The vibration character and reducing vibration analysis about series manipulator’base

Wu Zai Xin¹ and Li Tai¹,*

¹School of Electrical and Mechanical Engineering Lanzhou University of Technology Lanzhou 730050, China

*E-mail: 18394026438@163.com

Abstract. During the running of serial manipulator, unbalanced force produced by base with respect to the floor has a great effect on the accuracy of manipulator’s end. Aiming at the above problem, we take the three-degree-of-freedom serial manipulator as an example to analysis. First, taking advantage of the methodology of Newton-Euler dynamics to derive the relative force between two joint rods and base with respect to the floor while the manipulator is at the period of working. Then, building the spring-damp vibration model to calculate the parameter formula of the base with relative to the ground. Finally, analysing the characteristics of vibration and giving measures of reducing vibration, simulating to prove the effectivity using MATLAB. The simulation results show that when choosing other values of ωᵦ and ξ, vibration amplitude has significant decrease compared with the conditions of ωᵦ = ω₁ or ξ =0.414 when other parameters unchanged, which provides a certain reference for further research on vibration reduction of series manipulator.

1. Introduction
The series manipulator has the characteristics of large working and good control decoupling, which makes it has a good application prospect and becomes a hot spot of robot research[1,2]. At present, series manipulator is widely used in painting, automatic assembly, welding and other industrial fields [3-5]. Its research can be roughly divided into kinematics and dynamics modeling, control and algorithm, structure performance analysis and optimization design. The position accuracy of the end of the manipulator is an important index in the research. Factors affecting the position accuracy of the end of the series manipulator are related to the precision of clearance fit[6], vibration generated by the interaction between components. The vibration that affects the end accuracy can be divided into two aspects according to the source. On the one hand, it is the vibration generated by the interaction force of each bar; on the other hand, it is the vibration generated by the interaction between the base of the manipulator and the ground. For now, ignoring external distractions, considering only the vibration generated by the interaction force of each member, the research is divided into two aspects: vibration at the flexible joint[7], deformation of the flexible bar and residual vibration[8,9]. For the impact of vibration between the base of the manipulator and ground, the main method is to reduce the reaction force and reaction torque to achieve dynamic balance. Aiming at the problem of dynamic balance during the operation of the manipulator, Walker, M. J.[10], van der Wijk, V[11], Ye, Z., Smith, M, R.[12], Tepper, F. R[13] present methods of balance optimization in terms of dimension relation of structure and adding balancer.
In this paper, a three-degree-of-freedom manipulator is studied. Firstly, based on the transfer matrix method of linear multi-body system, a simplified model of rigid three-degree-of-freedom series manipulator with load is established; then, based on the model, Newton-Euler[14] dynamics method was used to deduce the interaction forces between the bars, transferring the force to base of manipulator; secondly, the spring-damping vibration reduction model of the base is established and the corresponding vibration parameter equation is solved; Finally, based on the vibration parameter equation, the vibration reduction measures are proposed and the situations that should be avoided in the process of vibration reduction are indicated. The measures are proved by using MATLAB to simulation.

2. Modeling and dynamic analysis

A simplified model of rigid three-degree-of freedom series manipulator with load is established, determining the DH parameter table and transfer matrix. The simplified mechanical arm model is as follows:

![Figure 1. Three DOF mechanical arm model.](image)

From the figure 1, there is a table of DH parameters:

|   | $a_i$ | $a_i$ | $d_i$ | $\theta_i$ |
|---|---|---|---|---|
| 1 | 0 | -90° | $d_1$ | $\theta_1$ |
| 2 | $l_2$ | 0 | $d_2$ | $\theta_2$ |
| 3 | 0 | 90° | $l_3$ | $\theta_3$ |

The transfer matrix between the coordinate systems of the manipulator can be derived from the table 1: DH parameter, such as $^0T_1, ^1T_2, ^2T_3$.

Using Newton-Euler iterative dynamics method to split the manipulator and analyze the relationship between force and torque of each member. Supposing the mass of each homogeneous bar is $m_i$. The center of mass $s_i$ lies at the geometric center of the bar section. The vector from the center of mass to the end of the rod in the near base coordinate system is $n_i$, corresponding distance is $c_i$. The vector from the center of mass to the other end is $m_i$.

