SYNTHESIS OF FEEDBACK LINEARIZATION CONTROLLER WITH PARAMETERS OPTIMIZATION BASED ON BAT ALGORITHM FOR A MAGNETIC LEVITATION SYSTEM

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Abstract

In this paper, the method design controller based on the feedback linearization control (FLC) method with optimal parameter for time response thanks to BAT algorithm for magnetic levitation system (MLS). Feedback linearization controller based on equivalent transformations brings a nonlinear system into linear form, then uses the poles-placement method to find parameters for the linear tracking controller. The selected pole does not optimize the controller parameters when the system needs to satisfy a rapid response condition. Therefore, the authors use the BAT algorithm to find linear tracking controller parameters based on ITAE cost function. The controller with optimized parameters is verified through simulation and experiment results. The proposed controller efficiency is compared with the feedback linearization controller through the simulation results.

Keywords: *Magnetic levitation system; feedback linearization control; BAT algorithm; optimization parameters; ITAE.*

1. Introduction

Magnetic lavitation system is of practical importance, applied in many technical systems such as maglev (derived from magnetic levitation), frictionless bearings, vibration isolation of sensitive machinery, hot metal lifting melt in induction furnaces and lift metal plates during manufacturing [2-4]. The MLSs can be classified as suction or propulsion systems based on the magnetic force. The control of the ball's position in the MLS has attracted the attention of many researchers because the mathematical model is strong nonlinear and has many uncertainties, so there have been many studies the controller for this system. Studies [5, 6] show the control law of the MLS using the PID controller. In [7, 8], a serial multi-layer neural network is used to model the system in which learning and control are performed simultaneously. In addition, the adaptive controller techniques studied in [9, 10] have good results. Adaptive control with rules to adjust unknown parameters in the system model and adaptive PID control is proposed to

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control position in [11, 12]. The sliding mode control is presented in [13], but the mathematical model used is linear. Sliding mode controller with adaptive parameters using Neuron network is presented in [14], the simulation results show the effect when the disturbance is white noise. The linear quadractic regulator (LQR) for the MLS is presented in [15], but the choice of controller parameters is still based on the trial error method. Fuzzy logic controller [16] and adaptive fuzzy logic controller [17] are proposed to stabilize the position of the ball. In addition, Javadi and Pezeshki [17] compared the performance of the adaptive fuzzy logic controller and the nonlinear H∞ controller. The studies of feedback linearization control in [18, 19, 22] show the effectiveness of this method. But the choice of parameters for the tracking controller is the trial error, leading to certain difficulties when choosing the parameters. Testing the parameters of each membership function is often time-consuming and tedious. Parametric optimization techniques for feedback linearization controller are presented in [20], but it is not a good result on the high-order nonlinearity systems and the multi-objective functions. The optimization algorithm based on Nature-Inspired Metaheuristics is a development trend. There have been many optimization algorithms built successfully from the behavior of animals and have been widely published such as genetic algorithms (GA), ant colony optimization (ACO), bat algorithms (BA), bee algorithms, differential evolution(DE), particle swarm optimization (PSO), harmony search (HS), the firefly algorithm (FA), cuckoo search (CS), and the flower pollination algorithm (FPA), and others [1, 21]. This paper presents a method of designing a feedback linearization controller and optimizing its parameters to reduce the transition time based on the Integral Time Absolute Error (AITE) cost function. The controller is illustrated by simulation results on MATLAB software and experimental results on the actual system. The efficiency of the optimized control law is shown when compared with the traditional feedback linearization control laws. The main contributions of this paper are summarized as follows:

(1) Designing feedback linearization controller with optimized tracking control based on BAT algorithm.

(2) Evaluating the design controller quality based on simulation results and realization results on real systems.

The rest of the paper is organized as follows: Section 2 presents the mathematical model of the magnetic levitation system. Section 3 presents the BAT algorithm. Section 4 presents the design of feedback linearization control law for the magnetic lavitation system and the optimization of controller parameters. Section 5 presents simulation and experimental results and a related discussion. Finally, Section 6 gives the conclusions and further work of this paper.

2. Mathematical models of the MLS

The model of the magnetic levitation system is shown in Figure 1. In which, $u(t)$ is the control input, changed to control the electromagnetic force F to lift or lower the ball by a distance x_0 from the electromagnet. The x distance between the ball and magnet is also the output of the target. The distance between the ball and the magnet is determined by the Hall-effect sensor.

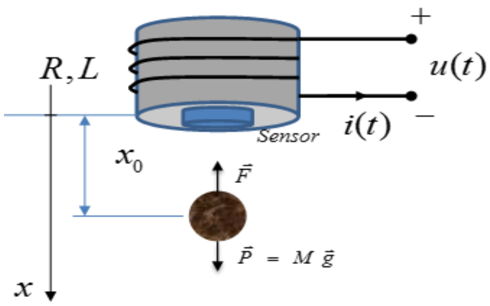

Fig. 1. Model of magnetic levitation system.

Based on [14, 23, 24], the mathematical model of the magnetic levitation system has the following form:

$$\begin{cases} \dfrac{dx}{dt} = v \\ \dfrac{Mdv}{dt} = Mg - C\left(\dfrac{i}{x}\right)^2 \\ Ri + \dfrac{d\left(L(x)i\right)}{dt} = u \end{cases} \tag{1}$$

where x (m) is position of ball; v (m/s) is verlocity of ball; i (A) is current in the coil; u (V) is the voltage supplied to the coil; R (Ω) is coil resistance, L_1 (H) is inductance of the coil; C (Nm^2/A^2) is magnetic force constant; M (kg) is mass of ball ; and g (m/s^2) is acceleration of gravity.

According to [14, 23], the inductance of the coil is a function of the position of the ball, determined by the equation (2):

$$L(x) = L_1 + \frac{2C}{x} \tag{2}$$

where L_1 is a parameter of the system. With the state variables as follows:

$$x_1 = x, \qquad x_2 = v, \qquad x_3 = i,$$

the state equations of the system (1) is rewritten:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = g - \dfrac{C}{M}\left(\dfrac{x_3}{x_1}\right)^2 \\ \dot{x}_3 = -\dfrac{R}{L}x_3 + \dfrac{2C}{L}\left(\dfrac{x_2 x_3}{x_1^2}\right) + \dfrac{1}{L}u \end{cases} \tag{3}$$

The control goal is to keep the ball steady at the desired position x_0 under the variation of the model parameter, as well as the effect of the disturbance.

