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Optimal active-disturbance-rejection control for propulsion of anchor-hole drillers

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Dear editor,

The propulsion module of an anchor-hole driller controls the drilling speed with a hydraulic cylinder that provides the axial force when driving a drilling rig to break the surrounding rocks. This drilling process is traditionally controlled manually by operators that tend to set the machine at the maximum drilling speed. In typical conditions in which the surrounding rocks have variable hardness and density, drilling at a fixed speed results in inefficiencies due to broken drill pipes, and even more severe faults. To reach the optimal operation of an anchor-hole driller, appropriate control of the drilling speed according to the characteristics of the surrounding rocks is required.

As an emulsion is utilized for power, the propulsion process is generally controlled using an electro-hydraulic servo system according to the rotary pressure [1]. The severe nonlinearities and time-varying parameters of the propulsion force-servo system, the vibration interference resulting from the interaction between the drill pipe and the surrounding rock during drilling, and self-flow disturbances of the proportional over-flow valve have negative influences on control performance. Various control methods [2–5] have been applied successfully in electro-hydraulic servo systems. Among these, active-disturbance-rejection controller (ADRC) offers the distinct advantages of suppressing disturbances and only weak dependence on the system model.

We have designed an optimal ADRC for the propulsion of drilling rigs. Because the key parameters of an ADRC controller are set empirically, and an optimal propulsion operation when drilling under variable surrounding rocks is difficult to determine, we employ the particle swarm optimization (PSO) algorithm to seek the optimal parameter settings for all parts of the ADRC. The optimal expected reference trajectory is especially important with variable surrounding rocks. In addition, the optimal propulsion force can be estimated according to the hardness coefficients of the surrounding rock, which can be computed from the monitored rotary pressure.

In the propulsion module of an anchor-hole driller, an emulsion from a quantitative pump that is driven by an asynchronous motor is employed to control the direction of motion of the hydraulic cylinder via a two-way valve that can take two positions. Movement of the hydraulic cylinder in the positive or inverse direction determines whether the bit is drilling or retracting. The propulsion force is controlled by the pressure of the hydraulic cylinder, which is adjusted using an electro-hydraulic proportional relief valve. The force-servo component, composed of the proportional relief valve and the hydraulic cylinder can be simplified as a typical second-order system [5]. The resulting optimal second-order ADRC for drill propulsion is shown in Figure 1.

Determined from the relationship between the propulsion force, the breaking-work ratio of the surrounding rock, and the drilling speed, the appropriate propulsion force can ensure that the anchor-hole driller runs within the optimal drilling zone and achieves the maximum drilling speed and efficiency. Excessive propulsion force tends to result in drill pipes breaking when they encounter hard surrounding rock. If we let F_v be the expected propulsion force, D be the diameter of the drill pipe, and f be the hardness coefficient of the surrounding rock, with k_v as a proportional coefficient, the expected propulsion forces for the surrounding rocks with various hardness coefficients can be set as $F_v = k_v f D$.

A tracking differentiator (TD) is employed to generate the expected transition process. If we let R denote the expected propulsion force, v_1 and v_2 be the expected transition process and its first-order differential signal, h be the sampling period, h_0 and r be the filter and speed factor, and fhan() be the optimal control function [5], then TD can be formulated as follows:

$$\begin{cases} v_1(k+1) = v_1(k) + h v_2(k), \\ v_2(k+1) = v_2(k) + h f(k), \\ f(k) = \mathrm{fhan}(v_1(k) - R(k), v_2(k), r, h_0). \end{cases}$$

Taking the control voltage and the propulsion force as inputs, an expansion state observer (ESO) is utilized to

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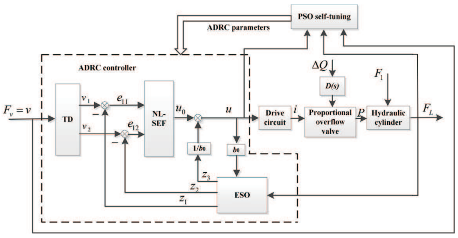

