Research Article

Vibration Control Method of an Electromagnetic Isolation System Based on LQR and Coevolutionary NGA

Lei Zhang^{1,2} and Xiangtao Zhuan^{2,3}

¹Key Laboratory of Metallurgical Equipment and Control Technology, Ministry of Education, Wuhan University of Science and Technology, Wuhan 430081, China

²Department of Artificial Intelligence and Automation, School of Electrical Engineering and Automation, Wuhan University, Wuhan 430072, China

³Shenzhen Research Institute, Wuhan University, Shenzhen 518057, China

Correspondence should be addressed to Xiangtao Zhuan; xtzhuan@whu.edu.cn

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An electromagnetic isolation system can dynamically adjust the output characteristic parameters of the system in real time through the active control strategy, which has strong adaptability to the external environment. In order to control the electromagnetic vibration isolation system effectively, an active control method is presented based on the linear quadratic regulator (LQR) approach and the coevolutionary niche genetic algorithm (NGA). In this paper, the dynamical equation and state equation of the electromagnetic isolation system are built, which include the nonlinear relationship between electromagnetic force and coil current and gap. The LQR approach is employed to maintain a steady state of an isolated object on the vibration isolation system. Meanwhile, a coevolutionary niche genetic algorithm is put forward to optimize the parameters in Q and R matrices. Simulation and experimental results demonstrate that the electromagnetic isolation system with the LQR approach and coevolutionary NGA can effectively isolate the vibration and maintain a steady state for an isolated object in comparison with the passive isolation system.

1. Introduction

With the development of science and technology, a lot of precision measuring instruments, such as scanning probe microscope, laser interferometer, and so on, have found wide applications in actual engineering. However, the vibration produced by motors and pumps inside precision instruments will affect the measurement accuracy [1, 2]. In recent years, high-precision CNC machine tools are widely used in the field of manufacturing and processing, but the vibration of CNC machine tools and cutting tools will damage the surface finish of the workpieces and reduce the life of mechanical systems [3, 4]. In addition, the vibration of various mechanical power systems during operation will also reduce the life of mechanical equipment [5]. Accordingly, an effective isolation system is necessary to develop which

needs to isolate vibrations coming from not only outside environment but also equipment itself.

In order to ensure the normal operation of equipment, various vibration isolation systems and vibration control technologies have been developed for vibration reduction and noise reduction of working machinery, stability control of precision measuring instrument and test bed, improvement of vehicle comfort, and so on [6, 7]. In general, the vibration isolation systems can be divided into passive vibration isolation systems and active vibration isolation systems. The passive isolation systems have simple structures and require neither external power sources nor control systems in the process of operation, which are usually composed of elastic elements, damping elements, or inertia elements, such as steel springs, air springs, rubber pads, polymer materials, and so on. In recent years, an eddy

current damper, as a passive vibration isolation system, is widely used to resist the vibration with the advantages of no mechanical contact, good stability, and high reliability [8, 9].

Although the passive vibration isolation systems have reported considerable success in those works, the output parameters cannot be adjusted according to the actual operation conditions. Active vibration isolation systems operate with external power sources and flexible control methods to control vibration for the purpose of keeping machinery performing at its best precision. Based on the measured state signals by sensors, the controller in the vibration isolation system generates control signals to achieve the purpose of vibration isolation. Compared with the passive vibration isolation system, active vibration isolation system can dynamically adjust the output characteristic parameters of the system in real time according to the given control strategy, which has strong adaptability to the external environment. As such, the active vibration isolation system can not only overcome the shortcomings of passive vibration isolation system but also meet the requirements of vibration control.