The interaction force and torque on the bar one are shown in the figure 2:

![Figure 2. Stress analysis of the first bar.](image)

The interaction force and torque on the bar two are shown in the figure 3:

![Figure 3. Stress analysis of the second bar.](image)
When the load mass of rod three is \( m_3 \), the force and torque are shown in the figure 4:

**Figure 4.** Stress analysis of the third bar.

According to the balance relationship between force and moment, it is known that each member satisfies the following conditions:

\[
\begin{align*}
F_0 + F_1 + m_1 g K & = m_1 a_1^0, \\
Q_0 + n_1^0 \times F_0 + m_1^0 \times F_1 & = I_1^0 \alpha_1^0, \\
F_2 + F_2^0 + m_2 g K & = m_2 a_2^0, \\
Q_2 + n_2^0 \times F_2 + m_2^0 \times F_2 & = I_2^0 \alpha_2^0, \\
F_0 + (m_3 g + m_4 g) K & = m_3 a_3^0, \\
Q_2 + n_2^0 \times F_2 + m_4 g K & = I_3^0 \alpha_3^0.
\end{align*}
\]

Where \( F_1, Q_1, a_1, \alpha_2, I_3 \) express force, torque, acceleration, angular acceleration, moment of inertia in the global coordinate system. \( m_0, n_0 \) express the direction of the vector in the global coordinate. \( K \) represents the unit vector in the z direction of the global frame. The calculation formula of each quantity is:

\[
\begin{align*}
a_0^i & = \dot{d}_0^i + a_0^i \times (r_0^i - d_0^i) \times \omega_0^i, \\
\ddot{d}_0^i & = \dot{\omega}_0^i \times d_0^i + \omega_0^i \times \dot{d}_0^i \times \omega_0^i, \\
\omega_{i-1,i} & = \omega_{i-1,i}^0 \times \omega_{i-1,i}^0.
\end{align*}
\]

\( \omega_{i-1,i}^0, d_0^i \) represent the angular velocity and joint vector of the ith bar relative to the i-1th bar in the global coordinate system, \( r_0^i, d_0^i \) represent the centroid vector and terminal vector of the ith bar in the global coordinate system. Such as \( d_0^i = n_0^i \times m_0^i, r_0^i = n_0^i \).

Comprehensive formulas (1)-(8) can derive the interaction force \( F^0 \) and torque \( Q^0 \) on each bar. Here we consider the vibration force of the base during the operation of the manipulator, i.e. main solution \( F_0^0 \).

3. Vibration reduction method and model establishment

\( F_0^0 \) is space force, changed with the position and time of each member of the manipulator. Dividing it into X, Y and Z directions, i.e. \( F_0^0_x, F_0^0_y, F_0^0_z \). Setting the mass of the base of the manipulator is \( m_0 \), by the relationship of action and reaction, the vibration force is \( -F_0^0 \). The equivalent model of spring and damping is established as follows:

**Figure 5.** Vibration reduction model.

From the figure 5, the vibration equations are as follows:

\[
\begin{align*}
m_0 \ddot{x}(t) + c_x \dot{x}(t) + k_x x(t) & = -F_0^0_x, \\
m_0 \ddot{y}(t) + c_y \dot{y}(t) + k_y y(t) & = -F_0^0_y, \\
m_0 \ddot{z}(t) + c_z \dot{z}(t) + k_z z(t) & = -F_0^0_z.
\end{align*}
\]

Taking the equations into the form:

\[
\begin{align*}
x(t) + 2\xi_0 x(t) + \omega_0^2 x(t) & = -F_0^0/m_0, \\
\end{align*}
\]

Thus corresponding solution method of \( \xi, \omega_0 \) is known.
Equations (9)-(11) are inhomogeneous equations, and the solution form of the corresponding homogeneous equation is:

$$x(t) = e^{-\omega_0 t} (X_1 e^{\omega_0 \sqrt{t^2 - \xi t}} + X_2 e^{\omega_0 \sqrt{t^2 - \xi t}})$$

X1, X2 are determined by the initial conditions. During the forced vibration, owing to the existence of the damping factor $\xi$, the free vibration will decay quickly, leaving only the forced vibration. Here, the position and pose of each arm member can be represented by corresponding angle $\theta_1$, converting it into the product of angular velocity and time: $\theta(t) = \omega_1 t$. Similarly, the corresponding angular acceleration is expressed as $\alpha$. Using the method of solving inhomogeneous equation, trigonometric transformation method to calculate the vibration solutions of the manipulator base in three directions in the space global coordinate system.

