient of controller, respectively. Reasonable selection of control parameters can obtain better dynamic performance and improve the control effect of the system.

3.2. Fopidadrc Controller

ADRC consists of tracking differentiator (TD), extended state observer and nonlinear state error feedback controller [16]. The transition process v_1 and the differential signals of each order of v_1 of system input v can be obtained by tracking differentiator. The nonlinear error feedback calculates the control signal u_0 according to the state error e_1~e_n of the system. ESO is the core module of ADRC, which is used to estimate and compensate the internal and external disturbance of system in real time.

For the second-order ADRC system, TD can be expressed as [16] :

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = -rsign(x_1 - v(t) + \dfrac{x_2|x_2|}{2r}) \end{cases} \tag{4}$$

where, r is the parameter to adjust the tracking speed. The larger the value of r, the faster the tracking speed. *sign* is a symbolic function. Since $\dot{x}_1 = x_2$, x_2 can be estimated as the derivative of the input signal. For the internal and external disturbance of the system, the state of the system and all the disturbances z_3 are estimated in real time to give some compensation to the system. The third-order ESO can be expressed as [16] :

$$\begin{cases} e = z_1 - y_1 \\ \dot{z}_1 = z_2 - \beta_1 fal(e) \\ \dot{z}_2 = z_3 - \beta_2 fal(e) \\ \dot{z}_3 = -\beta_3 fal(e) \end{cases} \tag{5}$$

where z_1, z_2 and z_3 is observed value of x_1, x_2 *and* x_3, respectively, x_3 is total disturbance of system; β_1, β_2 and β_3 is the gain of ESO, which can influence the strength of the observed signal. When the value of is selected appropriately, the state of the system can be accurately estimated. *fal* is nonlinear function which can be expressed as[14]:

$$fal(e,\alpha,\delta) = \begin{cases} \dfrac{e}{\delta^{1-\alpha}}, |e| < \delta \\ |e|^{\alpha} sign(e), |e| > \delta \end{cases} \tag{6}$$

where δ and α is adjustable parameters. If $\alpha = 1$, the value of nonlinear function is e. We can get the traditional Luenberger observer, also known as linear observer, which is a special case of the nonlinear extended state observer [17].

The output of ESO is z_1, z_2 and z_3. Thus, the control law can be expressed as:

$$u = u_0 - \frac{z_3}{b} \tag{7}$$

where b is compensating factor. u_0 is the virtual control law. FOPID controller is introduced into ADRC controller as linear state error feedback controller. Therefore, the virtual control law u_0 can be expressed as:

$$u_0 = K_p(e_1 - z_1) + \frac{K_i}{s^\lambda}(e_2 - z_2) + K_d s^\mu (e_2 - z_2) \tag{8}$$

The diagram of compound FOPID-ADRC is shown in figure 1.

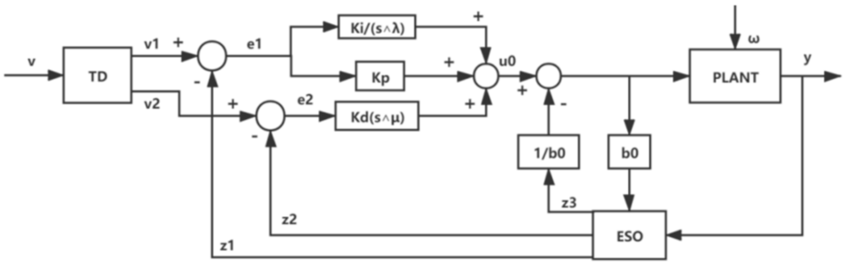

Figure 1. The structural diagram of FOPID-ADRC

4. Simulation Analysis

FOPID, LADRC and FOPID-ADRC control methods are used to simulate the temperature control system of vacuum induction furnace during melting period. A vacuum induction furnace is taken as the experimental object. The frequency was set as 18863Hz, and the change of its temperature with time was observed. Temperature changes are recorded every 30 seconds. MATLAB is used for data fitting, and the fitting rate of the second-order system can reach 96.99%, as shown in Equation. (1). The fitting result is shown in figure 2.