According to various types of actuators, a lot of active vibration isolation systems have been designed and utilized in the field of vibration control. Wang et al. [10] analyzed the dynamic behavior and decoupling approach and developed a decoupling control strategy for a six-DOF vibration isolation platform with eight pneumatic actuators which is verified through experiments of the platform. Baz and Poh [11] presented a modified independent modal space control method to optimize the location, control gains, and select excitation voltage of the piezoelectric actuators to control the structural vibrations of flexible beams. Huang et al. [12] developed a giant magnetostrictive actuator for the active control of a stay cable model and proposed an active control method of stay cable vibration using the designed giant magnetostrictive actuator. All of the above active vibration isolation systems can effectively control and isolate vibration. However, the active vibration isolation systems based on pneumatic actuators have the disadvantages of large equipment volume and mass, low control accuracy, and long response time. In addition, the active vibration isolation systems based on piezoelectric actuators or magnetostrictive actuators have the nonnegligible hysteresis and complexity, which make the design and control quite difficult. In recent years, the electromagnetic vibration isolation system, a typical active isolation system with variable noncontact dynamical parameters, flexible control methods, and fast response during operation, has been widely used in the field of vibration control.

Due to the fact that the controller plays an important role in the electromagnetic vibration isolation system, the control method in the controller determines the performance of the system. Zhang and Xu. [13] presented an isolation scheme for control moment gyroscopes on satellites and selected the appropriate parameters of the PID controller to attenuate the disturbances and improve the attitude stability. Barkana and Kaufman [14] utilized a robust adaptive control method to control the vibration of large flexible space structures and proved the stability of the adaptive control algorithm in

detail. In order to control the vibration of the magneto-rheological suspension to improve ride comfort, Dong and Yu [15] put forward an adaptive fuzzy logic control approach and utilized the hybrid Taguchi genetic algorithm to optimize parameters and control rules. Gosiewski and Mystkowski [16] proposed a robust control of a rigid rotor vibration and confirmed its robustness by experimental results which show the effectiveness and robustness of the control system. Chen et al. [17] designed a controller based on neural network for vibration control, which could greatly attenuate the vibration of resonance and external disturbance.

The aforementioned works can effectively control vibration with various control methods. However, the problems of the above control methods are five-fold. Firstly, the PID controller needs to conduct lots of experiments to determine K_p , K_i , and K_d parameters. Secondly, the parameters of the adaptive control algorithm are easy to be affected by the measurement accuracy, which is not conducive to the practical engineering application. Thirdly, the determination of fuzzy rules and functions depends entirely on subjective experience, and the stability of the fuzzy logic control approach is relatively poor. Once again, the robust control algorithm cannot balance the robustness and system performance, and the selection of weight function mainly depends on human experience which has a direct impact on the performance of the robust controller. Finally, the performances of the neural network control methods are usually affected by initial parameters, and thus their control results are unstable.

In recent years, the linear quadratic regulator (LQR) approach, an effective optimal control method in many fields, has achieved considerable success in the field of vibration control. The optimal control method finds the optimal control strategy according to the established control objective function and constraint conditions to achieve the control objective. Feng et al. [18] adopted LQR control strategy to mitigate vibration and maintain the structural integrity and stability for a spatial tensegrity beam. Gokul Prasad and Malar Mohan [19] presented an innovative design of adaptive air suspension system based on LQR control strategy which is tuned by particle swarm optimization (PSO). Bendine et al. [20] utilized the LQR control algorithm to provide a damping effect on the composite plate with piezoelectric actuator and employed genetic algorithm (GA) to evaluate the optimal configuration. However, the parameters in objective function are usually fixed by human subjectivity or the intelligent control algorithms (PSO and traditional GA), which are easy to produce local optimal solution.

Based on the aforementioned discussions, an active control method based on LQR approach and coevolutionary niche genetic algorithm is proposed to simultaneously control multiple electromagnetic isolation units in the active electromagnetic isolation system. The novelties and contributions of the present work are two-fold. On the one hand, the active isolation system is discretized and the objective function is established to design the RHC controller, which can simultaneously control multiple

electromagnetic isolation units in the system and keep the stability of the isolated object. On the other hand, the coevolutionary NGA algorithm is proposed to optimize the weights in Q and R matrices for the objective function. In order to avoid obtaining the local optimal solution, two populations evolve independently and the individual fitness of a population is evaluated with other populations through the NGA algorithm.