Assuming $\omega_{12} = \omega_1 + \omega_2$, $\omega_{13} = \omega_1 - \omega_2$, $\omega_{123} = \omega_1 + \omega_2 + \omega_3$. The oscillatory solution in the X direction in the global coordinate system is:

$$x(t) = e^{-\omega_0 t} (X_1 e^{\omega_0 \sqrt{t^2 - \xi t}} + X_2 e^{\omega_0 \sqrt{t^2 - \xi t}}) A_1 (\omega_{12}^2 - \omega_0^2)^2 + 2\omega_0 \omega_1 A_2 \left[ (\omega_{12}^2 - \omega_0^2)^2 + 4\omega_0 \omega_1 \right] \sin (\omega_1 t_1 + \omega_2 t_2) + B_1 (\omega_{12}^2 - \omega_0^2)^2 + 2\omega_0 \omega_1 B_2 \sin (\omega_1 t_1 - \omega_2 t_2) + C_1 (\omega_{12}^2 - \omega_0^2)^2 + 4\omega_0 \omega_1 C_2 \sin (\omega_1 t_1 + \omega_2 t_2 + \omega_3 t_3) + D_1 (\omega_{12}^2 - \omega_0^2)^2 + 2\omega_0 \omega_1 D_2 \sin (\omega_1 t_1 - \omega_2 t_2 - \omega_3 t_3) \right)(12)

The corresponding terms of the X direction vibration solution are as follows:

$$A_1 = \frac{1}{2m} \left[ -\omega_2^2 m_2 l_2 + \omega_2^2 m_2 l_2 - \omega_1^2 m_2 (l_2 - c_2) + \omega_1^2 m_2 (l_2 - c_2) - \omega_1 \omega_2 m_2 l_2 \right],$$

$$A_2 = \frac{1}{2m} \left[ -\omega_2^2 m_2 l_2 + \omega_2^2 m_2 l_2 - \omega_1^2 m_2 (l_2 - c_2) + \omega_1^2 m_2 (l_2 - c_2) - \omega_1 \omega_2 m_2 l_2 \right],$$

$$B_1 = \frac{1}{2m} \left[ -\omega_2^2 m_2 l_2 + \omega_2^2 m_2 l_2 - \omega_1^2 m_2 (l_2 - c_2) + \omega_1^2 m_2 (l_2 - c_2) - \omega_1 \omega_2 m_2 l_2 \right],$$

$$B_2 = \frac{1}{2m} \left[ -\omega_2^2 m_2 l_2 + \omega_2^2 m_2 l_2 - \omega_1^2 m_2 (l_2 - c_2) + \omega_1^2 m_2 (l_2 - c_2) - \omega_1 \omega_2 m_2 l_2 \right],$$

$$C_1 = \frac{1}{2m} \left[ -\omega_2^2 m_2 (c_3 - l_3) + \omega_1^2 m_2 (c_3 - l_2) - \omega_1 \omega_2 m_2 l_2 - \omega_1 \omega_2 m_2 l_2 \right],$$

$$C_2 = \frac{1}{2m} \left[ -\omega_2^2 m_2 (c_3 - l_3) + \omega_1^2 m_2 (c_3 - l_2) - \omega_1 \omega_2 m_2 l_2 - \omega_1 \omega_2 m_2 l_2 \right],$$

$$D_1 = \frac{1}{2m} \left[ -\omega_2^2 m_2 (c_3 - l_3) + \omega_1^2 m_2 (c_3 - l_2) - \omega_1 \omega_2 m_2 l_2 - \omega_1 \omega_2 m_2 l_2 \right],$$

$$D_2 = \frac{1}{2m} \left[ -\omega_2^2 m_2 (c_3 - l_3) + \omega_1^2 m_2 (c_3 - l_2) - \omega_1 \omega_2 m_2 l_2 - \omega_1 \omega_2 m_2 l_2 \right].$$

