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Flutter Analysis and Modal Test of A Six-degree-of-freedom Industrial Manipulator

Zhendong Song, Jiaping Li, Gang Li*, Yuanyi He, Fengshan Zou

***Abstract*—Industrial manipulator plays an irreplaceable role in assembly line, aerospace, shipbuilding and other industrial fields. However, due to the low overall stiffness of industrial manipulators and other reasons, the actual application of the manipulator can produce flutter that will influence the normal operation. In this paper, the flutter of six-degree-of-freedom industrial manipulator caused by the similar resonance frequencies of joint motor and reducer and the low overall stiffness is analyzed. The flutter mechanism is analyzed through the structural modeling and theoretical mechanical modeling of the manipulator. Then the vibration joint and frequency are determined by simulation analysis and vibration test. The flutter problem of the manipulator is solved by restraining and avoiding the relevant frequency.**

I. Introduction

With the implementation of China's Intelligent Manufacturing 2025 Plan, industrial robots, as multi-degree-of-freedom manipulators for industrial fields, have been widely used in automated production lines in automotive, electronic, metallurgical, food, aerospace, shipbuilding and other industries[1-9]. According to statistics, nearly 230,000 industrial robots were installed worldwide in 2014[1-3]. Among them, nearly 57096 industrial robots have been installed in China, an increase of nearly 59% over the same period last year, and it is increasing year by year[4,5]. FANUC, KUKA, Kawasaki, ABB, Yaskawa, SIASUN, ESTUN, EFORT, Guangzhou CNC and Shanghai Xinshida continue to increase their efforts in the field of industrial robots. Six-degree-of-freedom industrial manipulator is one of the more competitive directions.

During the operation of a six-degree-of-freedom industrial manipulator, the whole robot body, including its connecting rod and end-effector, must perform complex motion in space. A simple motion can be expressed by a transformation matrix, so complex motion needs to be expressed by multiple transformation matrices, and then multiplied by them. Therefore, the result of six changes and matrix multiplication is the homogeneous transformation matrix of the whole robot. Therefore, in order to study the motion of the robot, it is necessary to use a suitable coordinate method, namely D-H coordinate method, to describe the position and posture of the end effector of the robot through the transmission of the coordinate system of each joint[16].

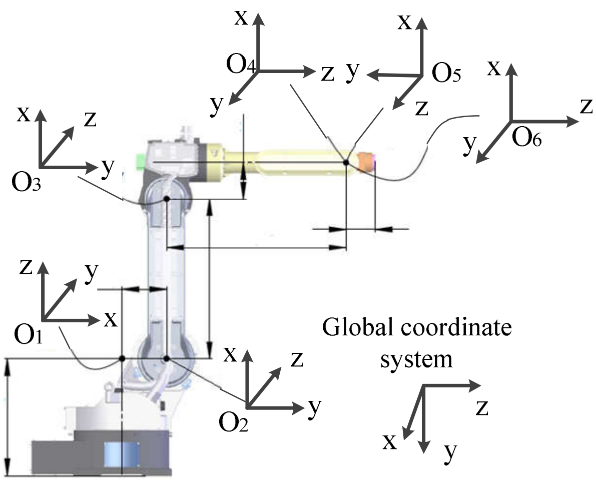

Figure 1 Robot structure and coordinate system

Generally, industrial robots are mainly composed of control system, servo system, electrical fittings and accessories, and robot body. The robot body is composed of servo motor, reducer and robot body.

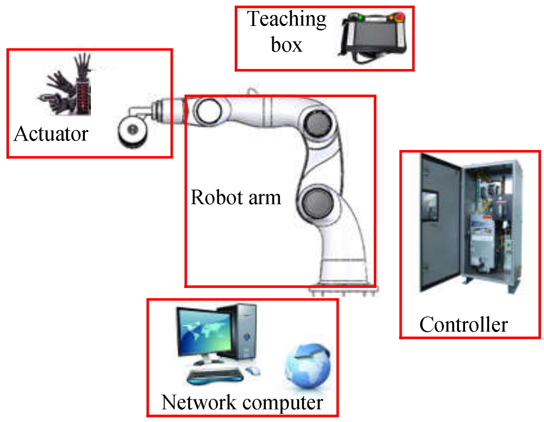

Figure 2 Composition of robot system

Although industrial robots play an irreplaceable role in actual production, due to the difference of control algorithm, the difference of overall stiffness of robots, the frequency of vibration generated by gear meshing of reducer is similar to the natural frequency of robots, there are different degrees of flutter in the use of manipulators. In this paper, a theoretical mechanical model will be established based on the structural model of the six-degree-of-freedom industrial manipulator, and then the flutter mechanism caused by the overall structure

