Design of Adaptive Mechanical Fixture and Optimization of Clamping Force for Complex Parts

Li Liu, Jian Zhang*

CHANGCHUN TECHNICAL UNIVERSITY OF AUTOMOBILE, Changchun, 130013, China
**Corresponding author: 2018012@caii.edu.cn*

Abstract: *A change in the normal vector and mutations of the local curvature for complex curved-surface parts will result in immediate overdetermination or underdetermination of the constraints on the degree of freedom of the fixture, and the force-deformation coupling with load variation over time will further worsen the problem of clamping stability control. Design of an Adaptive Mechanical Fixture and Optimization Strategy for Clamping Force: A Method for Characterizing the Degree of Freedom Fluctuation Based on Second-Order Differential Geometry Parameters is Proposed; Dynamic Matching of the Configuration to Part Morphology is Achieved by Adaptive Contact Element Layout and Topology-Scale Co-design; A Nonlinear Force-Deformation Mapping is Constructed; The Minimum-Norm Solution of Clamping Force is Obtained through Convex Quadratic Programming; Rolling Horizon Dynamic Programming is Used to Handle Time-Varying Loads; A Parametric Scheme for Variable-Stiffness Flexible Units is Designed; A Force-Position Stability Criterion Under Excitation Disturbance is Established; And an Adaptive Closed-Loop Regulation Mechanism for Stiffness and Clamping Force Coordination is Built. Stiffness is taken as the control degree of freedom equal to the clamping force in this way, and it can be used to accurately machine complex parts.*

Keywords: *Adaptive Mechanical Fixture, Complex Parts, Clamping Force Optimization, Force-Deformation Coupling, Variable Stiffness Flexible Unit, Closed-Loop Stability Control*

Introduction

Aero-engine blades and mould cores are representative examples of complex parts in mechanical processing, and because they have free-form surface shapes and local concave features, good adaptability of the fixtures is required. The traditional six-point location method is based on the assumption that the body is ideal and rigid; therefore, it cannot address the problem of degree-of-freedom fluctuation caused by continuous changes in the part's surface normal vector, and there is often local overconstraint or contact slippage. At the same time, under the clamping force, there will be an elastic deformation of thin-walled or cantilever structures; thus, the distribution of contact forces will change, and a force-deformation nonlinear coupling will be formed; changes in cutting force, inertial force and vibration during machining will also affect positioning stability. Therefore, in order to improve the machining quality of the complex part, a fixture system that can be adapted to the geometry of the part and dynamically adjust the clamping force needs to be designed. Most of the current research is either on the static optimisation of fixture layout or single-objective optimisation of clamping force, and rarely has it considered the coordination between the structural stiffness of the fixture and clamping force as control variables. There is no general rule for the force-position stability of excited states. The two main problems in this paper are the geometric adaptability and clamping stability of the complex part. The three research directions are the generation of fixture configuration, dynamic allocation of clamping force and stiffness-force coordinated closed-loop regulation, and thus a full theoretical basis for adaptive fixture design and optimisation has been established.

1. Adaptive Fixture Configuration Generation under Geometric Feature Constraints of Complex Parts

1.1 A Method for Characterizing the Degree-of-Freedom Fluctuation of Complex Curved-Surface Parts

Due to the irregular shape of the curved surface and a local concave feature, there will be a deviation in the theoretical locating positions and the actual contact condition of the traditional six-point locating method. The reason is that the surface normal vector of the part is constantly changing; thus, there is always an instantaneous overdetermination or underdetermination of the degree-of-freedom constraint for the clamping system during the fixturing process. To quantify this characteristic, the second-order differential geometry parameters of the surface, that is, the principal curvatures and Gaussian curvature, are used to numerically describe the local shape of the part surface, and a degree-of-freedom contribution matrix for the tangent plane constraints at the contact points is constructed. The distribution of the eigenvalues of this matrix can show the range of fluctuation in the part's translation and rotation amplitudes about the equilibrium position in the absence of external forces.

