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An Intelligent Vacuum Fixture Controlled by Built-in PLC in CNC System

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Abstract: An intelligent vacuum adsorption fixture was presented, which can automatically detect the loading of workpiece by means of proximity switches. In addition, it can be called into a NC program by an M code developed based on the communication between the computer numerical controller (CNC) and programmable logic controller. Firstly, the conceptual design of the intelligent fixture was put forward. Secondly, the control method of the intelligent fixture was investigated to ingrate it with the CNC machine tool. Thirdly, the intelligent fixture prototype was established on the platform of Mitsubishi M64 CNC system. Then the clamping ability was estimated from two aspects: statics analysis and dynamic simulation. Furthermore, a milling experiment of a thin plate held by the intelligent vacuum fixture prototype was performed. Experimental results indicated the developed fixture could work well to facilitate the workpiece loading process. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Programmable logic controller, Fixture, Numerical control system, Miscellaneous function, Clamping ability.

1 Introduction

A major concern in mechanical industry today is to continue to improve the integration, intelligence and flexibility of manufacturing systems. The intelligence level of a manufacturing system depends on not only the intelligence of machine tools but also the intelligence of other subsystems: tooling, production logistics, process planning and so forth. Therefore, more and more intelligent tooling has been employed to reduce the non-cutting time as well as the manual labor, such as automatic tool changers, automatic pallet changer, flexible fixtures and industrial robots.

In terms of the flexible workholding system, many methodologies have been developed for intelligent CNC solutions, enabling highly flexible work cells and innovative manufacturing processes. As B. Shirinzadeh presented [1], these include various strategies: modular and reconfigurable fixtures; sensory-based assembly techniques; programmable conformable clamps; phase-change fixtures; adaptable fixtures; and others. The most widely used and researched in industry are modular and reconfigurable fixtures. The former achieves flexibility by selection and assembly of various elements with standard interface, while the latter indicates flexibility by changing adjustable variables to accommodate various shapes and sizes of workpieces [2]. M. Jonsson and coworkers [3] further summarized the different approaches to reconfigure a flexible fixture: manual, industrial robot, NC machine and actuators. As D. Walczyk et al defined [4], the reconfigurable fixturing system is considered active if the end effectors can be automatically repositioned based on a computer model; otherwise it is considered passive. In contrast with the flexible fixture, the intelligent clamping systems are able to offer many advanced (intelligent) functions: forces and torque measuring, clamping cycle monitoring, optimal fixturing operation and other job-oriented functions [5]. For the thin-sheet workpiece, R. Avvenente and coworkers proposed a self-reconfigurable intelligent swarm fixture system, which collaborate to hold and position the workpiece without human interference [6]. U. Zuperl et al presents an intelligent fixturing system that can optimally adjust the clamping forces as the position and the magnitude of the cutting forces vary during machining [7].

For aircraft skins trimming operations, an active reconfigurable fixturing system was designed by Beijing aeronautical manufacturing technology research institute. As a partner, the author developed a special location parameters solution software system to transfer the aircraft skins digital model into the numerical control data [8, 9]. However, the control system of the active reconfigurable fixture is fully independent of the CNC system of the machine tool. Hence, it cannot be programmed to automatically lower, raise and time each actuator to avoid collisions with the cutter during the machining process. In this paper, an intelligent vacuum adsorption fixture was developed, which not only can automatically detect the workpiece loading, but also can be programmed and controlled via the CNC system.

Section 2 introduces the conceptual design and configuration of the proposed intelligent vacuum fixture. Section 3 illustrates the control method of the intelligent fixture c based on the communication model between the computer numerical controller and programmable logic controller. Section 4 discusses the clamping ability of the fixturing system from two aspects: statics analysis and dynamic stiffness. Section 5 shows the intelligent fixture prototype established on the platform of Mitsubishi M64 CNC system. Some conclusions and discussion of future work are given in Section 6.

2. Conceptual Design of an Intelligent Vacuum Fixture

In many manufacturing processes, e.g. machining, handling, measuring, welding, coating and assembly, clamping components with vacuum is always a widely used choice as a well-established and reliable technology. Conventionally, vacuum chucks, suction cups, and the like are the basic elements of vacuum fixtures.