Zhendong Song is with Shenzhen Polytechnic, Shenzhen, Guangdong 518055, China. (e-mail:szdeer@szpt.edu.cn)

Jiaping Li is with SIASUN Robot & Automation CO., LTD, Shenyang, Liaoning 110189, China. (e-mail:lijiaping@siasun.com)

Gang Li is with SIASUN Robot & Automation CO., LTD, Shenyang, Liaoning 110189, China. (Corresponding author phone: +86- 17642006081, e-mail:ligang19870527@126.com)

Yuanyi He is with SIASUN Robot & Automation CO., LTD, Shenyang, Liaoning 110189, China. (e-mail:heyuanyi@siasun.com)

Fengsha Zou is with SIASUN Robot & Automation CO., LTD, Shenyang, Liaoning 110189, China. (e-mail:zoufengshan@siasun.com)

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and the resonant frequency of the reducer will be analyzed. Through simulation analysis and vibration test, the joints and frequencies causing vibration are determined, and the flutter problem of the manipulator is solved by suppressing and avoiding the related frequencies.

II. DESIGN AND MECHANICAL MODELING OF 6-DOF INDUSTRIAL MANIPULATOR

A. *Design of 6-DOF industrial manipulator*

The industrial robot manipulator is structurally divided into base, big-arm, small-arm and end effector. In this paper, a 20 kg 6-DOF industrial manipulator is selected as an example for design and analysis.

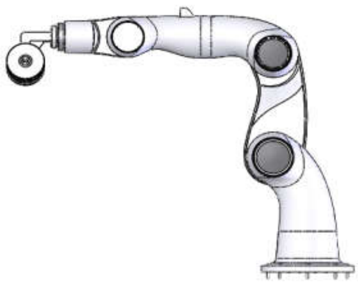
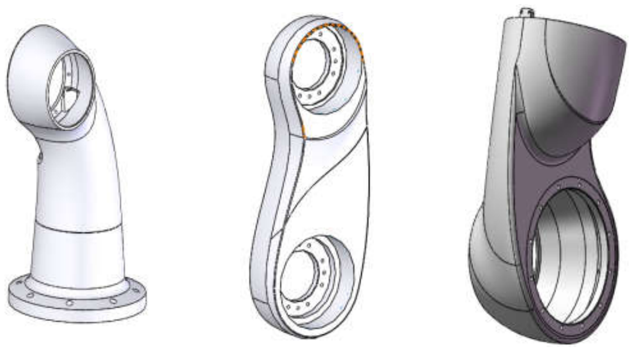


Figure 3 6-DOF industrial manipulator structure

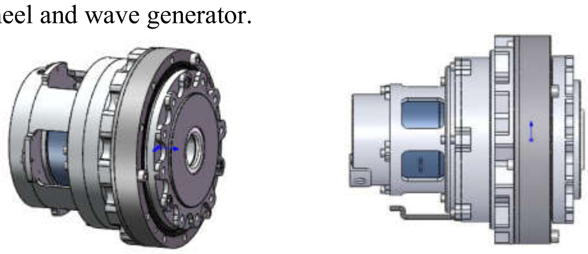
At the same time, in order to satisfy the design parameters such as motion range, the auxiliary mechanical structures such as mechanical limit and zero mark should be designed for each joint rotating pair.



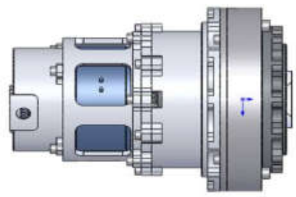
(a) Base (b) Big-arm (c) Small-arm

Figure 4 Shell and connecting flange structure

The joint of 20kg manipulator adopts integrated joint design, in which joint 1, joint 2 and joint 3 adopt 40 joints, joint 4 and joint 5 adopt 32 joints and joint 6 adopt 25 joints. Each joint adopts harmonic reducer. Compared with other reducers, harmonic reducer has the characteristics of high speed ratio, coaxial line, fast response, small size and light weight. Harmonic reducer generally includes rigid wheel, flexible wheel and wave generator.