The paper is organized as follows. In Section 2, an active vibration isolation system with two electromagnetic isolation units is presented and the nonlinear relationship among the parameters of coil current, gap, and electromagnetic force is established by COMSOL simulation. The RHC controller is designed in Section 3. The coevolutionary NGA is proposed in Section 4. In Section 5, simulation and experimental results are given. Some conclusions are given in Section 6.

2. Isolation Structure and Nonlinear Relationship

2.1. Structure of the Electromagnetic Isolation System. In order to analyze the control problem of the vibration isolation system with multiple electromagnetic isolation units, the structure of the system with two electromagnetic isolation units is shown in Figure 1. The system is comprised of two electromagnetic isolation units, two displacement sensors, the plate, and the base. Each electromagnetic isolation unit is composed of two electromagnets and a spring. Two electromagnets are located in the spring to save space to achieve compact structure.

The isolated object, such as precision measuring instrument, mechanical equipment, and so on, is laid on the plate. During operation of the isolated object, the vibration of the isolated object and the plate may be produced by motors and pumps inside the isolated object or an exciting force from outside environment. In order to guarantee the stability of the isolated object, two electromagnetic isolation units in the isolation system will, respectively, produce the electromagnetic forces when current is passed through two electromagnets in each electromagnetic isolation unit. Consequently, two electromagnetic forces from two electromagnetic isolation units in the isolation system, two elastic forces from two springs, and the damping force from the isolation system are employed to reduce vibration together. Two displacement sensors are used to measure the variations of displacement of the isolated object. Based on the displacement values from two displacement sensors, the electromagnetic force of the electromagnetic isolation system will be aroused to counteract the vibration of the isolated object and the plate by controlled currents.

2.2. Nonlinear Relationship. During the vibration isolation system operation, each electromagnetic isolation unit operates independently with the nonlinear relationship among electromagnetic force, the gap between two electromagnets, and current in an electromagnet. In order to achieve the nonlinear relationship among electromagnetic

FIGURE 1: Structure of the electromagnetic isolation system.

force, the gap, and coil current to design the LQR controller, two electromagnets are simulated with the electric currents in COMOSOL Multiphysics.

In the electromagnetic isolation system, four cylindrical electromagnets are identical entirely. The height and diameter of an electromagnet are 30 mm and 65 mm. The height and the diameter of iron core in the electromagnet are 30 mm and 36 mm. The coil of an electromagnet has 0.53 mm in diameter, which includes 2700 rings.

Based on the above parameters, two electromagnets are simulated in COMOSOL Multiphysics to acquire the relationship among electromagnetic force, the gap, and coil current. The COMSOL simulation results are shown in Figure 2; the nonlinear relationship can be then fitted as shown in the following equation (for more details, readers are referred to [21]):

$$f_e(y, i) = 8259.7863 * y_0^2 + 2.4055 * i^2 - 61.9546 * y_0 + 3.1128 * i - 311.2811 * y_0 * i - 0.509, \quad (1)$$

where f_e is the electromagnetic force, y_0 is the gap between two electromagnets, and i is the coil current in an electromagnet.

3. Linear Quadratic Regulator of the Isolation System

3.1. Isolation System Model. There are two identical electromagnetic isolation units in the vibration isolation system [22]. Based on the structure of the vibration isolation system as shown in Figure 1, each electromagnetic isolation unit model can be simplified as shown in Figure 3. The damping coefficient of each electromagnetic isolation unit is d , and the stiffness of spring is k . The mass of an electromagnet is m , and f_{e1} is the controllable electromagnetic force in an electromagnetic isolation unit. After the plate or the isolated object is subjected to an exciting force f_{d1} , the plate and the isolated object will produce the vibration displacement variation x_1 . The downward direction is assumed as the positive direction.