Figure 1 Optimal ADRC control system for propulsion.

estimate the sum of the disturbances. Using z_1 and z_2 as the state variables, z_3 as the total interference, and fal() as a nonlinear function [5], we have

$$\begin{cases} z_1\left(k+1\right) = z_1\left(k\right) + h\left(z_2\left(k\right) - \beta_{01} e\left(k\right)\right), \\ z_2\left(k+1\right) = z_2\left(k\right) + h\left(z_3\left(k\right) - \beta_{02} \mathrm{fal}\left(e\left(k\right),\right.\right. \\ \qquad\qquad \left.\left. 0.5, \delta\right) + b_0 u\left(k\right)\right), \\ z_3\left(k+1\right) = z_3\left(k\right) + h\left(-\beta_{03} \mathrm{fal}\left(e\left(k\right), 0.25, \delta\right)\right), \\ e\left(k\right) = z_1\left(k\right) - y\left(k\right). \end{cases}$$

Nonlinear state error feedback (NLSEF) is used to nonlinearly combine the outputs of the TD and ESO, while compensating for the total interference.

$$\begin{cases} u\left(k\right) = u_0\left(k\right) - \frac{z_3(k)}{b_0}, \\ u_0\left(k\right) = \beta_{11} \mathrm{fal}\left(e_1\left(k\right), a_1, \delta_1\right) + \beta_{12} \mathrm{fal}\left(e_2\left(k\right),\right. \\ \qquad\qquad \left. a_2, \delta_1\right), \\ e_1\left(k\right) = v_1\left(k\right) - z_1\left(k\right), \\ e_2\left(k\right) = v_2\left(k\right) - z_2\left(k\right), \end{cases}$$

where u_0 is the output of NLSEF; β_{11} and β_{12} are the gain and the differential coefficients of the controller. The nonlinear coefficients, a_1 and a_2, generally satisfy the relation $0 < a_1 < 1 < a_2$, so they are set to $a_1 = 0.75$, $a_2 = 1.25$, $\delta_1 = 0.001$.

In the ADRC, r and h_0 are employed to determine the response velocity and the steady-state error of an expected transition process. β_{01}, β_{02}, β_{03}, b_0, β_{11}, and β_{12} have a clear influence on the control performance. Previous studies on optimizing the control parameters focused mainly on those of the ESO and NLSEF [6]. A reasonable transition process that can be used for a range of drilling environments, however, will have a real effect on the expected control performance. To achieve satisfactory control performance, the PSO algorithm is employed to adjust these parameters adaptively.

In PSO, each particle represents a candidate in the decision space. We assume that a swarm contains m particles, with the position and the velocity of the i-th particle being x_i and v_i, respectively. The i-th particle adjusts its direction of motion constantly. The velocity is set according to the local optimum, which is denoted by p_i, and the global optimum is denoted by p_g, as follows:

$$\begin{cases} v_{id}^{n+1} = w v_{id}^{n} + c_1 r_1 (p_{id}^{n} - x_{id}^{n}) + c_2 r_2 (p_{gd}^{n} - x_{id}^{n}), \\ x_{id}^{n+1} = x_{id}^{n} + v_{id}^{n+1}, \end{cases}$$

where w is the inertia weight, and is usually set to 0.6. c_1 and c_2 represent the acceleration factors and are set to 2. r_1 and r_2 are two random variables in the range of [0,1], distributed uniformly. n is the number of generations. Because all the parameters to be adjusted in the ADRC are real, each particle is encoded as a set of real values, denoted as $x_i = (r, h_0, \beta_{01}, \beta_{02}, \beta_{03}, \beta_{11}, \beta_{12}, b_0)$.

During the drilling process, the desired propulsion force is expected to track as soon as possible with no overshoot, for improving the drilling efficiency and avoiding drilling faults. To assure the rapidity and accuracy of the control system, the integrated-time absolute error is employed as one objective of the optimization problem. Overshoot is taken as the other objective because of the stability requirement. Let ω_1 and ω_2 denote the weights of the two objectives, $e\left(t\right)$ denote the transient error, and M_p denote the overshoot to formulate a comprehensive objective function. $J = \int_0^\infty \left(\omega_1 t \left|e(t)\right| + \omega_2 \left|M_p\right|\right) \mathrm{d}t$. As the two objectives are equally important for control performance, we set the weights as $\omega_1 = \omega_2 = 0.5$.