(a) 40 joint (b) 32 joint



(c) 25 joint

Figure 5 Manipulator joints

B. *Mechanical modeling*

In order to meet the design targets of high speed, light weight and low energy consumption, this paper uses harmonic reducer to drive joint motion. Harmonic reducer has certain flexibility, therefore, the flexible characteristics of the joint make the manipulator inevitably produce low-frequency vibration in the process of motion, which seriously affects the dynamic accuracy and stability of the manipulator. In order to accurately study the dynamic performance of industrial manipulators, the flexible deformation of some parts has a great impact on the accuracy of manipulators. Therefore, industrial manipulators are usually a multi-rigid and multi-flexible coupling system.

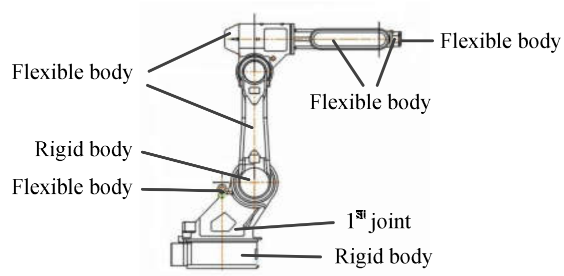


Figure 6 Rigid-Flexible Coupled Manipulator Model

According to the dynamics theory of multi-rigid-body system, the motion equation of rigid-body in rigid-flexible coupling system is established as follows:

$$\begin{cases} m\ddot{s} + \varphi_r^T \lambda = F \\ J\omega + \varphi_r^T = n^A - \tilde{\omega} J \omega \\ \varphi_r \ddot{\gamma} + \varphi_\pi \omega = \eta \end{cases} \tag{1}$$

m——Mass of rigid body;

F——The sum of external forces acting on a rigid body;

s—— Displacement of rigid body center;

J—— Rotating inertia of rigid body in relative centroid coordinate system;

ω ——Angular velocity of rigid body in centroid coordinate system;

φ_γ ——Kinematic constraints;

φ_π ——Drive constraint;

λ ——Lagrange multiplier vector。

Establishment of differential equations of motion for flexible bodies by finite element method

$$m\ddot{\xi}+\dot{m}\dot{\xi}-\frac{1}{2}[\frac{\partial m}{\partial \xi}\dot{\xi}]^{\mathrm{T}}\dot{\xi}+K\xi+G+D\dot{\xi}+[\frac{\partial \psi}{\partial \xi}]^{\mathrm{T}}\lambda=Q \quad (2)$$

ξ —— Derivatives of generalized coordinates to time;

m—— Mass Matrix of Flexible Body;

$\dot{m}$ —— Reciprocal of mass matrix of flexible body to time;

K—— Modal stiffness;

G—— Gravity;

D—— Symmetric matrix with damping coefficient。

The dynamic model of the whole system of industrial manipulators is formulated by a mixed differential equation system composed of formula (1) and formula (2). Through the establishment of the equations and the external excitation, the forced vibration analysis can get the modal response of the whole manipulator by adding external excitation to the model to excite the response. Among them, the differential equation of simple harmonic excitation motion for a single DOF mass-spring-damper system is:

$$m\ddot{x}+c\dot{x}+kx=Pe^{iwt} \quad (3)$$

k—— (N/m)Spring stiffness;

m——(kg)Mass;

C——(Ns/m)Damping system;

$Pe^{i\omega t}$ ——(N)Harmonic excitation。

III. FLUTTER MECHANISM ANALYSIS AND SIMULATION ANALYSIS

A. Flutter mechanism analysis

Stiffness is an important index to meet the requirement of machining accuracy and performance of manipulators. Most of the manipulators are in series with connecting rods, which leads to the low overall stiffness of the manipulator, and the stiffness characteristic of the manipulator is one of the main factors that cause the flutter in the course of its use. In addition, resonance is another factor in flutter generation. There are two conditions for resonance: the period (frequency) of the exciting force is close to or consistent with the natural period (frequency) of the object; and the duration of the exciting force is long enough to make the vibration of the object develop fully. In a six-degree-of-freedom industrial manipulator, when the resonant frequency of the reducer is close to or consistent with the inherent modal value of the manipulator, large amplitude of flutter will be produced.