FIGURE 2: Simulation results in COMSOL multiphysics.

FIGURE 3: The model of an electromagnetic vibration isolation unit.

It is known that the electromagnetic force is related to the gap y_0 and the current i . Based on the structure of the electromagnetic isolation system in Figure 1 and the above parameters, the relationship between x_1 and y_0 is expressed as follows:

$$x_1 = L_0 - 2 \times h_0 - y_0, \quad (2)$$

where $L_0 = 0.083$ m is the original length of a spring and $h_0 = 0.03$ m is the height of an electromagnet.

Based on the above relationship, equation (1) can be rewritten for keeping the unity of the variables as follows:

$$\begin{aligned} f_{e1}(x_1, i) = & 8259.7863 * x_1^2 + 2.4055 * i^2 - 317.9956 * x_1 \\ & - 4.0467 * i + 311.2811 * x_1 * i + 2.4351. \end{aligned} \quad (3)$$

Due to the fact that two electromagnetic isolation units are identical in the vibration isolation system, they have the same parameters, such as the stiffness of the spring k , the damping coefficient d , and the mass of an electromagnet m . After the plate or the isolated object is subjected to an exciting force, the kinetic equation of the two electromagnetic isolation units is written as follows:

$$\begin{cases} M\ddot{x}_1 + d\dot{x}_1 + kx_1 + f_{e1}(x_1, i) = f'_d, \\ M\ddot{x}_2 + d\dot{x}_2 + kx_2 + f_{e2}(x_2, i) = f'_d, \end{cases} \quad (4)$$

where x_1 and x_2 are measured by displacement sensor 1 and displacement sensor 2, respectively. The electromagnetic forces of two electromagnetic isolation units are $f_{e1}(x_1, i)$ and $f_{e2}(x_2, i)$. It is assumed that $M = (m + m_0)/2$ and $f_d = f'_d/2$, in which the mass of the isolated object is m_0 and the external disturbance is f_d . Thus, the state equation of the electromagnetic isolation system can be written as follows:

$$\begin{cases} \dot{X} = AX + BU + EF, \\ Y = CX, \end{cases} \quad (5)$$

where $X = [x_1, x_2, \dot{x}_1, \dot{x}_2]^T$ is the state variable, $U = [u_1, u_2]^T = [f_{e1}(x_1, i), f_{e2}(x_2, i)]^T$ is the control variable, and F is the external disturbance. In order to keep the stability of the isolated object and the plate of the isolation system, the vibration displacements measured by two displacement sensors are selected as output $Y = [y_1, y_2]^T = CX = [x_1, x_2]^T$ and

$$\begin{aligned} A &= \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -\frac{k}{M} & 0 & -\frac{d}{M} & 0 \\ 0 & \frac{-k}{M} & 0 & -\frac{d}{M} \end{bmatrix}, \\ B &= \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ \frac{-1}{M} & 0 \\ 0 & \frac{-1}{M} \end{bmatrix}, \\ E &= \begin{bmatrix} 0 \\ 0 \\ \frac{1}{M} \\ \frac{1}{M} \end{bmatrix}, \\ C &= \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}. \end{aligned} \quad (6)$$

3.2. Discretization. Due to the fact that the controller is discrete in engineering, the state equation of the electromagnetic isolation system can be discretized based on the

zero-order hold method with sampling period T_s . It is assumed that

$$\begin{cases} A(k) = I + T_s A, \\ B(k) = T_s B, \\ M(k) = T_s M, \end{cases} \quad (7)$$

where T_s is the sampling period.

Based on the aforementioned analysis, the model of the electromagnetic isolation system is discretized to design the LQR controller as follows:

$$\begin{cases} x(k+1) = A(k)x(k) + B(k)u(k) + M(k), \\ y(k) = Cx(k), \end{cases} \quad (8)$$

where $M(k) = E(k)F(k)$ is the disturbance matrix.