The change in the degree of freedom can be expressed as the rate of change of the condition number of the constraint Jacobian matrix in the part coordinate system. Most of the complicated parts, such as turbine blades and mould cores, are very curved and have saddle points on their surface; these are the critical transition states for the degree-of-freedom constraints. Build a discrete point set of surface sampling, calculate the distribution of singular values for the constraint matrix at each point, and then obtain the statistical characteristics parameters of the overall degree-of-freedom fluctuation of the part, such as the mean fluctuation amplitude and the local range. The kind of characterisation above can provide quantitative input conditions for the layout optimisation of the fixture contact elements, and it is possible to actively change the spatial arrangement of contact points in an adaptive fixture according to changes in the geometry of the part surface[1].

1.2 Adaptive Layout Criteria for Contact Elements Based on Local Morphology of the Workpiece

The Position of the contact elements on the surface of a complex part directly affects the stability of the constraint for the degrees of freedom of the part in the fixture system. The old rule of even spacing or uniform distribution cannot meet the clamping requirements in areas where there is a change in the curvature of the surface, and there will be local over-constraint or contact slippage. Therefore, this paper proposes a contact element adaptation criterion based on the local morphology curvature radius, which is that the arrangement density of contact elements should be positively correlated with the second-order change rate of the part surface. In Areas with relatively large slopes and small radii of curvature, the density of the distribution of contact elements should be increased, and the distance between these elements should be reduced to prevent the release of rotational degrees of freedom in that section.

Based on the above, the geometry of the end face of the contact element should be in the direction of the local surface normal. A point-contact ball-type unit is used for the part with a convex curve to avoid stress concentration at the contact line, and for the section that is concave or has a groove, a swingable roller-type contact head can be employed to change the normal force at the contact point. Based on the normal vector and the direction of the principal curvature at each node of the part surface mesh model, parametric constraint conditions are set for the spatial position of the contact elements in this way. According to the above conditions, change the topology of the fixture contact system in accordance with the local shape of the part and keep the rank of the constraint Jacobian matrix constant at all times.

1.3 Topology and Scale Co-Design Strategy of the Reconfigurable Fixture Mechanism

All the locating and clamping branches of the Reconfigurable Fixture Mechanism are driven independently. The Topology of the connection for the branches and the linkage scale parameters are related to each other, and together they determine the reachable workspace and stiffness distribution of the clamping system. The Structure of the topology determines the kind of kinematic pair in each branch and whether these pairs are connected in series or parallel; generally, a four-bar linkage mechanism with planar redundant actuation characteristics or a six-degree-of-freedom serial manipulator structure is chosen. Based on the topology above, the length of each link and the joint offset have been modified so that the end contact elements of the fixture can cover all the surfaces to be clamped on the complex part[2].

The Goal of the Optimisation Problem is Topology and Scale Co-design. Topological variables are used to discretely code the type of kinematic pair and its connection order, and scale variables are continuous and represent the geometric parameters of a link. The two goals of this study are to increase the total stiffness of the clamping system and to reduce the fluctuation in driving torque; at the same time, the set of reachable positions for the contact elements must include all the candidate locating points on the part surface. Nested Optimisation is employed; the outer loop is a Genetic Algorithm to find the best topology, and in the inner loop, a non-linear programming problem is solved for the scale parameters of each candidate topology. Co-design does not need to separate the design of topology and scale, as is done in the traditional design of fixtures; thus, it can improve the geometric adaptability of the adaptive fixture for complex parts.