Among them, the correlation formula between input speed and natural frequency of harmonic reducer is as follows:

$$N=\frac{f}{2}\times 60 \quad (4)$$

N——(rad/s)Input speed;

f—— (Hz)Natural vibration frequency of vibration system including reducer。

The formula for calculating f is expressed as follows:

$$f=\frac{1}{2\pi}\sqrt{\frac{K}{J}} \quad (5)$$

f—— (Hz)Natural vibration frequency of vibration System including reducer;

K—— (Nm/rad)Spring constant of reducer;

J—— (kgm^2)Load inertia。

At the same time, when the rigidity of the manipulator is poor, it has a certain modal value. When the input excitation frequency (motor speed or control pulse) of the system is close to or equal to the natural vibration frequency of the reducer or the overall modal value of the manipulator, the larger vibration of the manipulator can be excited, which seriously affects the accuracy and stability of the manipulator. When the manipulator is working, the joints interact with each other, so when there is a large flutter, it is important to locate which joint is the main contributing excitation source for solving the flutter problem of the manipulator.

B. Simulation analysis

Based on the theory of vibration, mode refers to the vibration form of multi degree of freedom system when it vibrates at a certain natural frequency. At this time, the proportional relationship between the displacements of each point in the system is called the natural mode. Natural frequencies and corresponding modal modes are attributes of any structure and component. Studying and analyzing the natural frequencies and vibration modes of the manipulator lays a foundation for analyzing its vibration characteristics.

In modal analysis, it is not necessary to impose any external loads on the analytical model, but only to deal with its boundary conditions. Based on the established 20 kg model, the modal analysis is carried out.

