Research on vibration suppression of rigid flexible coupling manipulators based on genetic algorithm optimization

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Abstract. Aiming at the problem that the rigid flexible coupling manipulator generates elastic vibration during movement, which reduces the positioning accuracy and work efficiency, we propose a method of end vibration suppression based on cosine function superposition and multi population genetic algorithm. First, we get the relationship between the elastic vibration of the flexible arm and the joint trajectory motion according to the dynamic model of the system. Then, the cosine function superposition is used as the basis function to construct motion parameters of joints and the minimum residual vibration amplitude at the end of the flexible arm is used as the objective function. The undetermined coefficients in the basis function are optimized by multi population genetic algorithm to obtain the optimal trajectory. Finally, the simulation and experiment results show that the residual vibration amplitude is reduced by 60.6%. The proposed method can suppress the residual vibration at the end of the flexible arm and improve the work efficiency.

Keywords: rigid flexible coupling mechanical arm; Vibration suppression; Multi population genetic algorithm; Trajectory optimization.

1. Introduction

With the continuous progress of industrial automation technology, flexible arm is widely used in engineering. However, flexible arm will experience elastic vibration due to energy exchange when moving. Vibration deformation not only affects the position control accuracy of the manipulator, but also reduces the tracking accuracy [1-3]. Therefore, it is very important to suppress the elastic vibration at the end of the flexible arm. Vibration suppression methods include "trajectory optimization" and "tracking control"[4-5]. Most of the previous studies were conducted from the perspective of "tracking control". However, due to the complex coupling relationship between the state variables of rigid flexible manipulator, it is very complex to use tracking control to suppress the elastic vibration of the end of flexible manipulator. The vibration suppression method based on trajectory optimization is to convert the required motion into the trajectory defining the time series between the starting point and the end point, and meet the constraint conditions according to the application. This method is simpler, more direct, and has more significant vibration suppression effect[6]. Therefore, we propose a method based on genetic algorithm to optimize the joint trajectory, which can suppress the elastic vibration of the flexible arm. The cosine superposition function(CFS) is used as the initial motion path, and the minimum residual vibration amplitude at the end is used as the objective function. The undetermined coefficient in the joint path is optimized by Multi population genetic algorithm(MPGA) to obtain the optimal motion path from the initial position to the target position, which can suppress the residual vibration at the end of the flexible arm.

2. Modeling of Rigid Flexible Coupling Manipulators

The rigid flexible coupling manipulators we studied consists of a rigid link and a flexible link. According to the theory of dynamic boundary conditions of cantilever beam and Euler Bernoulli beam model, the simplified model of rigid flexible manipulator is shown in Figure 1. Where, OXY is the base coordinate system of the base of the manipulators; θ_1 and θ_2 are the relative motion angles of the rigid arm and the flexible arm, $O_1X_1Y_1$ is the local coordinate system of the base of the rigid arm; $O_2X_2Y_2$ is the local coordinate system of the base of the flexible arm; The length of the rigid arm is l_1, the length of the flexible arm is l_2, $w(x,t)$ is the deformation amount of the flexible arm with distance x from the base coordinate.

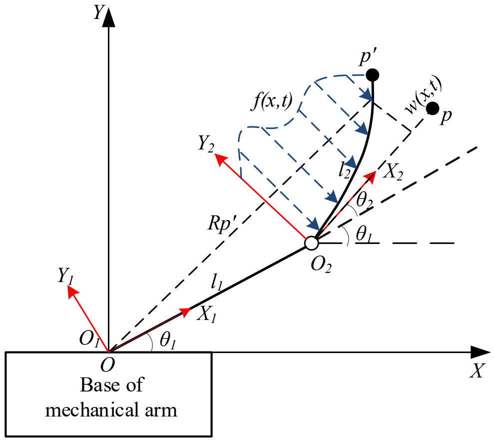


Fig. 1 Simplified model of rigid flexible coupling manipulator

According to the results of literature[7-8], we get the dynamic model of rigid flexible coupling manipulator as follows:

$$M\ddot{Z}+V\dot{Z}+KZ+F=T \tag{1}$$

Where, M is the generalized mass matrix, K is the stiffness matrix, V is the generalized damping matrix, F is the nonlinear formula under the action of centrifugal force and Coriolis force, T is the generalized driving torque, and the specific expressions of each matrix are as follows:

$$\begin{cases} Z=[\theta_1,\theta_2,q_1,q_2,q_3]^T \\ V=diag[\delta_1,\delta_2,\delta_3,\delta_4,\delta_5] \\ K=diag[k_1,k_2,k_3,k_4,k_5] \\ T=[\tau_1,\tau_2,0,0,0]^T \\ F=[f_1,f_2,f_3,f_4,f_5]^T \end{cases} \tag{1}$$

