Modal parameter identification of the support frame of the high-speed pick-and-place cable-driven parallel robot

Liping Wang\textsuperscript{1, 2, 3}, Lian Chen\textsuperscript{1, 3, a}, Zhufeng Shao\textsuperscript{2, b}, Haisheng Li\textsuperscript{1} and Li Du\textsuperscript{1}

\textsuperscript{1}Advanced Manufacturing Equipment Research Institute, University of Electronic Science and technology, Chengdu, 611731, China.
\textsuperscript{2}Beijing Key Lab of Precision/Ultra-precision Manufacturing Equipment and Control, Tsinghua University, Beijing 100084, China.
\textsuperscript{3} State Key Laboratory of Tribology & Institute of Manufacturing Engineering, Tsinghua University, Beijing 100084, China.

\textsuperscript{a}201621080141@std.uestc.edu.cn
\textsuperscript{b}Corresponding author e-mail: shaozf@mail.tsinghua.edu.cn

Abstract. Parallel manipulators of Delta and Part4 are widely adopted as high-speed, pick-and-place robots. Inertial force generated by high-speed motion has raised the demand for dynamic match between the robot and the support frame. In this study, the proposed high-speed, pick-and-place, cable-driven parallel robot is adopted as the research object. The modal parameters of the support frame are identified via the experimental method, and the first three orders are determined. The mode shape passed the orthogonality matrix check, thereby proving the reliability of the experimental results. This study establishes a foundation for the dynamic match and input filtering control of high-speed, pick-and-place parallel robots.

1. Introduction

Industrial robots can be classified into series robots and parallel robots according to their configuration. The base of the series robot is usually fixed on the ground and adopts single kinematic chain to control terminal position and posture [1]. The terminal accuracy and vibration of the series robot is affected only by its own body because its base is directly fixed to the ground [2, 3]. With the wide application of high-speed, pick-and-place robots in various fields, higher requirements for the comprehensive performance of industrial robots are proposed [4]. Main indexes include high speed, low self-weight, low energy consumption, and high precision [5]. To enhance the work efficiency of the series robot, a parallel robot with multiple kinematic branches is presented.

At present, the best crawling performance is delivered by the Delta robot [6], followed by high-speed, parallel, pick-and-place robots, such as Part4 [7] and X4 [8]. High-speed, pick-and-place robots adopt rigid branches as a transmission mechanism. To improve pick-and-place speed and reduce energy consumption, the concept of a cable-driven parallel robot (CDPR) is proposed [9, 10]. When the rope is used as a driving branch, the weight of the CDPR is considerably reduced, and its adaptability to the working environment is remarkably enhanced. As shown in Fig. 1, Kawamura et al. [11] invented a high-speed, pick-and-place robot called FALCON, which added internal force control between drive ropes, resulting in a maximum operating speed and acceleration of up to 13 m/s and 43g, respectively.
For the wind tunnel test, Lafourcade et al. [12] designed a six-degrees-of-freedom (DOF), cable-driven, parallel robot and completed the derivation of its kinematic and dynamic model, which established the foundation for subsequent vibration suppression control. Guglielmetti et al. [13] established an elastic dynamic model of Delta high-speed, pick-and-place, parallel manipulator to solve the residual vibration problem generated during high-speed motion. Static platforms (bases) of parallel robots (rigid branch parallel and cable-driven parallel robots) are usually fixed to the support frame due to multiple kinematic chains [14]. Considering the cost, the stiffness of the support frame is limited [15]. Therefore, the terminal accuracy and vibration of the parallel robot are affected by the dynamic characteristics of the support frame [16, 17]. Dynamic matching between the support frame and parallel robot means that the motion of the robot will cause limited vibration of the support frame and obtain required terminal accuracy.

Therefore, identifying the modal parameters (stiffness and damping coefficient) of the support frame is important in studying the matching problem of the dynamic characteristics between the parallel robot and the support frame. It also establishes a research foundation for improving the terminal motion accuracy of the high-speed parallel robot. Existing modal parameter identification methods are mainly divided into two categories: theoretical analysis and experimental method. Feng et al. [18] used SolidWorks to establish a 4-DOF parallel mechanism model and adopted the ANSYS software for modal analysis to obtain the natural frequency and vibration mode. Yoshimura [19] used an iterative method to identify the stiffness and damping parameters of bolted joints. Zhao [20] et al. used the ANSYS software to perform modal analysis on 1 MW horizontal blades. Combining the transfer function measured by experiments, Tsai [21] proposed different methods for identifying the dynamic parameters of joints, considering that the joints are elastic on both sides. Tlusty [22] and Inamura [23] successively proposed to obtain the complete vibration mode of the experimental modal parameters of a structure to directly identify the stiffness and damping parameters of joints. Compared with theoretical analysis, the experimental method obtained less error.