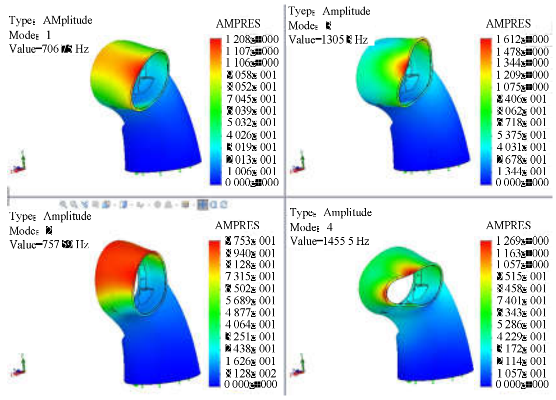


Figure 7 Fourth-order mode shapes of the base

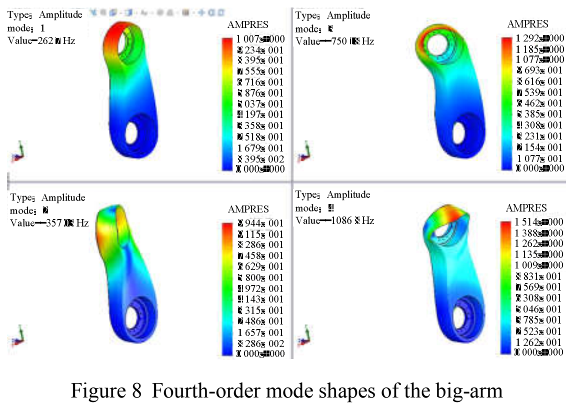


Figure 8 Fourth-order mode shapes of the big-arm

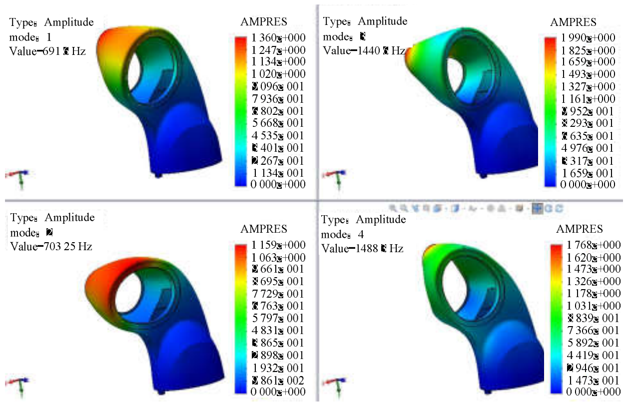


Figure 9 Fourth-order mode shapes of the small-arm

Because the vibration characteristics of the structure are greatly affected by the low-order modes, the low-order modes determine the dynamic characteristics of the structure. Therefore, when studying the response of the system, only the natural frequencies and mode vectors of low-order modes need to be known. In this paper, the first four modes of base, arm and arm shell are extracted, and their first four natural frequencies and natural modes are obtained.

TABLE I. MODAL VALUES OF COMPONENTS (HZ)

	1	2	3	4
Base	706.75	757.59	1305.3	1455.5
Big-arm	262.7	357.03	750.18	1086.8
Small-arm	691.6	703.25	1440.6	1488.3

IV. VIBRATION MODAL EXPERIMENTS

The vibration test and analysis system of the manipulator includes force exciter, acceleration sensor (unidirectional sensor, three-directional sensor), force sensor, signal transmission data line, data acquisition and analysis software and other related experimental equipment. In the experiment, the accelerometer is placed in the specific position of the manipulator body, and connected to the data acquisition equipment through the transmission data line. The data acquisition equipment transmits the signal through the network line to the host computer for later data processing and analysis.

Due to the rapid development of data acquisition equipment and software, the discrete Fourier transform technology can be directly used on the host computer, and a random signal can be parsed into sinusoidal waves of different frequencies, which makes the frequency domain analysis of the signal possible. Therefore, this paper uses the upper computer analysis software to complete data recording and processing, and then carries out signal analysis in time or frequency domain, modal experimental analysis.

A. Data Acquisition and Data Processing of Manipulator Working Flutter

Through the teaching work, the working path of the manipulator is planned. Because of the overall structure and characteristics of the manipulator, based on the basic coordinates, the Y direction and Z direction are the main flutter directions of the manipulator.

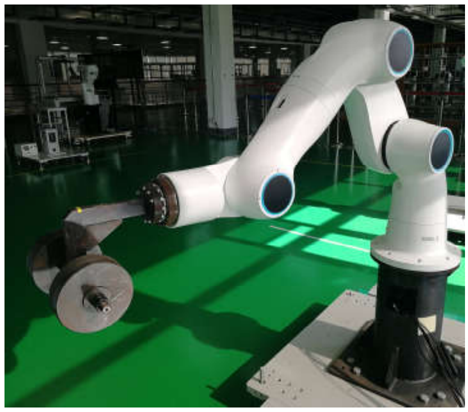


Figure 10 Modal Testing and Vibration Testing Sensor Installation of 20kg Manipulator

TABLE II. Y-DIRECTION INHERENT MODAL VALUE

Modal	Damping natural frequency（Hz）	Damping ratio（%）
1	8.21344	2.77845
2	26.20794	2.49518
3	42.17598	1.03436
4	66.64965	1.07842
5	129.60596	1.52675

TABLE III. Z-DIRECTION INHERENT MODAL VALUE

Modal	Damping natural frequency（Hz）	Damping ratio（%）
1	11.38238	2.44266
2	17.031198	3.19188
3	40.81592	0.83313
4	60.85557	1.62432
5	66.18627	0.86619

After testing and calculating the intrinsic modal value of the 20kg manipulator, the manipulator can reciprocate under normal working conditions by teaching. Acceleration sensors are arranged to collect the vibration data of the manipulator during its motion. The frequency response in Y direction and Z direction is obtained by processing and analyzing the upper computer software.