3.3. LQR. In order to keep the stability of the isolated object and reduce the impact of vibration produced by motors and pumps inside the isolated object or an exciting force from outside environment, the performance function is presented as follows:

$$J(k) = \int_0^\infty [q_1 y_1^2(k) + q_2 y_2^2(k) + q_3 (y_1(k) - y_2(k))^2 + r_1 u_1^2(k) + r_2 u_2^2(k)] dt, \quad (9)$$

where q_1, q_2 , and q_3 are the weights for displacement variations measured by two displacement sensors and r_1 and r_2 are the weights for the electromagnetic force in two vibration isolation units, respectively.

The LQR controller aims to minimize the displacement variations and the difference between two variations measured by two displacement sensors and ensure the electromagnetic forces are limited. It is assumed that $Q = [q_1 + q_2 - q_1 \ 0 \ 0; -q_1 \ q_1 + q_3 \ 0 \ 0; 0 \ 0 \ 0 \ 0; 0 \ 0 \ 0 \ 0]$ and $R = \text{diag}(r_1, r_2)$; the performance function can be rewritten based on equations (5) and (10) as follows:

$$J' = \int_0^\infty [X^T Q X + U^T R U] dt. \quad (10)$$

According to the extremum principle, the controlled electromagnetic force under the optimal output is obtained as follows:

$$U = -R^{-1}(N^T + B^T P)X = -KX, \quad (11)$$

where K is the optimal feedback matrix, P is the solution of Riccati matrix equation $PA + A^T P - PBR^{-1}B^T P + Q = 0$, and N is equal to 0.

4. The Coevolutionary Niche Genetic Algorithm

In recent years, the traditional genetic algorithm is widely used to optimize and search for problems. However, the genetic algorithm merely uses fitness to judge the quality of individuals in the process of evolution. When the fitness of some individuals has obvious advantages, they may multiply in the population and then occupy the whole population, which will destroy the diversity of the population. For the

aforementioned problem, the niche technology is a good assistant for genetic algorithm. The niche technology divides individuals in each generation into several categories and selects a number of individuals with larger fitness as an excellent representative of a category to form a group. Then, crossover and mutation are completed to generate a new individual group in the population or between different populations. At the same time, sharing mechanism could be used to complete the task, which is proposed by Goldberg and Richardson. The genetic algorithm based on the niche technology can keep the diversity of the population in the process of evolution. The main steps of the algorithm are as follows:

- (1) Calculate the value of shared function among individuals in a group as follows:

$$\text{sh}(d_{ij}) = \begin{cases} 1 - \left(\frac{d_{ij}}{\sigma}\right)^\alpha, & d_{ij} < \sigma, \\ 0, & \text{otherwise,} \end{cases} \quad (12)$$

where d_{ij} is the distance between the individual i and the individual j , σ is the niche radius, and α is the parameter for adjusting $\text{sh}(d_{ij})$.

- (2) Calculate the number of niche of the individual in population m_i as follows:

$$m_i = \sum_{j=1}^N \text{sh}(d_{ij}), \quad (13)$$

where N refers to group size, which is the sum of shared functions $\text{sh}(d_{ij})$ of the individual i and other individuals in the population.

- (3) Calculate the new fitness of the individual in the population after sharing as follows:

$$f'_i = \frac{f_i}{m_i}, \quad (14)$$

where f'_i is the true fitness of the individual i before sharing.

- (4) Based on the new fitness of the individual, the genetic operation can be conducted to generate new individuals and new populations.

The coevolutionary approach points out that various species cooperate with each other during evolution in the nature. Each species contributes to the whole evolution based on their evolutionary strategy. Various subpopulations are cooperatively evolved through the interrelated fitness based on the coevolutionary approach. This approach includes multiple species, in which each species stands for a part of the solution to the problem and evolves independently. In addition, the individual fitness of a species is calculated with other species which is the significance of the collaboration.