2. Dynamic Allocation Mechanism of Clamping Force and Multi-objective Optimization Model

2.1 Nonlinear Mapping Relationship of Force-Deformation Coupling During the Clamping Process

Due to the clamping force, a part with a certain shape will be elastically deformed, change its shape at the contact point, and thus distribute the contact force unevenly. The force-deformation coupling effect cannot be expressed as the sum of linear terms because the non-linear properties of the local stiffness at the part surface are closely related to the micro-slip behaviour of the contact interface. In order to build the mapping relationship above, Hertz's contact mechanics theory of contact and the finite element node force transfer matrix need to be introduced. The function of the clamping force vector and the node displacement vector of the part surface are given by an implicit differential equation in this paper. The term in this equation is the contact stiffness matrix, and as it changes with the current deformation, it is a representative nonlinear algebraic system.

To solve the problem of coupled mapping, an incremental iterative method is employed and the clamping process is divided into several load steps. At each load step, a stiffness matrix is computed based on the current contact conditions, and then after solving for the displacement increment, the contact boundary conditions are updated. The convergence condition is that the relative change rate of the Euclidean norm of the contact force vector between two consecutive iterations is less than a small number. Thin-walled or cantilever structures are often used for complex parts, and the nonlinear mapping is such that even a small increase in the local clamping force results in a large change in the displacement of the surrounding area; that is to say, there is a bifurcation point in the force-deformation curve. To find a particular kind of nonlinearity, we will set up the constraints in the following optimisation problem for clamping force.

2.2 Minimum Norm Solution for Clamping Force of Workpiece Positioning Stability

The Positioning Stability of the workpiece requires that at all contact points, there is neither separation nor slip; the corresponding mathematical constraints are that the normal contact force is positive and the tangential force meets the condition of the Coulomb friction cone. Given the above constraints, there are infinitely many possible solutions for the clamping force, and the minimum norm solution is the one that minimizes the two-norm of the clamping force vector. The above problem can be formulated as a convex quadratic programming problem; the objective function is to minimise the sum of squares of the clamping forces, the linear constraints are the force balance equation and the moment balance equation, and the inequality constraints are the tangential force limit conditions after linearisation of the friction cone. Since the number of workpiece locating points is usually larger than the required degrees of freedom for constraint, this optimisation problem is redundant, and the minimum norm solution is the same as that of the clamping scheme with the lowest energy consumption[3].

To solve the quadratic programming problem above, either the dual method or an active-set algorithm can be used. For a complicated part, the minimum-norm solution of the clamping force will generally distribute the clamping force more evenly at the contact area with high stiffness; that is to say, a small force in a stiff region can generate a large constraining moment. However, there will be some contact places with a very small clamping force, and they are likely to separate under dynamic load. Therefore, a regularization term needs to be added to the objective function, and instead of the standard two-norm, a weighted norm will be used; that is to say, the weight coefficient will be inversely proportional to the local stiffness at the contact point. The modified minimum norm solution is still a minimum clamping energy solution, and it will also have a reasonable margin in the distribution of clamping forces at all contact points.

2.3 Dynamic Programming Model of Clamping Force Under Time-Varying Load Conditions

At the time of machining, the cutting force, inertial force and vibration load are all time-varying, and the static distribution of the clamping force cannot keep up with the transient fluctuations of the load. Divide the whole machining period into a few sections and then apply Dynamic Programming. At each time step, it is assumed that the load is quasi-static and the clamping force can be different from that at other time steps. The state variables are the current position error and its rate of change of the workpiece, and the control variable is the increase in clamping force at that time. Discretise the dynamic equation of the clamping system and add the nonlinear term of force-deformation coupling to obtain the state transition equation. The objective function is a weighted sum of the accumulated square of the workpiece positioning error over the entire period and the energy consumption of adjusting the clamping force[4].