This study intends to use the experimental modal parameter identification method and identify the first three-order modal parameters of the support frame for CDPR, which is independently developed by the laboratory. Subsequent contents are organized as follows: Section 2 analyzes the role and stiffness distribution of the main components that make up the CDPR. Section 3 discusses how to use the experimental modal method in conducting modal experiments on the support frame of CDPR and obtaining various modes. Finally, the conclusion is presented.

2. Research object introduction

The research object of the present invention is shown in Fig. 1. The CDPR is mainly composed of six modules: three pairs of parallel cables and guiding pulleys; drive components; static platform (base); preload component; mobile platform; and support frame. As shown in the figure, the preload component is composed of a spring and a rigid rod with universal joints on both ends. Its function is to provide a preload for the cable and keep cables tight. Compared with the Delta robot, the motion mass and cost of the CDPR are remarkably reduced, and the CDPR exhibits good dynamics and large workspace, as well as good commercial potential.

The support frame is made of aluminum profile and a solid steel plate. A plate with a length and width of 1.3 m and a thickness of 12 mm was selected as the static platform to support the drive component, three pairs of cables, and guiding pulleys. The CDPR is designed to realize high-speed pick-and-place function. When the CDPR robot performs high-speed motion, large inertial force generated by the mobile platform and preload component causes the support frame to vibrate, affecting motion accuracy. The dynamic characteristics of this support frame must be studied to improve the performance of the robot.
3. Modal experiment

As mentioned above, the support frame is built with aluminum alloy profiles (AAP), and the joints of the profiles are bolted. This type of joint is less rigid than welded ones. A modal experiment is performed on the support frame (as shown in Figure 3) of this CDPR, and the modal parameters are identified by hammering.

3.1. Experimental preparation

Geometric test point arrangement: The main guiding principle is to reduce the test point to reduce the test cost, because vertex of the support frame can truly reflect the vibration of the measured object. The eight vertices of this rectangular support frame are the intersections of the aluminum profiles and are bolted together. This is less rigid than the AAP itself, and the vibration amplitude is largest at the intersection of the support frames during CDPR picking operations. Therefore, eight geometric points are used in this experiment and are distributed at the eight vertices of the rectangular support frame (numbers shown in black in Fig. 3).

Test channel scheme design: This modal test aims to measure the mode shape of the support frame in space accurately, such that it has three DOF. Then, each geometric point must test the vibration in three directions X, Y, and Z. Twenty-four test channels are required. After analysis, the wireframe model of the support frame is established in the structure generation module of the DASP software, and the arrangement of the relevant channels on the geometric points is completed (respective channel numbers shown in red in Fig. 4).
Test equipment selection: The first three natural frequencies are mainly concentrated in the low-frequency part, because the tested aluminum alloy support frame has low rigidity and cumbersome (250 kg). As shown in Fig. 5, a high stiffness of the hammer corresponds to a wide distribution of hammer energy in the spectrum. Therefore, a large elastic hammer with a DFD-2 type and rubber head was selected as excitation device. The force sensor model is 12-57 and the range is 1,000 N, thereby ensuring that enough energy is expended to excite the modality in the low-frequency range. For the acquisition system, the 8-channel data acquisition system model INV3018C adopted a variable-time-based sampling technology to acquire signals; the sampling frequencies of the excitation force and vibration signal can be adjusted separately to improve frequency resolution. The frequency resolution of the signal and low-frequency vibration signals is particularly suitable for large low-frequency modal tests. In addition, three models exist: INV824-type piezoelectric accelerometer (charge sensitivity: 160 Hz; voltage sensitivity: 160 Hz; testable frequency range: 1 Hz to 15 kHz), single-axis sensor, and a set of test software named DASP.

Sensor installation design: As shown in Fig. 6, this experiment is designed to measure the vibration of each geometric point in three directions. Thus, the tooling is designed (as shown in Fig. 6, red square plastic block). Three sensors are installed on three mutually perpendicular surfaces of the square plastic block. They are used to realize the function of the three-axis sensor, which can simultaneously measure the vibration in three directions in space. Installing the sensor is difficult because the aluminum profile cannot be adsorbed by a magnet. To solve these problems, the magnetic seat is fixed with the square plastic block first adsorbed on the angle iron, and then the angle iron is fixed by using the mounting groove and the bolt on the aluminum profile, thereby completing the installation of the sensor.