Build the phase plane at the work point x_{sp} = 0.02, $U = R\sqrt{\dfrac{gMx_{sp}^2}{C}}$ (Fig. 2), we see that the system is unstable at the work point.

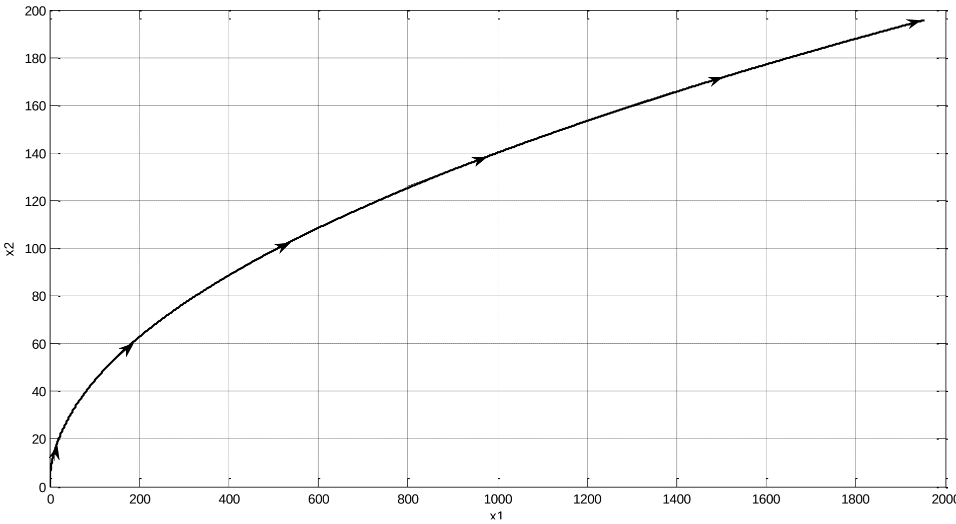

Fig. 2. The phase plane of system.

3. Basics of BAT algorithm

The standard BAT algorithm was developed by Xin-She Yang [21]. The main characteristics in the BA are based on the echolocation behavior of microbats. As BA uses frequency tuning, it is in fact the first algorithm of its kind in the context of optimization and computational intelligence. Each bat is encoded with a velocity v_i^t and a location x_i^t, at iteration t, in a d-dimensional search or solution space. The location can be considered as a solution vector to a problem of interest. Among the n bats in the population, the current best solution x_* found so far can be archived during the iterative search process.

Based on the original paper by Yang [21], the mathematical equations for updating the locations x_i^t and velocities v_i^t can be written as :

$$f_i = f_{\min} + \left(f_{\max} - f_{\min} \right) \beta,$$

$$v_i^t = v_i^{t-1} + \left(x_i^{t-1} - x_* \right) f_i,$$

$$x_i^t = x_i^{t-1} + v_i^t,$$

where $\beta \in [0; 1]$ is a random vector drawn from a uniform distribution.

In addition, the loudness and pulse emission rates can be varied during the iterations. For simplicity, we can use the following equations for varying the loudness and pulse emission rates:

$$A_i^{t+1} = \alpha A_i^t,$$

and

$$r_i^{t+1} = r_i^0 \left[1 - \exp(-\gamma t) \right],$$

where $0 < \alpha < 1$ and $\gamma > 0$ are constants.

The pseudocode of the basic bat algorithm is presented in Algorithm 1. The main parts of the BAT algorithm can be summarized as follows:

- First step is initialization (lines 1-3). In this step, we initialize the parameters of the algorithm, generate and also evaluate the initial population, and then determine the best solution xbest in the population.

Algorithm 1 Original Bat algorithm

Input : Bat population $x_i=(x_{i1}, \ldots, x_{iD})$ for i=1…Np MAX_FE

Output : The best solution x_{best} and its corresponding value $f_{min}=min(f(x))$.

1 : init_bat() ;
2 : eval=evaluate_the_new_population ;
3 : f_{min}=find_the_best_solution(x_{best}) ; {initialization}
4 : **while** termination_condition_not_meet **do**
5 : **for** i=0 **to** N_p **do**
6 : y= improve_the_best_solution(x_{best}) ;
7 : **if** rand(0,1)>r_i **then**
8 : y= improve_the_best_solution(x_{best}) ;
9 : **end if** {local search step}
10: f_{new}=evaluate_the_new_solution(y) ;
11: eval=eval+1 ;
12: **if** $f_{new} \le f_i$ **and** N(0,1)<A_i **then**

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13:         xi=y ; fi=fnew ;
14:     end if {save the best solution conditionally}
15:         fmin=find_the_best_solution(xbest) ;
16:     end for
17: end while
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• The second step: Generate the new solution (line 6). Here, virtual bats are moved in the search space according to updating rules of the bat algorithm.

• Third step is a local search step (lines 7-9). The best solution is being improved using random walks.

• In the fourth step evaluate the new solution (line 10), the evaluation of the new solution is carried out.

• In the fifth step save the best solution conditionally (lines 12-14), conditional archiving of the best solution takes place

• In the last step: find the best solution (line 15), the current best solution is updated.

4. Synthesize the feedback linearization control law with optimal parameters of the tracking controller by BAT algorithm for magnetic levitation system

The proposed control diagram for the magnetic levitation system has the form of Fig. 3. The synthesis of feedback linearization control laws with parameter optimization for the tracking controller by BAT algorithm consists of two stages: (i) Designing a feedback linearization controller; (ii) Optimizing parameters of the tracking controller by BAT algorithm.