Unlike common vacuum fixtures, as shown in the Fig. 1, the proposed intelligent vacuum adsorption fixture consists of a matrix of sensory end effectors and a table with grid holes. Each sensory end effector has a suction cup centered with four proximity switches. When all the four proximity switches detect the presence of the nearby workpiece, this end effector will be controlled to absorb the part automatically. Otherwise, if any proximity switch does not send out an open signal, the end effector will be ineffective. According to this principle, the matrix of sensory end effectors can intelligently clamp the workpiece regardless of its shape and its placement. Advantages offered by this fixturing solution can be listed as follows.

a) Distinctive ability of sensory detection. This innovation can reduce set up times between workpiece changeovers and thereby increases productivity.

b) Good modularity and extensibility. The sensory end effector is modularized and bolted to the grid holes plate that is easy to expand.

c) Programmable and integrated with the machine tool. This property would be discussed in detail later.

This intelligent vacuum adsorption fixture can be used for machining operations such as drilling, boring, routing, etc. Certainly, the limitation of this intelligent vacuum fixture is that the workpiece has to provide a nearly perfect flat surface for adsorption.

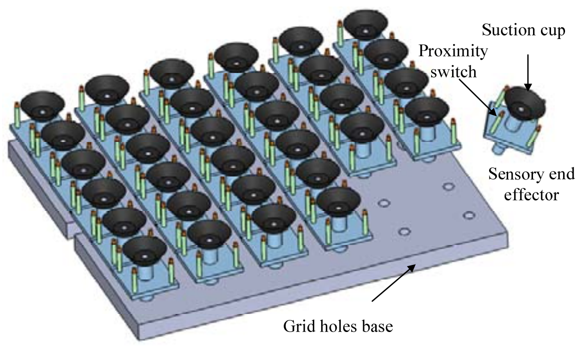


Fig. 1. Configuration of the intelligent vacuum adsorption fixture.

3. Control System of the Intelligent Vacuum Fixture

3.1. Control Scheme

As stated above, available approaches to recombine and reconfigure modular and reconfigurable fixtures are no more than three ways. Firstly, the fixture has no its own control system, which is recombined or reconfigured by manual operations, robots and the spindle head of the CNC machine tool. Secondly, the fixture has own stand-alone control system and can be programmed to reconfigure, but the control system is independent. Thirdly, the fixture shares the control system with the CNC machine tool. The third solution would assimilate the fixture into the CNC machine tool; thereby the spindle, cutter, axes and the tooling can be programmed and called cooperatively.

In this research project, the third approach was employed. The control system of the presented intelligent vacuum adsorption fixture was designed as shown in the Fig. 2. The air compressor supplies high-pressure clean air to the vacuum generator. And the vacuum generator is controlled by the solenoid valve to create a vacuum. The solenoid valve is connected with the PLC output and is controlled by the proximity switches tied to the PLC inputs.

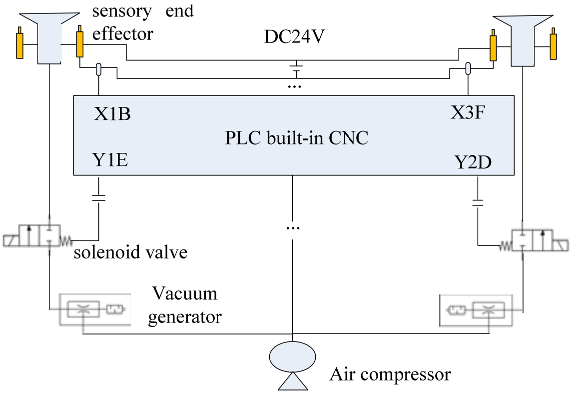


Fig. 2. Wiring diagram of the intelligent vacuum fixture.

3.2. PLC control Program

As it is known, after reading a NC program, the CNC controller decodes the G codes into pulses to control the driving system to perform the required motions. On the other hand, the CNC controller decodes the M and T codes as Boolean logic signals into the PLC unit to control machine spindle ON/OFF, coolant ON/OFF, tool clamp ON/OFF, etc.

Obviously, PLC plays an important role in CNC system as an inter-mediator between the CNC unit and machine tool. Generally, two types of PLC are used on the machine tool: built-in type and stand-alone type. Due to transferring data via the direct data bus, the built-in PLC has higher performance than the stand-alone PLC in data processing and reliability. On the other hand, the built-in PLC has less I/O points due to occupying I/O units of the CNC system. However, both of them have one unique and important feature, that of input and output circuitry to control machine mechanisms directly. In this paper, the prototype of the intelligent vacuum adsorption fixture was controlled by the built-in PLC of the Mitsubishi M64 CNC system.