When the flexible arm is moving, it will produce elastic vibration, especially when it reaches the target position. If the residual vibration at the end cannot be suppressed in time, the working efficiency of the manipulator will be reduced. Based on the system dynamics model, the relationship between the elastic vibration at the end of the flexible arm and the motion of each joint of the manipulator is derived:

$$\begin{bmatrix} m_{31} & m_{32} & 0 \\ m_{41} & m_{42} & 0 \\ m_{51} & m_{52} & 0 \end{bmatrix}\begin{bmatrix} \ddot{\theta}_1 \\ \ddot{\theta}_2 \\ 0 \end{bmatrix}+\begin{bmatrix} f_3 \\ f_4 \\ f_5 \end{bmatrix}=\begin{bmatrix} m_{33} & m_{34} & m_{35} \\ m_{43} & m_{44} & m_{45} \\ m_{53} & m_{54} & m_{55} \end{bmatrix}\begin{bmatrix} \ddot{q}_1 \\ \ddot{q}_2 \\ \ddot{q}_3 \end{bmatrix} + \begin{bmatrix} k_{33} & 0 & 0 \\ 0 & k_{44} & 0 \\ 0 & 0 & k_{55} \end{bmatrix}\begin{bmatrix} q_1 \\ q_2 \\ q_3 \end{bmatrix} \tag{2}$$

We have established the relationship between the elastic vibration of the flexible arm and the joint motion. It can be seen from equation (2) that the joint angular acceleration directly affects the change of vibration mode q, Therefore, the most effective and direct method is to plan the value of joint angular acceleration, but the planned trajectory will be used as the input of joint controller, and the error caused by integration will affect the accuracy of end position control, Therefore, the most effective and direct method is to plan the value of joint angular acceleration, but the planned trajectory will be used as the input of joint controller, and the error caused by integration will affect the accuracy of end position control, Therefore, it is necessary to adopt appropriate trajectory interpolation function to plan joint angular displacement to reduce integration error and suppress flexible arm end elastic vibration.

3. Vibralation Suppression Based on Mpga

3.1 Selection of basis function

Trajectory planning is not only to set the coordinates of the starting position and the target position, but also to limit the boundary conditions of the trajectory parameters to ensure the continuity and stability of the manipulator in motion. According to the motion characteristics of rigid flexible manipulator, we propose a joint trajectory interpolation planning method based on cosine function superposition(CFS). The basic expression of CFS is:

$$\theta(t)=(\theta_e-\theta_0)[a_0+\sum a_n\cos(\frac{n\pi}{t_e}t)]+\theta_0 \tag{3}$$

Where, θ_0 and θ_e are the initial joint position and target joint position, t_e is the time of motion planning, n is a positive integer($n=1,2,3\cdots$). The joint angular velocity and angular acceleration obtained from the first derivative and the second derivative are:

$$\begin{cases}\dot{\theta}(t)=\dfrac{(\theta_e-\theta_0)}{t_e}[\pi\sum(-na_n)\sin(\dfrac{n\pi}{t_e}t)]\\ \ddot{\theta}(t)=\dfrac{(\theta_e-\theta_0)}{t_e^2}[\pi^2\sum(-n^2a_n)\cos(\dfrac{n\pi}{t_e}t]\end{cases} \tag{4}$$

The boundary constraints are as follows:

$$\begin{cases}\theta(0)=\theta_0,\dot{\theta}(0)=0,\ddot{\theta}(0)=0\\ \theta(t_e)=\theta_e,\dot{\theta}(t_e)=0,\ddot{\theta}(t_e)=0\end{cases} \tag{5}$$

Substituting boundary condition (5) into equation (4), we get:

$$\begin{cases}\sum n^2a_n=0\\ \sum n^2a_n\cos n\pi=0\\ a_0+\sum a_n=0\\ a_0+\sum a_n\cos n\pi=0\end{cases} \tag{6}$$