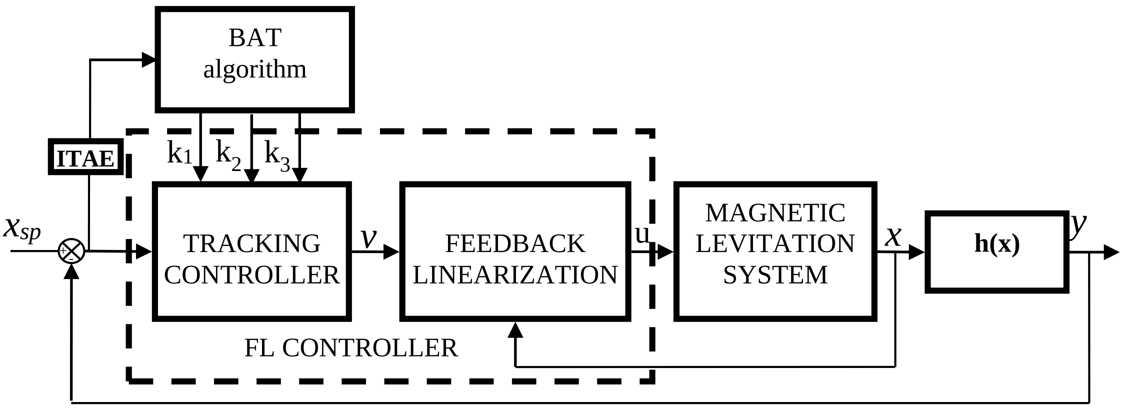


Fig. 3. The control diagram of magnetic levitation system with parametric calibration by BAT algorithm.

The form of feedback linearization control for non-linear systems [19] :

$$\begin{cases} \dot{x} = f(x) + g(x)u \\ y = h(x) \end{cases} \tag{4}$$

where $x \in R^n$ is state vector of system, $u \in R^p$ is input vector, and $y \in R^m$ is output vector.

We need to determine the control law $u = \alpha(x) + \beta(x)v$ and the differential transformation $z = T(x)$ such that the system (5) is linear.

$$\begin{cases} \dot{z} = Az + Bv \\ y = Cz \end{cases} \tag{5}$$

Applying on the magnetic levitation system (3):

$$x = [x_1 \quad x_2 \quad x_3]^T;$$

$$f(x) = \begin{bmatrix} x_2 \\ g - \dfrac{C}{M}\left(\dfrac{x_3}{x_1}\right)^2 \\ -\dfrac{R}{L}x_3 + \dfrac{2C}{L}\left(\dfrac{x_2 x_3}{x_1^2}\right) \end{bmatrix} \tag{6}$$

$$g(x) = \begin{bmatrix} 0 & 0 & \dfrac{1}{L} \end{bmatrix}^T; h(x) = x_1;$$

Using the differential transformation (7) brings the system (3) into the system (8):

$$T(x) = \begin{bmatrix} z_1 \\ z_2 \\ z_3 \end{bmatrix} = \begin{bmatrix} h(x) \\ L_f h(x) \\ L_f^2 h(x) \end{bmatrix} = \begin{bmatrix} x_1 \\ x_2 \\ g - \dfrac{C}{M}\left(\dfrac{x_3}{x_1}\right)^2 \end{bmatrix} \tag{7}$$

$$\begin{cases} \dot{z}_1 = \dot{y} = z_2(x) \\ \dot{z}_2 = \ddot{y} = z_3(x) \\ \dot{z}_3 = \dddot{y} = L_f^3 h(x) + L_g L_f^2 h(x) u = v \end{cases} \tag{8}$$

where L_f is differential operator Lie; $L_f^3 h(x) = \dfrac{2Cx_3}{mx_1^2}\left(\dfrac{Rx_3}{L_1 + \dfrac{2C}{x_1}} - \dfrac{2Cx_2x_3}{\left(L_1 + \dfrac{2C}{x_1}\right)x_1^2} + \dfrac{x_2x_3}{x_1} \right);$

and $L_g L_f^2 h(x) = -\dfrac{2Cx_3}{m\left(L_1 + \dfrac{2C}{x_1}\right)x_1^2}$;

The output $x(t)$ tracks the setting signal $x_{sp}(t)$. We define the control law $v(t)$ such that the linear tracking control law (9) has the characteristic equation in the form of the Hurwitz polynomial:

$$\dddot{e} + k_1\ddot{e} + k_2\dot{e} + k_3 = 0 \qquad (9)$$

where $e(t) = x_{sp}(t) - y(t)$; k_1, k_2, k_3 are determined according to the poles-placement method as follows:

$$\begin{cases} k_1 = -(s_1 + s_2 + s_3) \\ k_2 = s_1 s_2 + s_1 s_3 + s_2 s_3 \\ k_3 = -s_1 s_2 s_3 \end{cases} \qquad (10)$$

where s_1, s_2, s_3 are the roots of the characteristic polynomial of the tracking controller (9), selected so that all these roots have the real-part on the left side of the imaginary axis to ensure the error $e(t)$ go to 0.

From (9) deduced :

$$v = \dddot{y} = \dddot{x}_{sp} + k_1\ddot{e} + k_2\dot{e} + k_3 \qquad (11)$$

The feedback linearization controll is obtained as follows:

$$u = \left(\dddot{x}_{xp} + k_1\left(\ddot{x}_{xp} - g + \frac{C}{M}\left(\frac{x_3}{x_1}\right)^2\right) + k_2\left(\dot{x}_{xp} - x_2\right) + k_3\left(x_{xp} - x_1\right) - \frac{2Cx_3}{mx_1^2}\left(\frac{Rx_3}{L_1 + \frac{2C}{x_1}} - \frac{2Cx_2x_3}{\left(L_1 + \frac{2C}{x_1}\right)x_1^2} + \frac{x_2x_3}{x_1}\right)\right) \times$$
$$\times \frac{-m\left(L_1 + \frac{2C}{x_1}\right)x_1^2}{2Cx_3} \qquad (12)$$

With such a choice of roots s_1, s_2, s_3, it is clear that only the system will be asymptotic stable, while the quality of the control cannot be assessed. Because the quality of the control depends on the physical parameters of the system, such as the control signal limit, the oscillation boundary limits of the system states and the external disturbance conditions, as well as measurement disturbance. To reduce the transient time in the positional response, keeping the static error to zero and reducing the value of the control signal when there is a large deviation, the authors proposes a target function in the form of an integral time function and the Integral Time Absolute Error (ITAE) is in the form.