Similarly, the solution of the vibration in the Y direction in the global coordinate system is:

$$y(t) = e^{-\omega_0 t} (X_1 e^{\omega_0 \sqrt{t^2 - \xi t}} + X_2 e^{\omega_0 \sqrt{t^2 - \xi t}}) A_1 (\omega_{12}^2 - \omega_0^2)^2 + 2\omega_0 \omega_1 A_2 \left[ (\omega_{12}^2 - \omega_0^2)^2 + 4\omega_0 \omega_1 \right] \sin (\omega_1 t_1 + \omega_2 t_2) + B_1 (\omega_{12}^2 - \omega_0^2)^2 + 2\omega_0 \omega_1 B_2 \sin (\omega_1 t_1 - \omega_2 t_2) + C_1 (\omega_{12}^2 - \omega_0^2)^2 + 4\omega_0 \omega_1 C_2 \sin (\omega_1 t_1 + \omega_2 t_2 + \omega_3 t_3) + D_1 (\omega_{12}^2 - \omega_0^2)^2 + 2\omega_0 \omega_1 D_2 \sin (\omega_1 t_1 - \omega_2 t_2 - \omega_3 t_3) \right)(13)

The corresponding terms of the Y direction vibration solution are as follows:

$$A_1 = \frac{1}{2m} \left[ -m_2 (l_2 - c_2) \omega_1^2 + (m_2 + m_3) l_2 \omega_2^2 + m_2 (l_2 - c_2) \omega_2^2 + (m_2 + m_3) l_2 \omega_2 \omega_1 \right],$$

$$A_2 = \frac{1}{2m} \left[ -m_2 (l_2 - c_2) \omega_1^2 + (m_2 + m_3) l_2 \omega_2^2 + m_2 (l_2 - c_2) \omega_2^2 + (m_2 + m_3) l_2 \omega_2 \omega_1 \right],$$

$$B_1 = \frac{1}{2m} \left[ -m_2 (l_2 - c_2) \omega_1^2 + (m_2 + m_3) l_2 \omega_2^2 + m_2 (l_2 - c_2) \omega_2^2 + (m_2 + m_3) l_2 \omega_2 \omega_1 \right],$$

$$B_2 = \frac{1}{2m} \left[ -m_2 (l_2 - c_2) \omega_1^2 + (m_2 + m_3) l_2 \omega_2^2 + m_2 (l_2 - c_2) \omega_2^2 + (m_2 + m_3) l_2 \omega_2 \omega_1 \right],$$

$$C_1 = \frac{1}{2m} \left[ -m_2 (l_2 - c_2) \omega_1^2 + (m_2 + m_3) l_2 \omega_2^2 + m_2 (l_2 - c_2) \omega_2^2 + (m_2 + m_3) l_2 \omega_2 \omega_1 \right],$$

$$C_2 = \frac{1}{2m} \left[ -m_2 (l_2 - c_2) \omega_1^2 + (m_2 + m_3) l_2 \omega_2^2 + m_2 (l_2 - c_2) \omega_2^2 + (m_2 + m_3) l_2 \omega_2 \omega_1 \right],$$

$$D_1 = \frac{1}{2m} \left[ -m_2 (l_2 - c_2) \omega_1^2 + (m_2 + m_3) l_2 \omega_2^2 + m_2 (l_2 - c_2) \omega_2^2 + (m_2 + m_3) l_2 \omega_2 \omega_1 \right],$$

$$D_2 = \frac{1}{2m} \left[ -m_2 (l_2 - c_2) \omega_1^2 + (m_2 + m_3) l_2 \omega_2^2 + m_2 (l_2 - c_2) \omega_2^2 + (m_2 + m_3) l_2 \omega_2 \omega_1 \right].$$
B1 = \frac{1}{2m_0}[-(m_2 + m_3)l_2\omega_1^2 + m_2(l_2-c_2)\omega_1^2 + \omega_2^2m_2(l_2-c_2)-(m_2 + m_3)l_2\omega_1\omega_2],
B2 = \frac{1}{2m_0}[-m_2(l_2-c_2)\omega_2^2 + (m_2 + m_3)l_2\omega_2^2 + m_2(l_2-c_2)\alpha_1],
C1 = \frac{1}{2m_0}[-m_3l_3\alpha_3 + (\alpha_2 + \alpha_3)m_3(c_3-l_3) + \alpha_1m_3(c_3-l_3)],
C2 = \frac{1}{2m_0}[\omega_1\omega_3m_3l_3 - \omega_2^2m_2l_3 - m_2(c_3-l_3)\omega_1^2 - m_3(c_3-l_3)(\omega_2 + \omega_3)^2],
D1 = \frac{1}{2m_0}[\alpha_1m_3(c_3-l_3) - \omega_2^2m_2l_3 - (\alpha_2 + \alpha_3)m_3(c_3-l_3)],
D2 = \frac{1}{2m_0}[-\omega_2^2m_2l_3 - m_3(c_3-l_3)\omega_1^2 - m_2(c_3-l_3)(\omega_2 + \omega_3)^2 - \omega_1\omega_3m_3l_3].