The proposed coevolutionary niche genetic algorithm is shown in Figure 4. The weight matrices Q and R are

FIGURE 4: Flowchart of coevolutionary NGA.

optimized by population 1 and population 2, and the two populations evolve independently. According to the idea of collaboration, one of the two populations needs to employ another population to calculate its fitness. The real number coding is utilized for two populations in the process of collaboration. Figure 5 shows that the crossover operation between two chromosomes is completed in a single point, which means that the genes following the crossover points are exchanges. The mutation operation occurs in a mutation gene which is randomly selected and mutated with a certain probability. The performance function in equation (11) is conducted as the fitness evaluation function. It can be found that when the performance parameter has a maximum value, the fitness value has a minimum value.

5. Simulation and Experimentation

5.1. Simulation Diagram. The simulation diagram with the proposed active control method based on LQR and coevolutionary niche genetic algorithm is shown in Figure 6. In order to save computation time and improve the control efficiency, a state variable is employed to optimize the weight matrices Q and R based on the proposed active control method in the offline mode. According to the reference location, the weight matrices, and the LQR approach, the

control variables can be obtained to control the vibration isolation system with multiple electromagnetic isolation units.

5.2. Simulation Parameters. The electromagnetic vibration isolation system has the following parameters. The damping coefficient d and the stiffness of the spring k are 10 N·s/m and 589 N/m in an electromagnetic isolation unit, respectively. The mass of an electromagnet m is 530 g, and the gravity of Earth g is 9.8 N/kg. In the niche genetic algorithm, two populations with 100 in size are utilized for optimization, in which one is the weight matrix Q and the other is weight matrix R . The crossover and mutation probabilities are 0.8 and 0.1, respectively. The maximum number of evolutions refers to 50. The distance d_{ij} between the individual i and the individual j is calculated based on Euclidean distance method. The parameter α is 1. The niche radius σ is 50 in population 1 and 0.00000001 in population 2. The sampling period T_s is 0.01 s in simulation. Based on the aforementioned parameters and analysis, the weights for displacement variations q_1, q_2 , and q_3 in matrix Q are 99862, 96254, and 97264 and the weights for the electromagnetic force r_1 and r_2 in matrix R are 0.00000051 and 0.00000049, respectively. According to equation (10) and the control objective of the

FIGURE 5: Crossover and mutation operation in real-valued chromosomes.

FIGURE 6: Simulation diagram with the proposed active control method.

electromagnetic isolation system, the reference location y_r refers to $[0; 0]$.

5.3. Simulation Results. Due to the fact that a continuous load always imposes to the electromagnetic isolation system, a step signal is utilized as the external disturbance in simulation. The initial value and the final value of the step are 0 and 14, respectively. Based on the aforementioned parameters, the comparison of active electromagnetic isolation system based on the proposed LQR approach with the coevolutionary niche genetic algorithm and passive vibration isolation system is shown in Figure 7. It can be seen that the electromagnetic isolation system with the proposed active control method is stable at 1.77 s. When the active isolation system with the proposed control approach is stable, the outputs are 9.10×10^{-6} and 9.01×10^{-6} , which are measured by the displacement sensor 1 and the displacement sensor 2, respectively. Although the electromagnetic isolation system has a steady-state error, it is small enough to be ignored. The passive isolation system is stable at 0.51 s, and the outputs are both 0.0063 which is approximately 700 times bigger than the output value of the active isolation system. The simulation result demonstrates that the LQR approach and the weight matrices calculated by the proposed coevolutionary niche genetic algorithm can effectively control vibration and ensure the stability of the isolated object when the electromagnetic isolation system is subjected to the step signal.