$$ITAE: \quad F = \int t\left|e(t)\right| dt \tag{13}$$

The algorithm for optimizing parameters of the tracking controller (12) through three coefficients k_1, k_2, k_3 by BAT algorithm. The algorithm for finding a parameter set value by BAT algorithm include the following steps:

1) Initializing bat populations (n) with the loudness (A) and pulse emission rates (r), the bats have random positions (x_i) and velocity (v_i) for all 3 parameters k_1, k_2, k_3
2) Calculating the ITAE cost function of all bat individuals in the population.
3) Comparing the values of the cost function to find the bat (x_{best}) with the best cost function value.
4) Updating the pulse frequency f and the velocity v of all the bats using the following equation:

$$f_{k+1} = f_{\min} + (f_{\min} - f_{\max}) * rand;$$
$$v_{k+1} = v_k + (x_k - x_{best}) f_{k+1}$$

5) Updating the positions of all the bats with the following equation:

$$x_{k+1} = x_k + v_k$$

6) Updating the position of the bat individual again if the pulse width (r) is less than the randomly generated signal pulse width ($rand$).

$$\text{if}\,(rand > r)$$
$$x_{k+1}^{new} = x_{best} + \alpha.rand$$

In the study [1], parameter α is selected in the range (0.1). But in the search problem when the optimal value of the controller parameter when it has countless solutions and is far from the original starting point, so that the algorithm performs faster than the authors choose α to choose greater than 1 and will have may lose the optimal point, because the solution is not unique, so the algorithm can still find a solution.

7) Checking the condition $(rand < A \,\&\, f(x_{k+1}^{new}) < f(x_{k+1}))$ to accept the new population, increase the pulse width (r), and reduce disturbance (A) .
8) Checking: if the best value of the new position of bats is less than the required value (f_{min}) then end the algorithm, otherwise repeat the step 4.

5. Simulation and experimental results

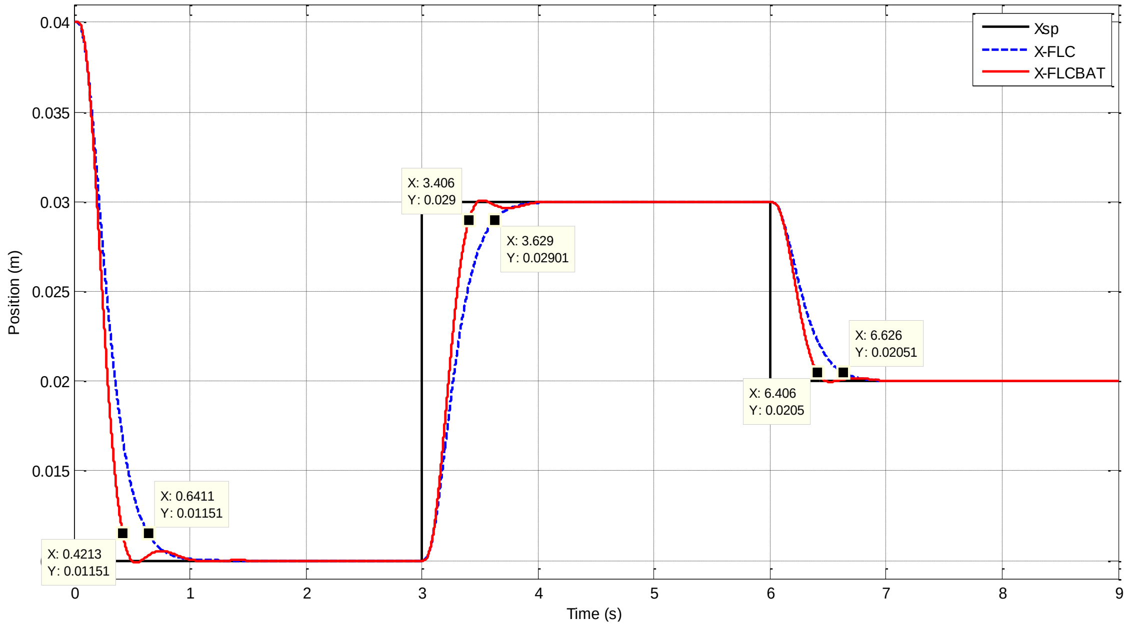
5.1. Simulation results

The simulation on Matlab software, with the following parameters of the magnetic lift system: R = 11.4 (Ω); L_1 = 0.6 (H); $C = 1.4 \cdot 10^{-4}$ (Nm^2/A^2); M = 0.006 (kg) and g = 9.8 (m/s^2). In order to optimize the parameters of the tracking controller, the authors selected the idea to slowly bring the magnetized object from 0.03 m to 0.02 m position for 2 s to value of cost function is less than 0.5 (f_{min} = 0.5). The initial value of the parameters of tracking controller are selected so that the polynomial (9) has three roots with real-part less than 0: s_1 = -10, s_2 = -10, s_3 = -10. By formula (10) we get the value: k_1 = 30; k_2 = 300; k_3 = 1000. Initialization data for the BAT algorithm include: Number of bats is 30, the loudness A = 0.5 and pulse emission rates r = 0.5. After optimizing the controller with the above conditions: k_1 = 17.4662; k_2 = 198.0436; k_3 = 831.0916. With the found parameters, we find the roots of equation (9) as follows: $s_1 = -5.4467 + 9.8375i$; $s_2 = -5.4467 - 9.8375i$; s_3 = -6.5728; with i - imaginary unit. From the results we see that the roots are on the left side of the z-plane, so the system is still stable.