The oscillatory solution in the Z direction in the global coordinate system is:

\begin{equation}
\begin{aligned}
z(t) &= e^{-\xi_0\omega_0 t}(X_1 e^{i\omega_0 t} - i + X_2 e^{-i\omega_0 t})
&+ \frac{m_2}{2m_0 \omega_0^2} \omega_1 \omega_2 d_2^2 + \frac{m_3}{2m_0 \omega_0^2} \omega_1 \omega_2 d_2^2 + \frac{m_4}{2m_0 \omega_0^2} \omega_1 \omega_2 d_2^2 + \frac{m_5}{2m_0 \omega_0^2} \omega_1 \omega_2 d_2^2
&\left[\begin{array}{c}
B(\omega_1^2 - \omega_0^2) \\
A(\omega_1^2 - \omega_2^2) + \frac{m_2}{m_0 \omega_0^2} \omega_1 \omega_2 d_2^2 + \frac{m_3}{m_0 \omega_0^2} \omega_1 \omega_2 d_2^2 + \frac{m_4}{m_0 \omega_0^2} \omega_1 \omega_2 d_2^2 + \frac{m_5}{m_0 \omega_0^2} \omega_1 \omega_2 d_2^2
\end{array}\right]
&\times \cos\left(\omega_1 t_1\right) + \frac{A_2(\omega_1^2 - \omega_2^2) + \frac{m_2}{m_0 \omega_0^2} \omega_1 \omega_2 d_2^2 + \frac{m_3}{m_0 \omega_0^2} \omega_1 \omega_2 d_2^2 + \frac{m_4}{m_0 \omega_0^2} \omega_1 \omega_2 d_2^2 + \frac{m_5}{m_0 \omega_0^2} \omega_1 \omega_2 d_2^2}{B(\omega_1^2 - \omega_0^2) + \frac{m_2}{m_0 \omega_0^2} \omega_1 \omega_2 d_2^2 + \frac{m_3}{m_0 \omega_0^2} \omega_1 \omega_2 d_2^2 + \frac{m_4}{m_0 \omega_0^2} \omega_1 \omega_2 d_2^2 + \frac{m_5}{m_0 \omega_0^2} \omega_1 \omega_2 d_2^2}
&\times \cos\left(\omega_2 t_2 + \omega_3 t_3\right)
\end{aligned}
\end{equation}

The corresponding terms of the Z direction vibration solution are as follows:

\omega_p = \omega_2^2 + \omega_2,
A1 = c_2 \alpha_2 m_2 l_2 c_2 m_3
A2 = l_2 \omega_2^2 m_0 \omega_2^2 m_0
B = -l_2 \omega_2^2 m_0 m_0
C1 = m_3(c_3-l_3)(\omega_2 + \omega_3)^2 l_3 \omega_2^2 m_3
C2 = \alpha_3 l_3 m_2 m_3(c_3-l_3)(\omega_2 + \omega_3)^2.

4. Vibration characteristic analysis and corresponding vibration reduction measures

Equations (12)-(14) give the vibration solution in three directions in detail. We discuss these equations in two aspects. On the one hand, it is the explanation of vibration parameter solution; on the other hand, it is the proposal of vibration reduction measures.

4.1. Description of vibration parameter solution

When the dimensions and quality of each rod of the mechanical arm are determined, the solution of vibration parameters can be regarded as the superposition of different sines and cosines; the component analysis shows that the parameters, such as A1 and A2, are related to the angular velocity and angular acceleration of each rod during the operation of the manipulator. The vibration parameter solution shows the vibration amplitude variation of the manipulator at time, and only if an angle changes, corresponding \omega_1, \alpha_1 have the effect, also needing to record the value of \omega_1 \xi_0 t_i i.e. \theta_i.

4.2. The proposal of vibration reduction measures

The equivalent elastic and damping ratio parameters are taken into account to calculate the vibration parameters of the ground.