The solution to the dynamic programming problem should be able to handle a large number of states and nonlinear constraints. A rolling-horizon optimisation method is employed in this paper to optimise the sequence of clamping forces for only a small number of future time steps at each decision time. The rate of change of the clamping force is limited to a certain value so that there is no saturation nonlinearity in the hydraulic valve or motor driver of the servo system. The Trajectory of the clamping force output by dynamic programming has a combined structure of feedforward and feedback; that is to say, the feedforward part adjusts the clamping force in advance according to the estimated trend of load variation, and the feedback part makes real-time corrections based on the actual pose deviation. Dynamic Programming can be used to adjust the clamping force of the mobile according to changes in load at the machining site and keep it stable.

3. Adaptive Fixture Stiffness Matching and Closed-Loop Stability Control

3.1 Design Method for Parametric Configuration of Variable-Stiffness Flexible Units

The first type of actuator that has achieved a variable-stiffness flexible unit is that its stiffness needs to be in a large range and changeable. Parametric configuration design is the geometric shape and material distribution of the flexible unit expressed as a set of independent design variables, such as the thickness, length and notch curvature of the flexure hinge, as well as the pre-compression amount of the stacked piezoelectric stack actuator. Change the ratio of the equivalent bending stiffness to the axial compression stiffness of the flexible unit to obtain a quantitative expression for the range of stiffness adjustment. Euler-Bernoulli beam theory is employed to construct a parametric model, and a follower boundary condition is added to describe the path of force transmission at the junction of the driving element and the flexible structure. In this way, we can also consider the geometric nonlinear effect of the flexible unit under large deformation, and by using an incremental finite element format, we can obtain the drift characteristic of stiffness variation with load to define the boundary curve between the linear stiffness region and the nonlinear hardening region in parameter space.

A Scheme of Geometric Parameterisation and Material Parameterisation is Used. Geometric Parameterisation can be used to describe the shape of a flexible part, such as the profile curve of a triangular, circular-arc or leaf-type flexure hinge; Material Parameterisation can be achieved by adding a thin layer of shape memory alloy, and the effective elastic modulus of the unit can be changed by varying the volume fraction of martensite in the alloy layer. The goal of the parametric Design is to increase the stiffness adjustment ratio of the flexible unit by more than an order of magnitude without moving the position offset of the contact point outside the tolerance range for part positioning. A Response Surface Method is used to build a mapping surrogate model of the Design variables and the Stiffness output, and then a fast calculation path for the next stiffness matching is obtained. Kriging interpolation is used to fit the residual term and improve the prediction accuracy of the surrogate model; the maximum prediction variance is taken as the criterion for refining the pointwise sampling region, and thus the stiffness prediction error of the variable stiffness unit at key operating points is within the engineering tolerance[5].

3.2 Force-Position Stability Criterion of the Clamping System under Excitation Disturbances

There will be a change in the cutting force at the contact point between the tool and the workpiece during machining; this force may cause vibrations in the structure of the fixture and result in a small slip or sudden separation at the contact position. According to the force-position stability criterion, determine whether the clamping system will maintain contact after a certain number of disturbances and at what amplitude of disturbance. Based on Lyapunov's second method, the clamping system is regarded as an autonomous system, and its state variable is the deviation of the workpiece pose; the stability of the equilibrium point depends on whether the generalized stiffness matrix and the generalized damping matrix of the system are positive definite. It is assumed that the excitation disturbance is bounded, and the input-output stability of the system is determined by the L2 gain. Krasovskii functionals can be employed to solve the problem of shrinkage in the stability boundary for delay differential equations of a hydraulic fixture with a time-delay effect.

The particular condition is that the ratio of the tangential force to the normal force at the contact point must be less than the product of the friction coefficient and the safety margin factor, and the peak value of the power spectral density of the contact force at the disturbance frequency shall not exceed a certain proportion of the static normal force. All the connection places of the multi-contact-point system must meet the above requirements. Based on the above, we can obtain an expression for the critical disturbance frequency; that is to say, when the excitation frequency is close to a certain natural frequency of the clamping system, the stability margin will be small. The above stability condition is that the fixture can be regulated in the presence of disturbances. To improve the engineering practicality of the criterion, a modal participation factor is added to weight the modes of the system, and only the main modal frequency bands that are sensitive to contact force disturbance are monitored; thus, the online computation load has been reduced and the real-time performance has been improved[6].