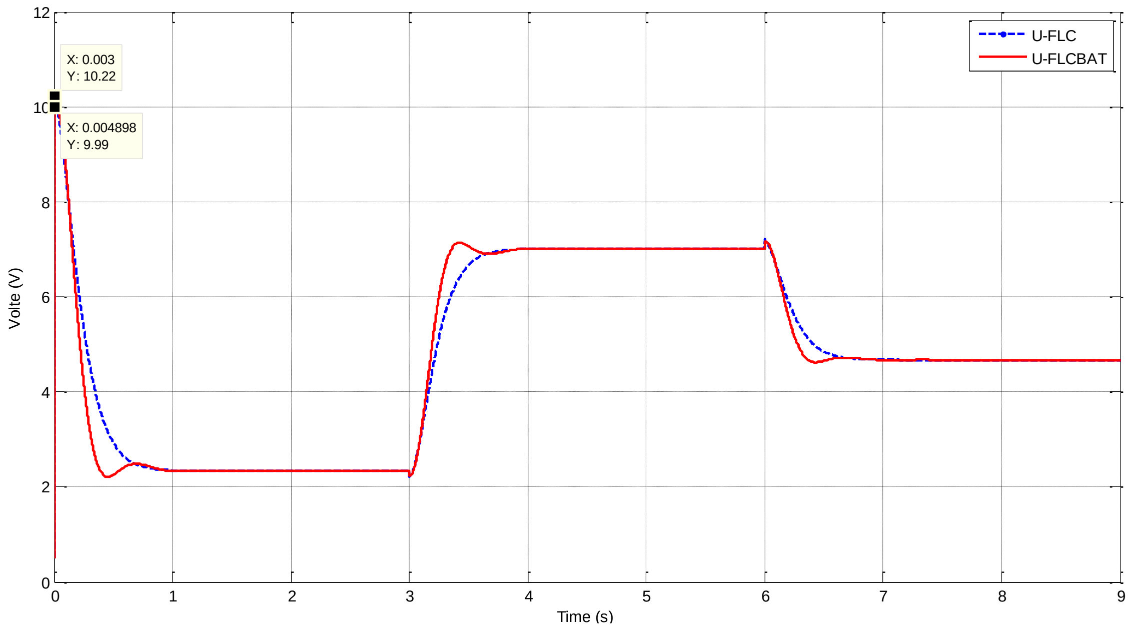
Figure 4 shows the position response (Fig. 4a) and the voltage applied to the electromagnet (Fig. 4b) when the set value of the position has a trapezoidal input. From the result of the position response to the trapezoidal input, it is clear that the response time of the controller with optimized parameters is better, for example between *0* s to *3* s. the transient time of the normal FLC controller is 0.6411 s, the response time of the controller with optimized parameters is 0.4213 s. In the following time when the set value changes, the response time of the proposed controller is better. In addition, the value of the control voltage at the first moment (t = 0 s) is also smaller. If the error is large, the FLC controller voltage will increase rapidly if the transient time is decreased. Although the position response still fluctuates, it is still within the allowed 5% deviation.

Figure 5 shows the position response (Fig. 5a) and the voltage applied to the electromagnet (Fig. 5b) when the set value of the position is in the set-point $sin(2t)$. From the result of the positional response to the input $sin(2t)$, it is clear that the response time of the controller with optimized parameters is better. In addition, the value of the control voltage at the first moment ($t = 0\ s$) is also smaller. If the error is large, the FLC controller voltage will increase rapidly if the transient time is decreased. Although the position response still fluctuates, it is still within the allowed 5% deviation.

Figure 6a shows the response of the ball's position to the effect of measuring noise Δx, in which the parameter Δx is is random value in the range [-0.0000015; 0.0000015] (m). Figure 6b shows the positional response of the magnetic levitation system when the system parameters are uncertain $M+\Delta M$, in which the parameter ΔM is random value in the range [-0.00595; 0.00605] (kg). From the above results it shows that the response of the system to the designed controller gives better results than the conventional linearized feedback controller.

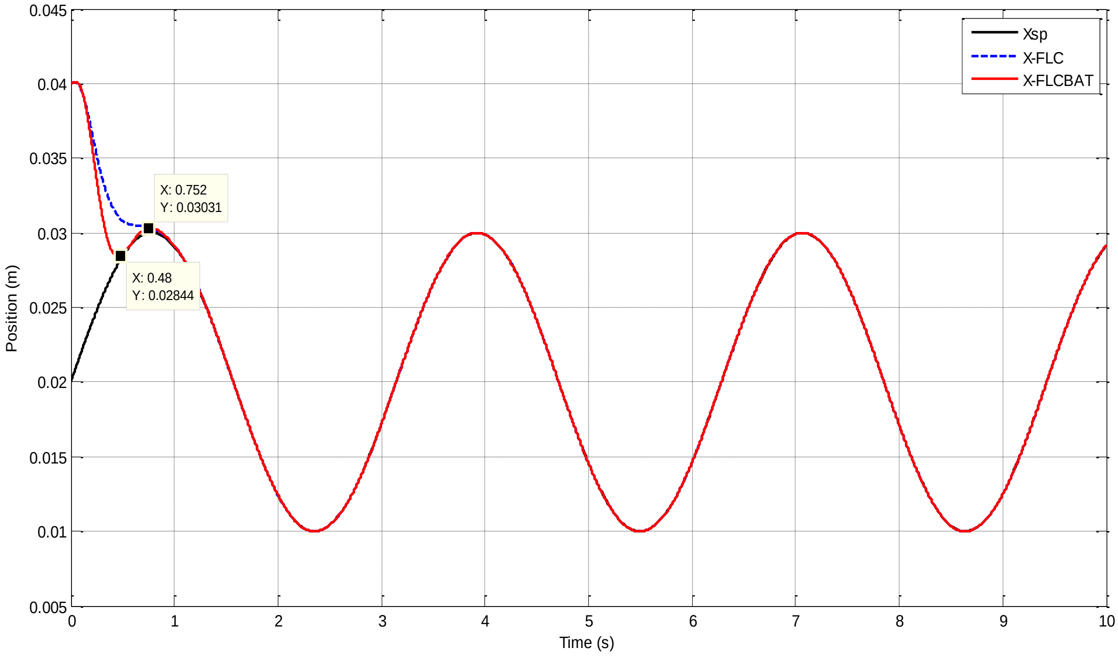


(a)