5.4. Experimental Results. In order to verify the effectiveness of the proposed LQR approach and the coevolutionary niche genetic algorithm, experiments are conducted on the electromagnetic isolation system. The physical photo of the vibration isolation system with two electromagnetic isolation

units is shown in Figure 8. The proposed control approach based on the LQR and the coevolutionary NGA is implemented on the STM 32 single-chip microcontroller, which is integrated with data acquisition equipment on the development board. The control cycle of the controller is 0.01 s. There are two displacement sensors in the electromagnetic isolation system to achieve displacement signals which are input to the objective function in LQR approach. All parameters in the experiment are equal to parameters in simulation.

Figure 9 shows the experimental results; it can be seen that the electromagnetic isolation system with the proposed control method is stable at 2.28 s with the outputs 9.10×10^{-6} and 9.01×10^{-6} , which are measured by the displacement sensor 1 and the displacement sensor 2, respectively. Due to the measurement errors in the actual system and errors in the processing of electromagnets, the stable time and the outputs are different from the simulation results. However, they have the same variation trend and the differences are small enough to be negligible. The experimental result demonstrates that the effectiveness of the simulation method and the proposed active control approach based on the LQR and the coevolutionary NGA can guarantee the stability of the isolated object.

5.5. Other Simulations. Due to the fact that experimental result is similar to the simulation result, the simulation approach with the proposed active control method can effectively describe and control the electromagnetic isolation system. In practical application, the external disturbances have the characteristics of complexity and variability. In order to verify the advantages of the proposed LQR approach and the coevolutionary niche genetic algorithm in the electromagnetic isolation system, a random signal and a sinusoidal signal are used for imitating the actual situation.

FIGURE 7: Simulation results under a step signal.

FIGURE 8: The experimental physical photo.

Figure 10 shows the result from the active isolation system based on the proposed LQR approach and the co-evolutionary niche genetic algorithm in comparison with the result from the passive isolation system when they are

subjected to a Gaussian random signal. It can be seen from Figure 10 that the maximum amplitude of the active isolation system with the proposed active control approach is 1.0043×10^{-5} and the maximum amplitude of the passive

FIGURE 9: Experimental result based on the active control approach.

FIGURE 11: Simulation results under a sinusoidal signal.

FIGURE 10: Simulation results under a random signal.

isolation system is 0.0102. The maximum amplitude of the passive isolation system is 1016 times bigger than the maximum amplitude of the active isolation system. The simulation result demonstrates that the LQR approach and NGA algorithm can effectively keep the stability of the isolated object and improve the effect of vibration isolation when the electromagnetic isolation system is subjected to the random signal.

When the vibration isolation system is disturbed by a sinusoidal signal, the result from the active electromagnetic isolation system based on the proposed LQR approach and

the coevolutionary NGA in comparison with the result from the passive isolation system is shown in Figure 11. The frequency and the bias of the sinusoidal signal are 6.28 rad/sec and 4. It can be seen that the maximum amplitude decreases from 0.0103 of the passive isolation system to 1.2313×10^{-5} of the active isolation system. In other words, the maximum amplitude of the passive isolation system is 837 times bigger than the maximum amplitude of the active isolation system, which implies that the proposed active method based on the RHC approach and the coevolutionary NGA can significantly control vibration and guarantee the stability of the isolated object.

6. Conclusion

In order to control multiple electromagnetic isolation units in the vibration isolation system, an active control method based on the LQR approach and the coevolutionary niche genetic algorithm is proposed to control vibration. The vibration isolation system with multiple electromagnetic isolation units is discretized to design the LQR controller with an objective function. For optimizing the weight matrices Q and R , the coevolutionary niche genetic algorithm is presented to avoid obtaining the local optimal solution and make the LQR controller have excellent performance. Simulation and experimental results demonstrate that the performance of the active isolation system with multiple electromagnetic isolation units based on the LQR approach and the coevolutionary niche genetic algorithm is better than the passive isolation system. The proposed active control method can effectively keep the stability of the isolated object and control vibration, which applies equally to vibration control in the vibration isolation system with three or more electromagnetic isolation units.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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