Excitation point scheme design: The tested aluminum profile may have a heavy root mode, because its support frame has a high degree of symmetry. On the basis of the above situation, excitation should be avoided on the same geometric point when selecting the excitation point. The final excitation point selection scheme is as follows: The X-direction excitation selects the 16th measurement point; the Y-direction excitation selects the 20th measurement point; and the Z-direction excitation selects the 18th measurement point. The sniper direction is shown in Fig. 3, and the measurement point number is shown in Fig. 4.
3.2. Experimental procedure
As mentioned in Section 3.1, only three single-axis sensors can be used in this experiment. In actual cases, 24 test points are required, and 24 single-axis sensors are needed to complete the measurement at one time. Therefore, eight sets of three single-axis sensors are needed. The experimental test procedure is described in detail as follows:

I. Key parameter setting: In this experiment, the sampling frequency is 4,096 Hz, and the variable time base multiple is 8. The parameter setting for the vibration signal data acquisition channel that should be used (2, 3, 4 channels correspond to X, Y, Z axis sensors, respectively) mainly includes the engineering unit set to $\frac{m}{s^2}$, and the calibration value parameter corresponds to the sensitivity parameter of each single-axis sensor.

II. The first channel is used as the excitation signal acquisition channel, the unit is set to N, and the calibration value parameter is the sensitivity parameter to the stress sensor.

III. The first set of experiments is performed. First, the first channel X1, 2, 3, 4 is named channels 1, 2, 3, and measurement point 16 is tapped to collect the system output response when the X direction is excited (To avoid test error, the hammer response measurement must be performed three times in the same direction, and then the average value is taken. The subsequent system output response measurement in each direction adopts this scheme.). Then, the 1 channel is named Y1, and 2, 3, and 4 channels are named 101, 102, 103, then the measurement point 20 is tapped to collect the system output response when the Y direction is excited; next, the 1 channel is named Z1, and 2, 3, 4 channels are named 201, 202, 203, then the measurement point 18 is tapped to collect the system output response when the Z direction is excited.

IV. The experiment is repeated eight times, and 96 original test data named X1–X8, Y1–Y8, Z1–Z8, 1–24, 101–124, and 201–224 are obtained.

3.3. Data processing
The data processing function is integrated in the DASP software, and the relevant procedure is as follows:

I. Frequency response function calculations are performed in the frequency domain.

II. The frequency response function is inverse Fourier transformed and converted into a frequency response function described in the time domain.

III. After modal fitting via the feature system implementation algorithm, a stable map can be obtained (as shown in Fig. 7), where $s$ represents the point in which the frequency, damping, and mode shape are stable; $f$ only means the frequency is stable; $o$ denotes the ordinary pole. To ensure the reliability of experimental results, the modality corresponding to the collection of $s$ points should be considered when collecting the modalities. Three columns of $s$ points are concentrated in the frequency band of about 5 Hz, and the frequency values corresponding to the three columns of $s$ points are the first three natural frequencies of the support frame.

IV. After clicking the vibrating animation, the vibration of each mode can be observed. The first-order mode (resonance frequency: 2.392 Hz, damping: 3.535) mainly vibrates along the short side of the rectangular support frame (Figure 8), and the second-order mode (resonance frequency: 3.134 Hz, damping: 3.502) is mainly along the long side of the rectangular support frame. Directional vibration (Figure 9), which is the third-order mode (resonance frequency: 5.614 Hz, damping: 5.517), is mainly torsional vibration along the vertical direction (Figure 10).
3.4. Reliability analysis of experimental results

To verify the reliability of the first three modes of the obtained mode, a modal check was performed through the vibration mode correlation matrix check graph generated by the DASP software. As shown in Fig. 11, this matrix is a strict diagonal dominant matrix that proves the accuracy of the selected mode shape. The existence of the s point in the high-frequency phase in the stability diagram (Fig. 7) is not reliable. This finding can be attributed to two main reasons: 1. The excitation energy of the hammer used in this experiment is mainly concentrated in the low-frequency band (within 30 Hz). 2. The modal fitting results (Fig. 12) indicate that a modal fit curve for regions above 15 Hz (vertical solid red line in the figure) produced a large offset relative to the actual frequency response curve. In summary, the mode shape above 15 Hz, even in the presence of point S, is not highly reliable.

4. Conclusion

In this study, the experimental method is used to identify the modal parameters and the first three modes of the support frame of the CDPR. Its damping parameters are successfully identified, thereby establishing a solid foundation for the dynamic match, input filtering control,
and engineering application of the high-speed CDPR. The reliability of the experimental results is proven by the orthogonality matrix. The modal parameter identification method described in this study is versatile, especially in determining modalities of the support frame for high-speed, pick-and-place parallel robots.

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