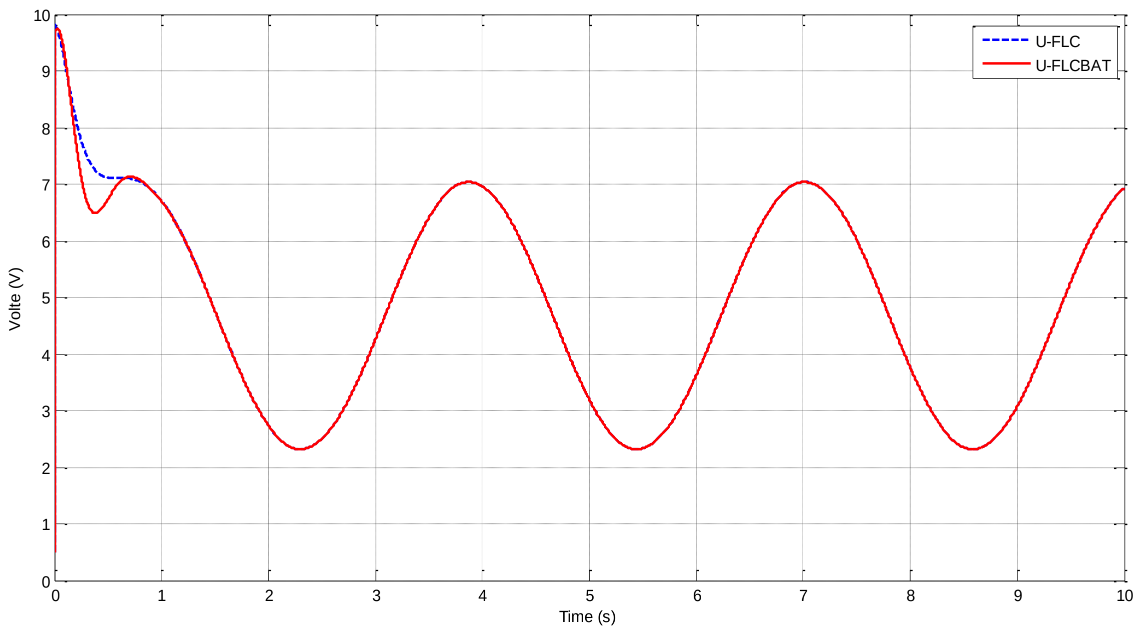


(b)

Fig. 4. The response of the system with the trapezoidal input.
(a) The response of the ball position;
(b) The supply voltage for the electromagnet.

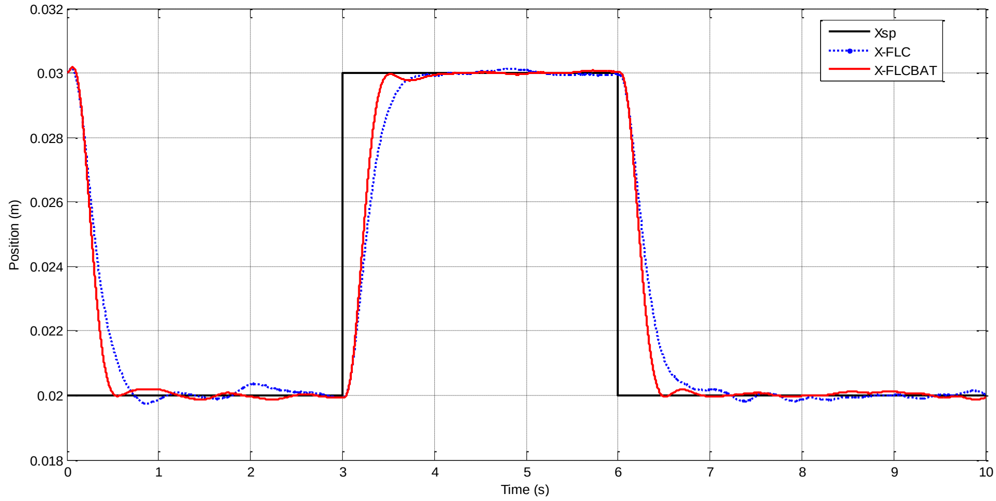


(a)

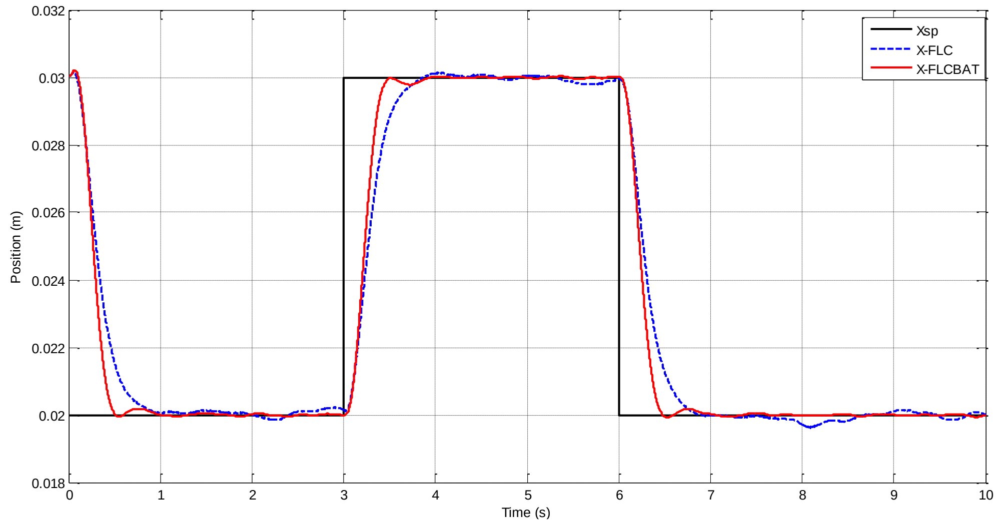


(b)

Fig. 5. The response of the system with the set-point sin(2t).
(a) The response of the ball position;
(b) The supply voltage for the electromagnet.



(a)



(b)

Fig. 6. The response of the system with nosie and uncertain parameters.
(a) The response of the ball position with nosie;
(b) The response of the ball position with uncertain parameters.

5.2. Experimental results

To demonstrate the effectiveness of the proposed control law, the authors have built the controller on the embedded system for the actual magnetic levitation system. Embedded control system is designed by the research team at the Department of Computing Techniques, which includes the following components: distance sensor module E49, ACS7 current sensor module, power amplifier circuit, Arduino Mega 2560, power supply circuit and magnetic levitation system. In addition, the system is also connected to a computer via RS-232 and monitoring software. The design model of the embedded controller and magnetic levitation system is illustrated in Fig. 7.