3.3 Adaptive Closed-Loop Regulation Mechanism for Coordination of Fixture Structural Stiffness and Clamping Force

Structural Stiffness and clamping force are related; that is, increasing the structural stiffness can reduce the demand for a large clamping force, but excessive stiffness will increase the impact load; on the other hand, although increasing the clamping force can prevent contact slippage, it will also worsen workpiece deformation and raise energy consumption. At the same time, change the proportional relationship of the two dynamically under the condition of maintaining positioning stability. The three parts of the closed-loop control are the sense-feedback connection, the decision-making-planning stage and the actuation stage. At the sensing end, continuously obtain the contact force vector and the field of workpiece surface displacement. The Decision-Making Link finds the best Stiffness-Force combination for the current load at this time. The actuation link can change both the stiffness setpoint of the variable stiffness unit and the output of the clamping force actuator simultaneously. The new way is to consider stiffness as a control degree of freedom, equal to the clamping force, and it does not need to be fixed in advance.

The first two links of the chain of decisions have been reinforced. Based on the type of machining step and the current load conditions, the upper part will be set at an appropriate ratio of stiffness and clamping force. The bottom one optimises the stiffness setpoint and force amplitude subject to the constraint that their ratio is fixed. Model Predictive Control will be employed to reformulate the problem of coordinated regulation as a rolling optimization problem over a finite time horizon. The predictive model of the clamping system is a nonlinear dynamic equation, and there is hysteresis in the variable-stiffness unit. The feedback correction link computes the difference between the actual measured value and the predicted value and adjusts the control variable at the next time step. A closed-loop system will be employed to adjust according to changes in machining conditions, and the clamp position of the workpiece will be fixed and undamaged. Another is an event-triggered control method; that is to say, the optimisation calculation is only performed when the deviation of the clamping force exceeds a certain threshold, and thus the energy consumption and processor utilisation of the control system are greatly reduced during the steady-state machining period.

Conclusion

The Design Method for the adaptive mechanical fixture and the clamping force optimisation strategy to solve the clamping problem in machining of complex parts will be introduced in this paper.

At the level of configuration, this paper proposes a way to quantify how much the number of degrees of freedom of complex curved surfaces changes, and based on the local shape, it also puts forward a layout rule for contact elements; thus, topology and scale co-design are used to adjust the reconfigurable fixture mechanism according to the shape of the component dynamically. Based on the mechanics established at the level of this paper, force and deformation are related nonlinearly; thus, the minimum-norm solution for clamping force under positioning stability is proposed, and active compensation for the time-varying characteristics of the load is achieved by means of a rolling-horizon dynamic programming model. Parametric Configuration Scheme for the Variable-Stiffness Flexible Unit at the Control Level is proposed in this paper, a force-position stability criterion under the influence of an excitation disturbance is derived, and finally, an adaptive closed-loop regulation scheme for the coordination of stiffness and clamping force is put forward.

The above methods have solved the problems of fixed stiffness and static distribution of clamping force in the traditional design of fixtures, and they have turned the fixture system into an intelligent actuation unit that can sense the shape of the part and load conditions to dynamically change its own mechanical properties. The three directions of the following research will be as follows: Extend the proposed theoretical model to multi-station assembly line fixture systems and study the transfer and coordination mechanism of clamping states among different stations; Introduce a model-free adaptive control method based on deep reinforcement learning to solve the problem of online clamping force decision-making for complex parts with incompletely known geometric parameters or under strong uncertainties in the machining environment; Explore new materials and driving methods for variable-stiffness flexible units, such as dielectric elastomers or magnetorheological materials, to increase the range and speed of stiffness adjustment and further reduce the energy consumption and volume of the fixture system.

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