Additionally, in order that the intelligent vacuum adsorption fixture can be called by an M code in the NC programming, a miscellaneous function M90 was developed based on the CNC-PLC communication. As presented in Fig. 3, the procedure to perform a miscellaneous function completely involves three key steps: decoding, M function implementation and finish confirmation. In this sequence process, the following points should be observed:

a) When the M function is commanded, the M function strobe (X230) and M code data (M90) is output.

b) MFn (X230) is always the trigger in the sequence process to start the M function process.

c) When the designated M function process is completed, the "M function finish" signal (Y226) is returned to the controller.

d) The controller waits for the rising of the M function finish signal and then turns MFn OFF.

e) MFn OFF is confirmed in the sequence process and then the "M function finish" signal is turned OFF.

In short, if the MFn conditions are inserted at the M function start and end signals, the CNC-PLC communication would be completed smoothly.

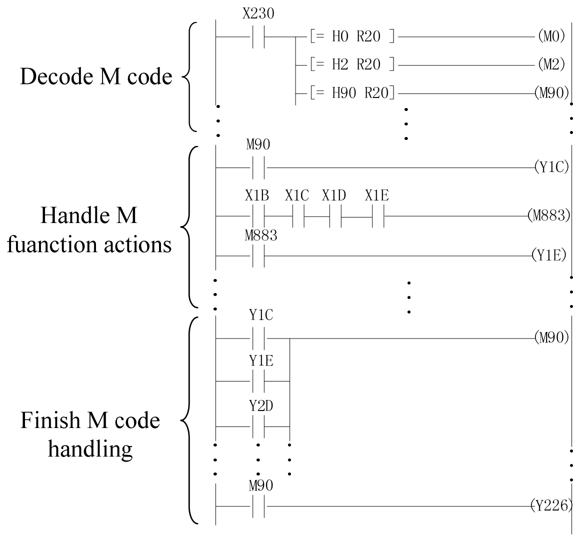


Fig. 3. Ladder figure of PLC control system.

4. Estimation of Clamping Ability

The clamping ability of the fixturing system should be estimated from two aspects: statics analysis and dynamic stiffness. The former determines the maximum forces that the fixture can afford, while the latter reflects its ability to dampen the vibrations from input forces. Especially, for the milling operations of low-rigidity parts, e.g. thin-walled structural parts and thin shell parts, dynamic stability is more difficult to control than static equilibrium.

4.1. Statics Analysis

In terms of the suction cup, its load bearing capacity depends on the following factors: size, pressure difference between the level of vacuum in the suction cup and the ambient pressure, load direction (vertical, parallel or sloped to the suction cup surface), and other factors.

If the load is positioned horizontally, the downward holding force results from the difference in pressure between the upper and lower component surfaces. If it is denoted by F_s. F_s can be calculated by,

$$F_s = PA, \quad (1)$$

where A represents the vacuum area and P indicates the degree of vacuum. Modern vacuum technology can easily reach a vacuum of approximately 98 percent of the atmospheric air pressure. Therefore, the downward holding force mainly depends on the contact surface area, which explains why the technique works best for large and flat parts.

Whereas the lateral holding force is always less than the downward holding force, it can be donated by F_f and can be estimated by,

$$F_f = \mu F_s, \quad (2)$$

where μ is the coefficient of friction between the sucker and the workpiece.

The diameter of the selected suction cup is 30 mm. In addition, the vacuum degree caused by the vacuum generator is 0.095 MPa. If the coefficient of friction between the suction cup and the workpiece is supposed to be 0.6, the downward holding force F_s and the lateral holding force friction F_f supplied by each suction cup can be calculated by Eq. (1) and Eq. (2), i.e. about 67 N and 40 N.

Evidently, to guarantee the machining accuracy and stability, the milling forces should be less than the resultant of F_s and F_f, i.e.,

$$\begin{cases} F_x, F_y \le nF_f \\ F_z \le nF_s \end{cases}, \quad (3)$$

where F_x, F_y and F_z are the components of milling forces in three directions. n represents the numbers of suction cups involved.