When n=2, the obtained solution has no independent variable and the programming function has no solution; When n=3, the planning function has no number of independent variables and all parameters are known; When n is 4, 5, and 6, the number of independent variables of the planning function is 1, 2, and 3. When the number of independent variables is too small, the obtained motion trajectory may change suddenly. Increasing the number of variables will make the trajectory smoother, but it will bring more parameter uncertainties to the system. Through comparative analysis, we take n=5 for optimization and calculation to obtain the joint trajectory function:

$$\begin{aligned}\theta(t)=(\theta_e-\theta_0)[a_0+a_1\cos(\frac{\pi t}{t_e})+a_2\cos(\frac{2\pi t}{t_e})+a_3\cos(\frac{3\pi t}{t_e})\\ +a_4\cos(\frac{4\pi t}{t_e})+a_5\cos(\frac{5\pi t}{t_e})]+\theta_0\end{aligned} \tag{7}$$

Take the derivative of equation (7) to get:

$$\begin{cases}\dot{\theta}(t)=\dfrac{\pi(\theta_e-\theta_0)}{t_e}[-a_1\sin(\dfrac{\pi t}{t_e})-2a_2\sin(\dfrac{2\pi t}{t_e})-3a_3\sin(\dfrac{3\pi t}{t_e})\\ \quad -4a_4\sin(\dfrac{4\pi t}{t_e})-5a_5\sin(\dfrac{5\pi t}{t_e})]\\ \ddot{\theta}(t)=\dfrac{\pi(\theta_e-\theta_0)}{t_e^2}[-a_1\cos(\dfrac{\pi t}{t_e})-4a_2\cos(\dfrac{2\pi t}{t_e})-9a_3\cos(\dfrac{3\pi t}{t_e})\\ \quad -16a_4\cos(\dfrac{4\pi t}{t_e})-25a_5\cos(\dfrac{5\pi t}{t_e})]\end{cases} \tag{8}$$

3.2 Parameter optimization based on MPGA

Genetic algorithm was proposed by Professor J. Holland in 1975[9-10]. This algorithm is an intelligent algorithm for optimal search. The MPGA includes the selection, mutation, crossover and other operations of the conventional GA algorithm, but the manual selection operator and immigration operation are added, which reflects the evolutionary idea of GA algorithm to constantly select the best. Through this operation, new populations are constantly generated. The algorithm optimization process is shown in Figure 2.

According to the optimization process of multi population GA algorithm, the specific selection of optimization parameters is as follows:

(1) Establish the optimization objective: we select the maximum amplitude $w(L,t)$ of the residual vibration at the end of the flexible arm as the optimization objective. When the first five orders of the basis function are taken as the interpolation function, there are four unknown parameters in the system: a_{41}, a_{42}, a_{51}, a_{52}. The optimization problem is described as:

$$\begin{cases} Min \rightarrow w(L,t) = \Phi_1(L)q_1 + \Phi_2(L)q_2 + \Phi_3(L)q_3 \\ s.t. \rightarrow -1 \le a_{41}, a_{42}, a_{51}, a_{52} \le 1 \end{cases} \tag{9}$$

(2) Select optimization parameters: set the initial population size as 100, mating probability as 0.6, mutation probability as 0.2, and the maximum number of iterations as 100.

(3) Select the fitness function: select the integral of the absolute value of the actual expected output and feedback error of the system as the evaluation index:

$$J = \int_0^\infty (|e(t)| \cdot t) dt \tag{10}$$

(4) Select algorithm operation: if the fitness value of individual i is f_i and the initial population size is 100, then the probability of individual i being selected is:

$$P_i = f_i / \sum_{k=1}^{100} f_k \tag{11}$$

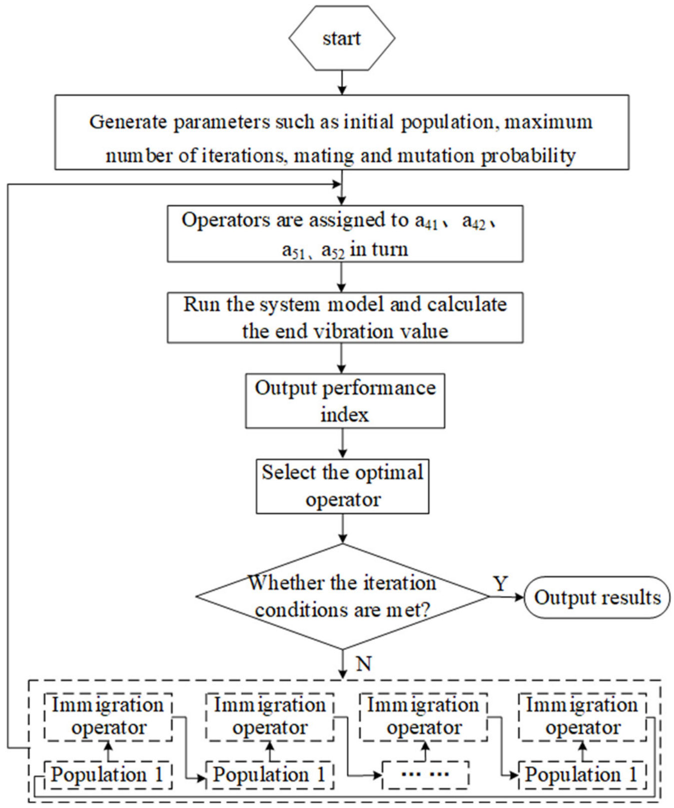


Fig. 2 Optimization flow of MPGA

4. Simulation and Experiment

4.1 Simulation analysis

The relevant physical parameters of the rigid flexible coupling manipulator we studied are shown in Table 1.In order to verify the effectiveness of the proposed trajectory optimization vibration suppression method, the quintic interpolation planning(QIP) and cycloidal interpolation planning(CIP) are selected as reference. The simulation algorithm is run in MATLAB and the optimization results are shown in Figure 3. Then, the optimized trajectory parameters are substituted into the original trajectory planning function, and the elastic vibration displacement change at the end of the flexible arm is obtained as shown in Figure 4.

Tab. 1 Basic Parameters of the System

Basic Parameters	Rigid Arm	Flexible Arm
Arm length /m	$l_1 = 0.33$	$l_2 = 0.30$
Mass moment of inertia /kg·m^2	$J_1 = 0.0812$	$J_2 = 0.138$
Linear density / kg·m^3		$\rho_2 = 0.4865$
Elastic modulus /N·m^2		$EI_2 = 26.06$
Load weight /kg	$M_p = 0$	$M_t = 0.521$

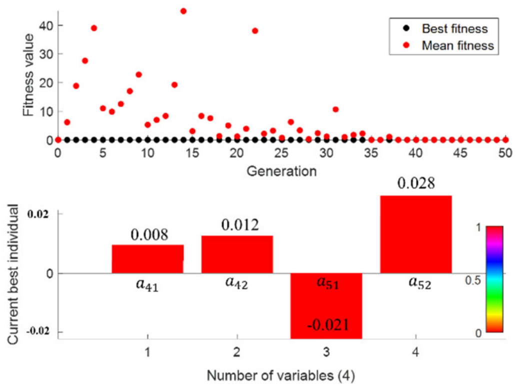


Fig. 3 Optimization result of algorithm

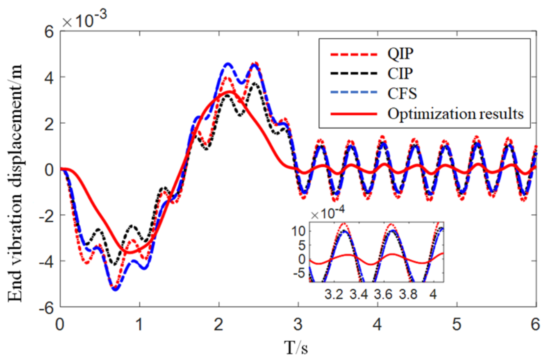


Fig. 4 End vibration displacement of flexible arm

From the simulation results, it can be seen that in the first 3s, the vibration displacement changes at the end of the flexible arm when the manipulator moves from the starting position to the target position; The last 3s: residual vibration changes at the end of the flexible arm when the mechanical arm reaches the target point. Three conventional trajectory planning methods will cause large elastic vibration at the end of the flexible arm, and the amplitude range of residual vibration at the end before optimization is [-1.26mm 1.28mm], The range of residual vibration amplitude at the end of the flexible arm optimized based on MPGA is [-0.5mm 0.5mm], and the residual vibration amplitude is reduced by 60.6%, which proves that the method can effectively suppress the residual vibration at the end of the flexible arm.

4.2 Experimental analysis

According to the relevant physical parameters and hardware connection requirements of the system, the experimental platform is built as shown in Figure 6. The upper computer obtains the real-time control parameters through the communication with the motion controller. The data acquisition system collects the data of the strain sensor and calculates the elastic vibration displacement of the end of the flexible arm according to the relationship between the strain gauge sensor and the elastic deformation, thus verifying the effectiveness of the proposed trajectory optimization algorithm.