$$G_{plant}(s) = \frac{0.16}{s^2 + 0.06s + 0.02} \tag{9}$$

The reference signal in figure 3 simulates the temperature rise process in the vacuum induction furnace. A parameter disturbance of size 10, which is used to simulate temperature mutation in vacuum furnace caused by thermal radiation and heat conduction in industrial process, is added at 150s, which is controlled by FOPID, LADRC and FOPID-ADRC respectively. It can be seen that when FOPID is used for control, the overshoot is the largest and the stability time is the longest. However, the overshoot of FOPID-ADRC is the smallest, and the stability time is much less than that of FOPID controller.

In order to verify the robustness of the FOPID-ADRC controller designed in this paper, the input was set as sinusoidal noise signal, which was used to simulate the uncertainty and complex reaction process in vacuum induction furnace. As shown in figure 4, in the case of interference, FOPID is greatly affected by noise and basically has no anti-interference capability. Compared with LADRC, FOPID-ADRC is less affected by load, has stronger anti-interference ability, and the tracking input tracking is more accurate.

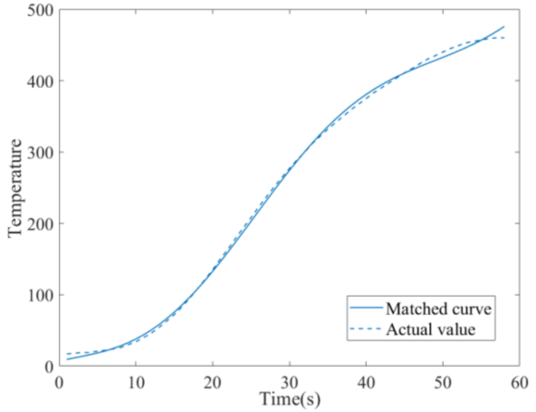

Figure 2. Data fitting results

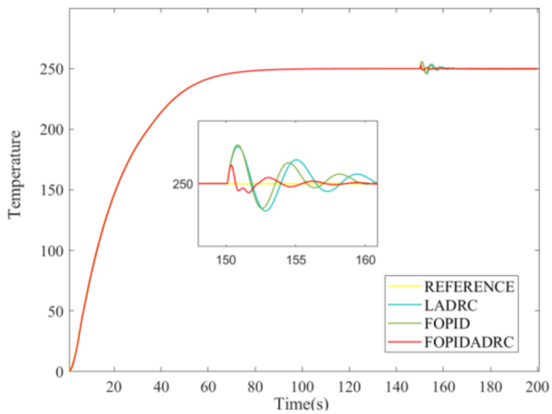

Figure 3. Compared control effects when numerical disturbance is added

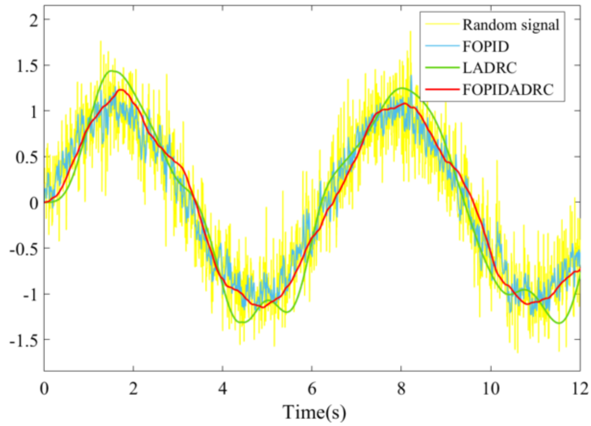

Figure 4. Compared output results when the input is random interference

5. Conclusions

Aiming at the temperature change in the melting period of vacuum induction furnace with complex and multi-interference, the design method of FOPID-ADRC composite controller is studied by combining FOPID control with ADRC. The simulation results show that compared with FOPID and LADRC, FOPID-ADRC not only has the accuracy of FOPID, but also has the anti-interference ability of ADRC. This paper provides a reference for the practical application of FOPID-ADRC in vacuum induction furnace.

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