With regard to the estimation of milling forces, four different approaches can be found: direct mapping method, mechanistic model, numerical simulation model as well as the prediction model based on the feed drive or spindle motor current [10]. However, no universal and low cost modeling method exists, which can predict milling forces accurately among a wide range of cutting conditions. Thereby the author provided an integrated approach based on the combination of the mechanistic model of milling forces, 3D finite element method (FEM) simulation of milling operations and the support vector regression method [10]. Fig. 4 indicated the steps of the proposed approach. The benefits of this approach are to dramatically eliminate the experimental machining work and ensure the estimation accuracy.

4.2. Dynamic Analysis

Another aspect that affects the clamping ability is the dynamic characteristics of the fixturing system. Generally, the eigenfrequencies of a structure and the occurrence of nonlinearities are strongly influenced by the location and the nature of its joints [11]. Therefore, not only should the rigidity of workpiece and fixture structure be explored, but also the contact interface between the workpiece and the fixturing elements. However, numerical modeling of joints is quite challenging, due to the difficulties in theoretically identifying the contact rigidity and damping parameters [12]. In this research, the finite element method was adopted to estimate the eigenfrequencies of the fixturing system.

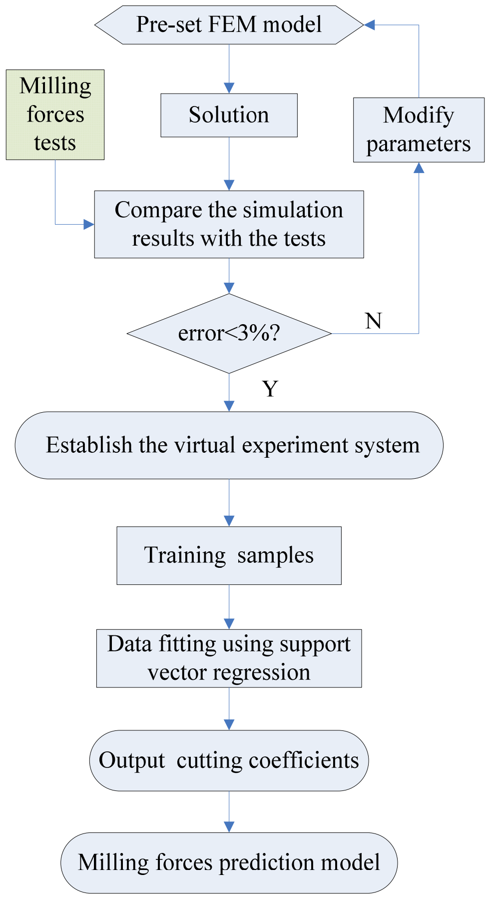


Fig. 4. Flowchart for milling forces prediction.

In the FEM modeling, the bolt joints may be treated as rigid joints, whereas the joints between the suckers and the workpiece cannot be regarded as fixed joints. Hence, this research supposes that the suction cup behaves as a spring with stiffness and damping coefficient. Then the COMBIN14 spring-damper element of ANSYS software was selected to simulate them. COMBIN14 has the longitudinal or torsional capability in 1-D, 2-D, or 3-D applications. In terms of the longitudinal option, the geometry, node locations, and the coordinate system for this element are shown in Fig. 5. The element is defined by two nodes, a spring constant K and damping coefficients C_{v1} and C_{v2}. The damping force F is computed as:

$$F = C_v \frac{du}{dt}, \quad (4)$$

where C_v is the damping coefficient given by

$$C_v = C_{v1} + C_{v2} V, \quad (5)$$

where V is the velocity calculated in the previous substep.

Fig. 6 indicated the dynamic simulation model of the fixturing system. One node is defined as fixed support. And the other node is defined by hard point that captured by a node during the meshing process of the workpiece. In addition, to automate the simulation in terms of parameters, a solution program was written using ANSYS parametric design language.

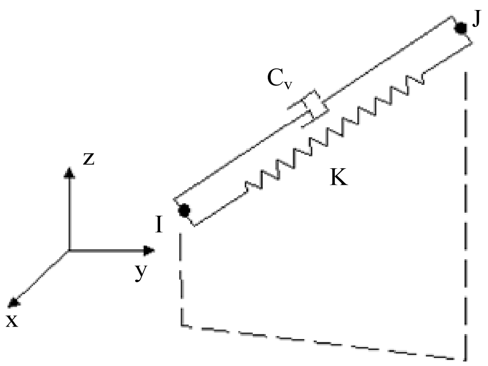


Fig. 5. COMBIN14 geometry.