According to the optimized joint trajectory motion parameters, the angle input is given to the servo motor through the control program. The angular displacement changes of the two joints during the experiment are measured through the encoder and compared with the expected angular displacement. The results are shown in Figure 7. When the flexible arm moves to the target position, the sampling time is T=0.02s, and the change value of the strain sensor is collected to obtain the residual vibration displacement at the end of the flexible arm, as shown in Figure 8.

From the experimental results, it can be concluded that the actual motion angle of each joint is consistent with the planned motion angle; The experimental value of the residual vibration at the end of the flexible arm is [-0.58mm, 0.55mm], and the change trend of the experimental results is consistent with the simulation results, which shows that the proposed trajectory optimization algorithm can effectively suppress the residual vibration at the end of the flexible arm and improve the motion efficiency.

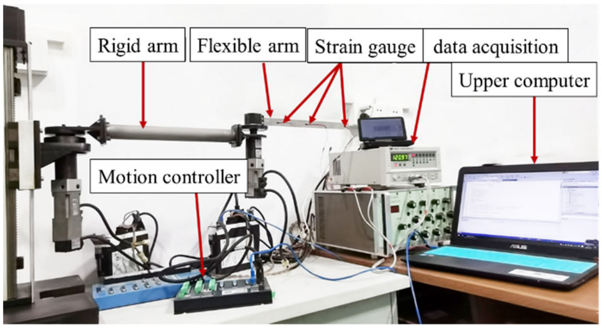
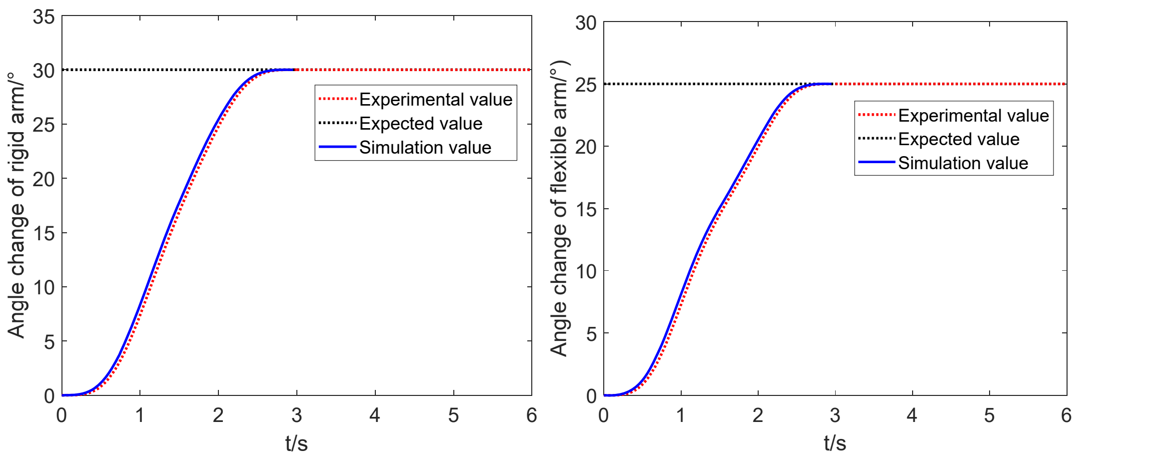


Fig. 5 Experimental platform



(a) Angular displacement change of rigid arm (b) Angular displacement change of flexible arm

Fig. 6 Change of joint angular displacement

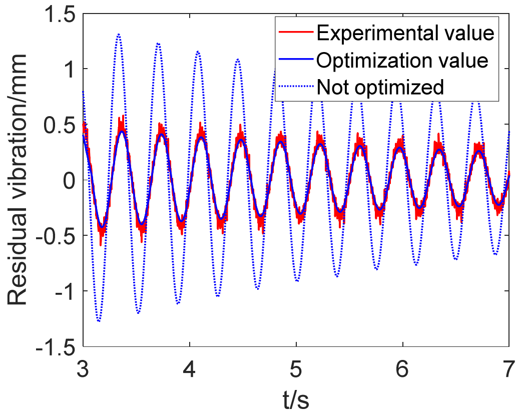


Fig. 7 Residual vibration change

5. IV Conclusion

From the point of view of trajectory optimization, we propose a residual vibration suppression method combining CFS and MPGA. The simulation and experimental results show that the trajectory optimization method proposed in this paper can reduce the elastic vibration of the end of the flexible arm and improve the motion efficiency of the manipulator. For other complex multi link flexible arm systems, if the relationship between joint motion parameters and vibration modes can be obtained, this optimization algorithm can also be used to suppress the elastic vibration of the flexible arm.

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