Because the distance sensor module E49 is linear in a very narrow range, the authors carry out lifting control of the magnetized object at a determined location without falling out of the working position. Figure 6 shows the results when stabilizing a magnetized object with mass M = 6 g away from the electromagnet a determined distance of 2 cm. From the results we see that the ball is stable at the desired position, but the ball also oscillates because of the form of the control signal and measuring disturbance of the sensor 49E. When there is a change of the set position from 1 (cm) to 2 (cm) in Fig. 8, the designed control law above still ensures that the ball is stable at the set value. Although there is fluctuation, the system still works stably.

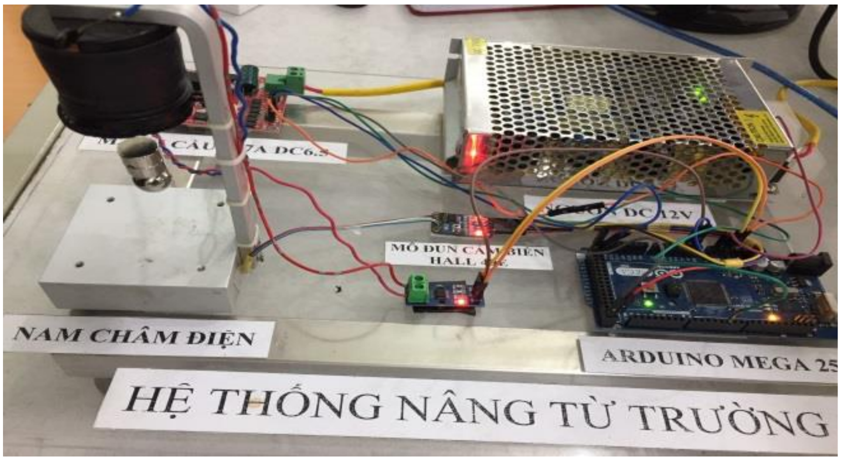


Fig. 7. Magnetic levitation system with the embedded controller.

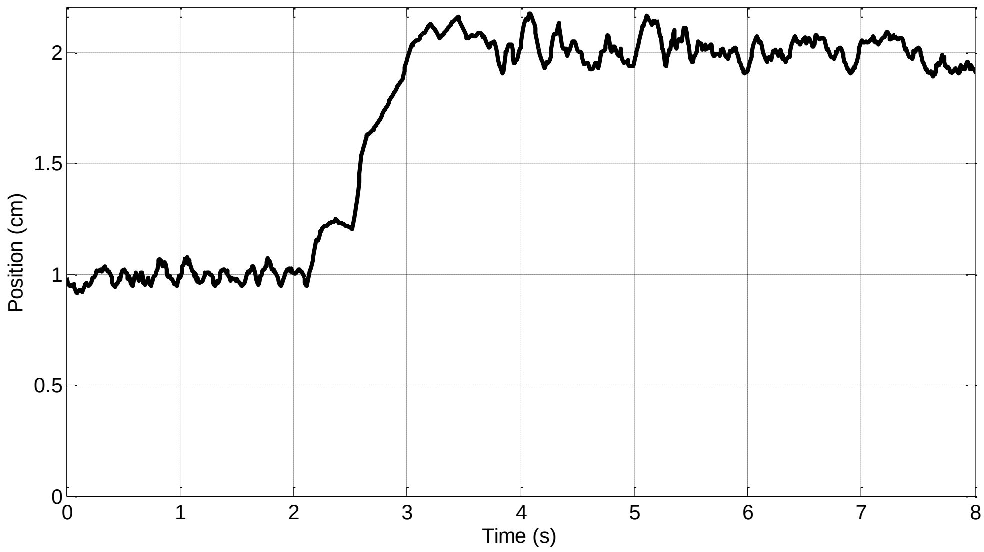


Fig. 8. The response of the ball position on the actual model.

6. Conclusion

In the study, the synthesis of a feedback linearization controller with optimal parameters for a magnetic levitation system has been presented. By using the BAT algorithm with the ITAE cost function, the authors found a set of parameters with transient time and static error is better than the set of parameters selected by the poles-placement method. Besides, this method also ensures the synthesized controller with the limit of the impact signals as well as the physical limits of the system. From the simulation results of the proposed controller and the conventional feedback linearizaion controller, it shows the advantages of the controller with the optimal parameter by the BAT algorithm. To demonstrate the effect of the synthesized controller, the authors applied the above control law for a magnetic lavitation system. The experimental results show that the effective controller on the embedded system is built, and the error guarantees the requirements of the real system. In the next studies, the authors will offer solutions to build fast-acting nonlinear controllers to improve the quality of the control system for magnetic levitation systems and improve the embedding system to give better results.

References

[1] Xin-She Yang, “Nature-Inspired Optimization Algorithms,” Elsevier First edition, 2014, 258 page.

[2] Jayawant BV, Sinha PK, Aylwin DG, “Feedback Control System for D.C. Electromagnets in Passenger-Carrying Vehicles,” *Int. J. Control*, 24 (5), 627-39, 1976.

[3] Mundher H.A. Yaseen, Haider J. Abd. “Modeling and control for a magnetic levitation system based on SIMLAB platform in real time,” *Journal “Results in Physics”*, 8, 153–159, 2018.

[4] Kosuke N, Masashi I, “A noncontact permanent magnet levitation table with electromagnetic control and it’s vibration isolation method using direct disturbance cancellation combining optimal regulators,” *IEEE Tran. on Magnetics*, 31(1), Jan 1995.

[5] M.K.A. Ahamed Khan, Shahid Manzoor, H. Marais, Ms Kalaiselvi Aramugam, I. Elamvazuthi, S. Parasuraman, “PID Controller design for a Magnetic Levitation system,” *2018 IEEE 4th International Symposium on Robotics and Manufacturing Automation (ROMA).*

[6] Pallav, Sumit Kumar Pandey, Vijaya Laxmi, “PID Control of Magnetic Levitation System based on Derivative Filter,” *International Conference on Magnetics, Machines & Drives (AICERA-2014 iCMMD) - 2014 IEEE*.