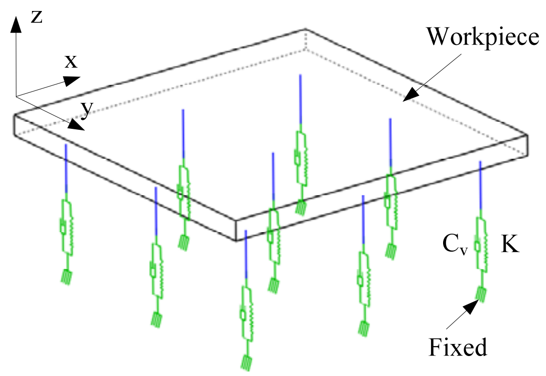


Fig. 6. Simulation model of the fixturing system.

For a case study, Fig. 7 gave a simulation result of a thin aluminum alloy plate with the thickness of 6 mm. The predefined parameters of the simulated system included the following items: elastic modulus 7.0×10^4 MPa; Poisson's ratio 0.3; damping coefficient 700 $N \cdot s/m$; spring constant 2.5×10^8 N/m. As the solution results shown, the first three natural frequencies are 2.75 Hz, 20.71 Hz and 28.05 Hz. Hence, for avoiding resonances, the vibrations from the cutting force should avoid the natural frequencies of the fixturing system.

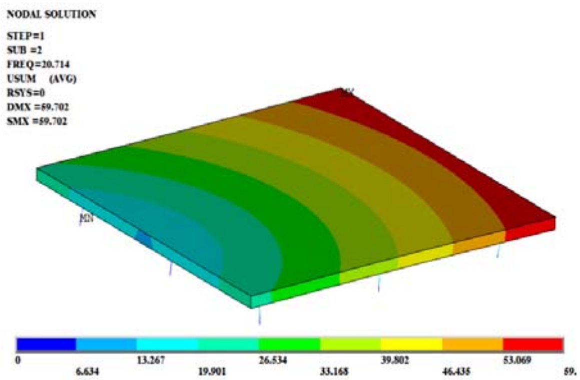


Fig. 7. Mode shape of the fixturing system using COMBIN14.

If sucker contact interfaces were treated as fixed joints, other all conditions were unchanged. The first three natural frequencies of the fixturing system are 2254.8 Hz, 2256.9 Hz and 2535.1 Hz. Obviously, the results were dramatically different with the above. In other words, the joint components contribute much of the flexibility and damping in the fixturing system. Ignoring joint effects and considering rigid connections between the workpiece and suction cups in modeling may result in different dynamic characteristics.

Certainly, the mode shape had varied greatly as Fig. 8 showed. Experiments suggested that the former simulation method was closer to the engineering reality than the latter.

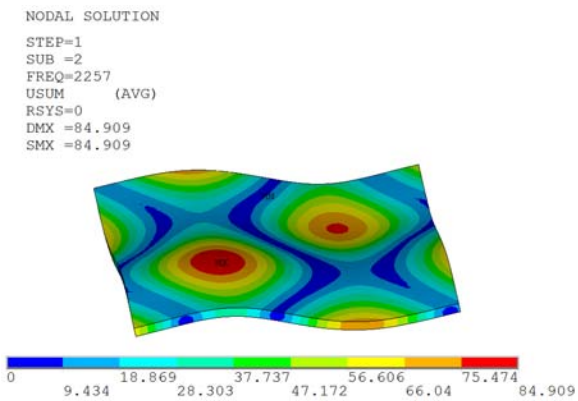


Fig. 8. Mode shape of the fixturing system using fixed joints.