In the process of forced vibration, the component of free vibration decays quickly, so the forced vibration component is mainly considered. Vibration solution formula (12)-(14) to form such as M sin at + N cos at at the overlay. Using trigonometric transformation, we have the form \sqrt{M^2 + N^2}\ sin(at + b), the vibration solution is converted into the form of amplitude, angular velocity and initial phase angle. The purpose of vibration reduction is to reduce vibration amplitude, in the
numerical, we search the value of $\xi$, $\omega_n$ to make the value of $(\omega_n^2 - \omega_1^2)^2 + 4\xi^2\omega_n^2\omega_1^2$ as large as possible, but should avoid the situation of $\omega_n = \omega_1$ and $\xi = \frac{\sqrt{2}}{2}$. The value of $\xi$, $\omega_n$ are determined by spring and damping.

5. The numerical simulation

During the operation of the mechanical arm, each joint does not move at the same time. The specific motion sequence of the joint is determined by the designed motion trajectory, the trajectory and position of the end of mechanical arm, and the corresponding angle of each joint. Vibration reduction is mainly considered when the force to the ground is relatively large, that is, when there is so simultaneous motion of three joints and the angular velocity of a single joint is 0 in a certain period of operation. Assuming that the operation is smooth and the angular acceleration of each joint is 0. Setting the centroid of the mechanical arm model as the geometric center of the rod length, the remaining parameters are shown in the table 2 below:

| Table 2. corresponding parameter value. |
|-----------------------------------------|
| length | $d_1$ | $d_2$ | $l_2$ | $l_3$ |
| unit: mm | 300 | 200 | 500 | 500 |
| mass | $m_1$ | $m_2$ | $m_3$ | $m_4$ |
| unit: kg | 5 | 3 | 3 | 1 |

Assuming $m_0=12$ kg, the initial position of the original manipulator is $\theta_0=0$, corresponding angular velocity: $\omega_1=60^\circ/s$, $\omega_2=90^\circ/s$, $\omega_3=90^\circ/s$.

5.1. The change of force $F_0^0$ in the operation of mechanical arm

The change of force $F_0^0$ generated in the direction of X(x0), Y(y0), Z(z0) during the operation of the mechanical arm are:

![Figure 6. Variation of component forces in X and Y directions of $F_0^0$.](image1)

![Figure 7. Variation of component force in Z direction of $F_0^0$.](image2)

From the figure 6 to figure 7, we know that from the assumed parameter simulation, the specific track of each lever of the mechanical arm, the component of force $F_0^0$ in three directions is always periodic. After comparing the specific forces, it is clear that the forces in the Z direction are much larger than those in the X and Y directions. However, the range of force variation is mainly in the X and Y directions. When only one bar move, i.e. $\omega_1$, $\omega_2$, $\omega_3$ changed with time singly, comparing with the situation of $\omega_1$, $\omega_2$, $\omega_3$ changed with time at the same time, neither the component of $F_0^0$, nor the whole value of $F_0^0$ has a stable proportional relationship.

5.2. The vibration reduction method is verified by simulation

The vibration receive by the base is forced vibration, the free vibration part quickly decays, attenuation speed determined by the factor of $\xi\omega_n$. The spring stiffness coefficient and the overall mass of the manipulator determine the natural frequency. For the purpose of vibration reduction, the larger natural frequency is taken. The forced vibration component is simulated, when the parameter value of $\xi$ and $\omega_n$: $\xi=2$, $\omega_n=180^\circ/s$. 

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When $\xi = \frac{\sqrt{2}}{2}$, other conditions unchanged, the amplitude is:

When $\xi = 2$, $\omega_n = \omega_1$, such as $\omega_n = \omega_1$, the corresponding amplitude changes have such following situation:

From the figure 8 to figure 13, when $\xi = \frac{\sqrt{2}}{2}$, with the same conditions, the amplitude variation range increases slightly, and when $\omega_n = \omega_1$, amplitude variation is more pronounced. By assuming the corresponding parameter values of $\xi$, $\omega_n$, the vibration amplitude of the foundation in three directions can be given.

6. Conclusion
Based on the three-degree-of-freedom space manipulator, Newton-Euler dynamics method is used to calculate the vibration force of the manipulator with respecting to the base in three directions in space,
the vibration model is established and the parametric solution of amplitude varying with time in three directions is given.

Choosing different factor $\xi, \omega_n$ numerical simulation verified the validity of the theory of vibration reduction measures.

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