The PSO-based method of adaptive parameter adjustment in the ADRC uses the following steps.

Step1. Initialize the position and the velocity of each particle in the swarm.

Step2. Taking the positions of the particles as the parameters for ADRC, calculate the objectives using the transient process of the control system.

Step3. Update the local- and global-best results.

Step4. Update the position and the velocity of each particle.

Step5. Judge whether the stopping criterion is met. If yes, output the optimal parameters; otherwise, go to Step2.

Based on a joint simulation platform composed of Matlab and AMESim, all experiments were conducted with data about the rock strata in the Fenghuang Mountain Coal Mine. The hardness coefficient of the rock increases gradually when drilling from sandy mudstone to middle sandstone step by step.

A traditional ADRC with pre-set parameters and a PI controller with the optimal parameters found by the PSO were also tested for comparison with the PSO-based ADRC. The parameters were adjusted within the following ranges that were set with a number of simulations in preliminary tests and based on experience: $r \in (10, 100000)$, $h_0 \in (0.001, 1)$, $\beta_{01} \in (0, 1000)$, $\beta_{02}, \beta_{03} \in (0, 10000)$, $\beta_{11} \in (0, 300)$, $\beta_{12} \in (0, 4)$, $b_0 \in (0.1, 3)$, $k_p \in (0.1, 1)$, and $k_i \in (0.1, 0.8)$. In addition, the population size and the maximum number of generations in the PSO are set to 100. The resulting optimal parameters are listed as follows. PSO-ADRC: $\beta_{01} = 878.8375$, $\beta_{02} = 8435.8676$, $\beta_{03} = 6022.1461$, $\beta_{11} = 199.8151$, $\beta_{12} = 3.5746$, $b_0 = 1.1956$; PI: $k_p = 0.624$, $k_i = 0.283$.

Firstly, the expected reference trajectories generated by TD with and without the optimal parameters were compared, and then the influences of traditional ADRC and PSO-based ADRC on control performance with variable surrounding rocks were analyzed. The simulation results indicate that when the drill pipe passes from sandy mudstone to middle sandstone, the settling time of the ADRC without the optimal parameters is longer than 1.2 s, and overshoot occurs for more than 2.5% of the time. An extremely large speed factor results in the rapid convergence of the reference trajectory. Overshoots are prevented and the settling time is less than 1.1 s when using the proposed controller with the optimal parameters for the TD when drilling through variable surrounding rocks.

Secondly, as the anchor-hole driller passes into middle sandstone from sandy mudstone, the desired propulsion force increases linearly under the rock strata with the gradual change, and the designed ADRC can track this transition more rapidly without overshoot. The expected propulsion force optimized by the PSO-based TD is a ramp signal changing from 409.6 to 985.6 N, and the output pressure is adjusted constantly.

Finally, under the rock stratum with the unique sandstone, the simulation results with an external disturbance of approximately 3000 N loaded at t=5 s show that neither controller overshoots. The designed controller shows excellent robustness with a shorter settling time (1.684 s) and smaller overshoots ($\approx$ 2 N). The controller completely satisfies the requirement of actual control systems with more internal and external disturbances.

To reduce drilling faults and improve drilling efficiency, we propose a PSO-based optimal ADRC that tracks the optimal propulsion force of an anchor-hole driller as it passes through varying layers of surrounding rocks. The expected propulsion force is estimated according to the properties of the surrounding rocks, and the key parameters of the ADRC are optimized based on PSO to improve the speed of tracking. In various rock strata, the simulation results show that the designed controller can rapidly track the optimal propulsion force with less settling time, no overshoots, and better robustness when drilling. These features reduce damage to the drill pipes and reduce failures of the anchor-hole driller to improve drilling efficiency.

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