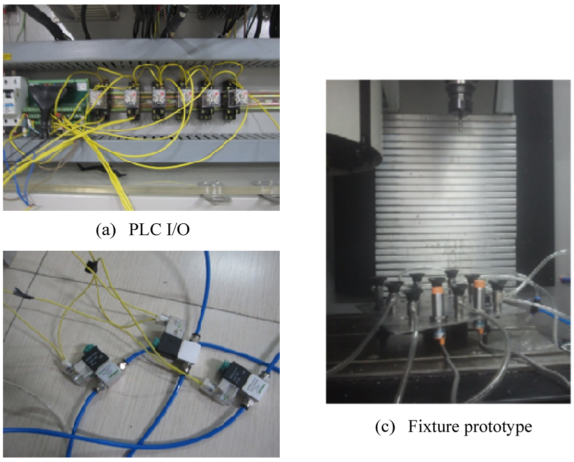
5. Prototype of the Intelligent Vacuum Fixture

5.1. Establishment of the Intelligent Fixture Prototype

A prototype of the intelligent vacuum adsorption fixture was built as shown in the Fig. 4. The used CNC system is the Mitsubishi M64 CNC system of our laboratory. The M64 controller is equipped with

RISC 64 CPU, and has high-standard hardware performance. Additionally, this CNC system was designed to be fully open and extensible. Therefore, there are some PLC communication I/O ports reserved for adding new functions. Naturally, this design offered us a convenient technical platform. When all components were connected properly Fig. 9(a) and Fig. 9(b), the experimental platform of the intelligent vacuum fixture was established Fig. 9(c). As an experimental prototype, the established intelligent vacuum adsorption fixture prototype has a 3×3 matrix of sensory end effectors. Moreover, the grid holes plate should be machined two U-shape slots for linking to the workbench of the machine tool.

As regards the PLC control program, it was firstly written in Mitsubishi GX Developer software according to the aforementioned handling process of miscellaneous function. Afterwards the PLC program was directly sent into the Mitsubishi M64 controller with RS232.



(a) PLC I/O

(b) Electrical wiring

(c) Fixture prototype

Fig. 9. Prototype of the intelligent vacuum adsorption fixture.

5.2. Experiments on the Intelligent Fixture Prototype

Using the built experimental prototype, a thin plate milling experiment was performed. Firstly, a NC program was written as follows.

O1122
N10 G54 M03 S3000;
N20 M90;
N30 G04 P30000;
N40 G00 X0. Y0. Z-200. F100.;
……
N 80 M30;

Then run the program above in automatic operations model. It would be observed that when the NC program reaches M90, the intelligent vacuum adsorption fixture would be triggered immediately. Then the thin plate would be fastened by the sensory end effectors. As soon as all actions are finished, the next line code would execute. Fig. 10 showed the experimental situation.

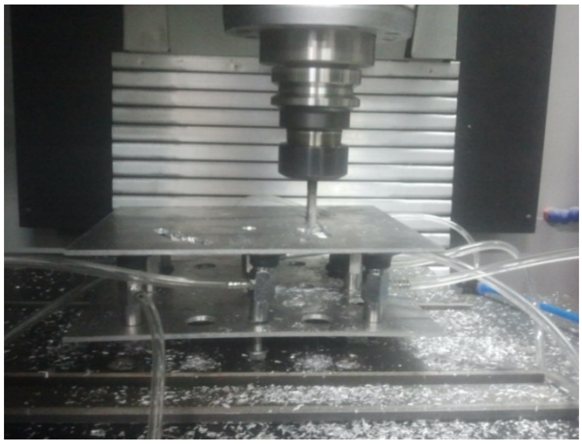


Fig. 10. Experimental setup.

Experimental results firstly embodied that the intelligent vacuum adsorption fixture can be triggered automatically and can clamp the workpiece intelligently. Secondly, the cutting vibration may break the clamping stability as long as the cutting vibration frequency exceeds the eigenfrequencies of the fixturing system. In this case, the optimization of cutting parameters becomes of great importance.

6. Conclusions

An intelligent vacuum adsorption fixture was presented, which can automatically detect the loading of workpiece by means of proximity switches. Meanwhile, it can be called in a NC program by an M code based on the communication between the CNC controller and PLC unit. Milling experiments on the intelligent fixture prototype indicated that it not only can expand the automation capabilities of the machine tool, but also can facilitate the workpiece loading process.

Another major contribution of this paper was to present a method to estimate the clamping capacity from two aspects: statics analysis and dynamic stiffness. Especially, the dynamic property of the joints between the suction cup and the workpiece surface was considered as a spring-damper model with stiffness and damping coefficient. Furthermore, the finite element simulation model for the dynamic characteristics of the whole fixturing system was established. Experiments results proved the validity of this approach.

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