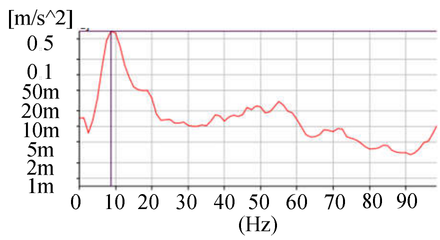


Figure 11 Frequency response of Y-direction vibration

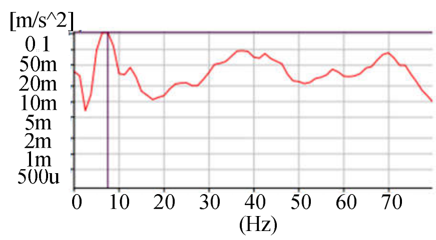


Figure 12 Frequency response of Z-direction vibration

B. Speed calculation and frequency analysis of each joint

When the robot carries out periodic teaching work, the final work is completed by the joint. Therefore, the motor speed of each joint, i.e. the input speed of the reducer, is different and periodic. From the formula (4), when the input speed is known, the vibration frequency can be calculated.

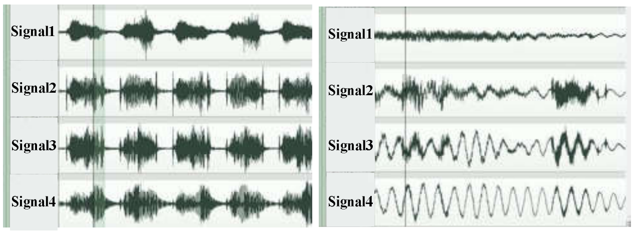


Figure 13 Acceleration time domain map

The position where the most serious flutter occurs can be determined by the real-time maximum vibration data of the three-direction acceleration sensor. Then the rotational speed of each motor joint in the current position is determined by the upper computer.

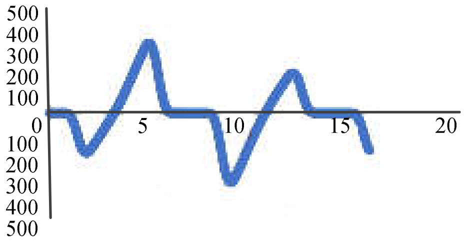


Figure 14 Speed periodic diagram of the second joint motor

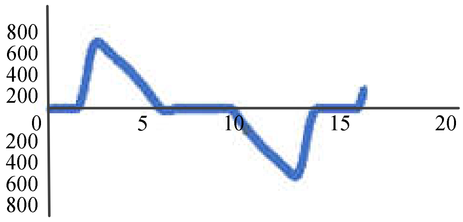


Figure 15 Speed periodic diagram of the third joint motor

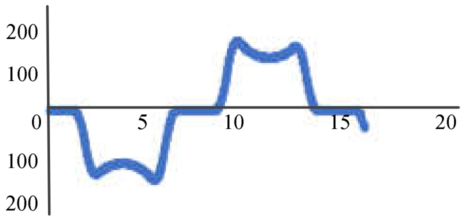


Figure 16 Speed periodic diagram of the fourth joint motor

$$f = \frac{N}{60} \times 2$$

The joints were calculated as follows.

$$f = 357 \div 60 \times 2 = 11.9 \text{ Hz}$$

$$f = 220 \div 60 \times 2 = 7.3 \text{ Hz}$$

$$f = 190 \div 60 \times 2 = 6.3 \text{ Hz}$$

According to the calculation and analysis, the first-order natural modal value in Y direction is about 8.5 Hz, and the first-order natural modal value in Z direction is about 11.4 Hz. Through the calculation of each joint, it is known that the speed of the second joint motor makes the reducer in the frequency range where resonance easily occurs, while the speed of the three-joint motor is close to the natural mode excitation frequency. Therefore, the reason of robot flutter may be that the vibration frequencies of two or three joint reducers are close to the natural frequencies of the robot.

V. CONCLUSION

In this paper, the natural frequencies of a 20 kg manipulator are obtained by modeling, simulation and modal analysis of the manipulator combined with the vibration analysis system. The time-domain signal of the trajectory vibration is obtained by measuring the vibration in the trajectory of a 20 kg manipulator, and the frequency-domain analysis is carried out. Based on the frequency domain analysis, the cause of the flutter of the working trajectory of the manipulator is obtained. Therefore, the method of avoiding the natural frequencies of the body at the joint points during the operation of the manipulator can reduce the occurrence of resonance, improve the working accuracy of the manipulator and realize the rapid positioning of the end.

ACKNOWLEDGMENT

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