[7] Hartert L, Sayed-Mouchaweh M, “Dynamic supervised classification method for online monitoring in non-stationary environments,” *Neurocomputing* 2014; 126:118-31.

[8] Soloway Donald, Haley Pamel J, "Neural generalized predictive control: A newton-raphson implementation," *NASA Technical Memorandum* Feb 1997; 110244.

[9] Huang Chao-Ming, Yen Jia-Yush, Chen Min-Shin, "Adaptive nonlinear control of repulsive maglev suspention system," *Control Eng. Pract*., 2000.

[10] Lughofer E, Sayed-Mouchaweh M, "Adaptive and on-line learning in nonstationary environments," *Evol. Syst.* 2015; 6:75-7.

[11] Morales R, Feliu V and Sira-Ramírez H, "Nonlinear control for magnetic levitation systems based on fast online algebraic identification of the input gain," *IEEE Transactions on Control Systems Technology*, 19(4), 757-771, 2011.

[12] Chih-Min Lin, Ming-Hung Lin and Chun-Wen Chen, "SoPC-Based Adaptive PID Control System Design for Magnetic Levitation System," *IEEE Systems Journal*, Vol. 5, No. 2, June 2011.

[13] Vimala Starbino A, Sathiyavathi S, "Design of sliding mode controller for magnetic levitation system," *Computers and Electrical Engineering*, 78, 184-203, 2019.

[14] Nguyễn Chí Ngôn, Phạm Thanh Tùng và Dương Hoài Nghĩa, "Điều khiển trượt dùng mạng nơron hệ nâng vật bằng từ trường," *Tạp chí Khoa học*, 2011:17b, 140-147.

[15] Engr. Sadaqat Ur Rehman, Engr. Muhammad Junaid and Engr. Obaid Ur Rehman, "Linear Quadratic Regulator controller for Magnetic Levitation System," *International Journal of Computer Science and Software Engineering (IJCSSE)*, Vol. 4, Iss. 1, January 2015, page: 6-9.

[16] Golob M and Tovornik B, "Modeling and control of the magnetic suspension system," *ISA Transactions*, 42(1), 89-100, 2003.

[17] Javadi A and Pezeshki S, "A new model-free adaptive controller versus non-linear controller for levitation of an electromagnetic system," *Transactions of the Institute of Measurement and Control*, 35(3), 321-329, 2013.

[18] Erkan Kayacan and Thor I. Fossen, "Feedback linearization control for systems with mismatched uncertainties via disturbance observers," *Asian Journal of Control*, 21(4), pp. 1-13, July 2019, Published online in Wiley Online Library (wileyonlinelibrary.com) DOI: 10.1002/asjc.1802

[19] Võ Hữu Hậu, "Điều khiển thiết bị nâng từ trường dùng phương pháp hồi tiếp tuyến tính hóa," *Tạp chí Khoa học & Ứng dụng*, Số 13 - 2010.

[20] Farhad Aghili, "Optimal Feedback Linearization Control of Interior PM Synchronous Motors Subjects to Time-Varying Operation Conditions Minimizing Power Loss," *Transactions on Industrial Electronics*, 65(7), July 2018. DOI: 10.1109/TIE.2017.2784348, IEEE

[21] Xin-She Yang, "Bat Algorithm: Literature Review and Applications," *Int. J. Bio-Inspired Computation*, Vol. 5, No. 3, pp. 141-149, 2013.

[22] Santanu Kumar Pradhan and Raghuwansh Singh, "Nonlinear Control of a Magnetic Levitation System using Feedbacl Linearization," *2014 IEEE Interational Conference on Advanced Communication Control and Computing Teclmologies (ICACCCT).*

[23] Nguyễn Xuân Chiêm, Nguyễn Trần Hiệp, Phan Nguyên Hải, Hoàng Lệ Thủy, "Thiết kế luật điều khiển phi tuyến cho hệ nâng từ trường sử dụng hệ ảo có tính tác động nhanh," *Hội nghị - Triển lãm quốc tế lần thứ 5 về Điều khiển và Tự động hoá - VCCA-2019.*

[24] Nguyen X.C., Le T.T., Phan N.H., Tran C.P., Truong D.Q., "Synthesis PD controller with optimal parameters by Bat algorithm for magnetic levitation system," *Международная научная конференция "Математические методы в технике и технологиях"* , Том 5 ММТТ-2020, page: 8-11.

TỔNG HỢP BỘ ĐIỀU KHIỂN HỒI TIẾP TUYẾN TÍNH HÓA VỚI TỐI ƯU THAM SỐ DỰA TRÊN THUẬT TOÁN BAT ỨNG DỤNG CHO HỆ NÂNG TỪ TRƯỜNG

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Tóm tắt: *Bài báo trình bày phương pháp thiết kế bộ điều khiển dựa trên phương pháp hồi tiếp tuyến tính hóa (FLC) với tham số tối ưu về thời gian đáp ứng nhờ thuật toán BAT cho hệ thống nâng từ trường. Bộ điều khiển hồi tiếp tuyến tính hóa dựa trên phép biến đổi tương đương đưa một hệ phi tuyến về dạng tuyến tính, sau đó sử dụng phương pháp gán điểm cực để tìm tham số cho bộ điều khiển bám tuyến tính. Việc lựa chọn gán điểm cực mang tính chủ quan chưa tối ưu tham số bộ điều khiển khi hệ thống cần thỏa mãn một điều kiện đáp ứng nhanh. Do đó, nhóm tác giả sử dụng thuật toán BAT để tìm tham số bộ điều khiển bám tuyến tính dựa trên hàm mục tiêu ITAE. Thuật toán tìm kiếm BAT dựa vào đặc tiểm của quần thể bầy đàn loài dơi trong tự nhiên có những ưu điểm khi tìm kiếm các hàm mục tiêu đa biến. Bộ điều khiển với tham số được tối ưu được kiểm chứng qua kết quả mô phỏng và thực nghiệm. Hiệu quả của bộ điều khiển đề xuất được so sánh với bộ điều khiển tuyến tính hóa hồi tiếp qua kết quả mô phỏng.*

Từ khóa: Hệ nâng từ; điều khiển phản hồi tuyến tính hóa; tối ưu tham số.

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