Rigid-Flexible Coupling Dynamics Simulation of 3-RPS Parallel Robot Based on ADAMS and ANSYS

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Abstract. This paper mainly investigated the rigid-flexible dynamics simulation method of multi-body system. The 3-RPS parallel robot dynamics model is created by ADAMS (multi-body dynamics software) and ANSYS (finite element analysis software). In accordance with the flexible-body theory, we analyzed mechanical characteristics of parallel robot with no-load or full-load working condition, and got the deformation of end measuring point, maximum stress position and dynamics stress curve. The analysis method is more intuitional and accurate, and can increase the accuracy of dynamic response analysis of links under the dynamic loads. The simulation results create conditions for structure design and optimization of 3-RPS parallel robot.

Introduction

In traditional design methods, components are mostly considered as rigid one without considering their elastic structural deformation. So, this system can’t reflect the coupling relationship between rigid motion and elastic deformation, or can’t reflect the real mechanical properties of components. However, multi-flexible body system dynamics research the coupling relationship above and its dynamic response. Modeling and analysis theory about multi-flexible body system is beneficial to precise modeling, virtual design, performance optimization, system matching and whole machine performance prediction.

Generally, flexible parallel robot works under high-speed and cyclic change load, and this would result in cycle fluctuation at manipulator’s end effectors. This kind of fluctuation phenomenon would lead to bad influence on working performance and operation precision of manipulators. Sometimes, lower order resonance phenomenon occurs and at the same time components bear drastic dynamic cycle stress. This aggravates components fatigue. If the maximum dynamic stress is greater than allowable stress of materials, component fails. So, it is necessary to research dynamic stress of components of flexible parallel robot. Meanwhile, this makes preparation for further understanding failure mode and fatigue life of components and is helpful to mechanism design and control strategy.

Establishment of flexible body’s computation model

Dynamic modeling of multi-body system works by lots of principle of dynamics, for instance, law of conservation of energy, Newton-Euler approach, Lagrange equation, Hamiltonian equation, Kane equation and so on. Based on the point of view of energy, Lagrange equation is established. This method is good for programming, modeling about kinematics and inverse kinematics problems, implementation of recursive type modeling and addition of controlling feedback. What’s more, the Lagrange equation method is more popular than others, and lots of multi-body system analysis software are based on this method.

Generalized coordinate of flexible body. Flexible body can be regarded as assembly of nodes of FEM and its deformation can be regarded as linear superposition of mode of vibration. As in Fig.1 shows, the point P is a node on the flexible body, and point \( P' \) is its position after deformation. B is flexible body coordinate system, and G is the base coordinate system.
Position of coordinate system $B$ relative to $G$ is \( \bar{x} = (x, y, z) \), orientation is \( \bar{\psi} = (\varphi, \theta, \psi) \), and model coordinate is \( \bar{q} = (q_1, q_2, \ldots, q_M) \) (M is the number of model coordinates). So flexible body’s generalized coordinate is:

\[
\bar{\xi} = \left\{ \bar{x}, \bar{\psi}, q_i \right\} \quad (i = 1, \ldots, M) \quad \bar{q}_i \rightarrow \left[ \bar{x}, \bar{\psi}, \bar{q}_i \right]^T.
\]  

(1)

**Flexible body’s differential equation of motion.** Position vector of point $P$ on the flexible body can be signified as:

\[
\bar{r}_p = \bar{x} + G_B A (s_p + u_p)
\]  

(2)

Where, \( G_B A \) is transformation matrix from $B$ to $G$. \( s_p \) is position of point $P$ in coordinate system $B$ before deformation. \( u_p \) is orientation of point $P'$ relative to point $P$. Where, \( u_p = \Phi_p q \), \( \Phi_p \) is modal matrix sub-block correspond to DOF of translation of Point $P'$. Speed of Point $P$:

\[
\bar{v}_p = \left[ I - G_B A (\bar{s}_p + \bar{u}_p) G_B A \Phi_p \right] \bar{\xi}
\]  

(3)

Where, the tilde presents that position vector is an asymmetric matrix. Matrix $B$ is defined as a transformation matrix during solving the derivative of Euler angle. Sequentially, kinetic and potential energy expression is:

\[
T = \frac{1}{2} \int_v \rho \dot{v}^T v dV = \frac{1}{2} \bar{\xi}^T M(\bar{\xi}) \ddot{\bar{\xi}}
\]  

(4)

\[
V = V_g (\bar{\xi}) + \frac{1}{2} \bar{\xi}^T K \bar{\xi}
\]  

(5)

Establish Flexible body’s differential equation of motion by Lagrange multiplier method:

\[
M \ddot{\bar{\xi}} + \dot{M} \dot{\bar{\xi}} - \frac{1}{2} \left( \frac{\partial M}{\partial \bar{\xi}} \right)^T \dot{\bar{\xi}} + K \ddot{\bar{\xi}} + f_g + D \dot{\bar{\xi}} + \left[ \frac{\partial \Psi}{\partial \bar{\xi}} \right]^T \lambda = Q
\]  

(6)

Where, $K$ is modal stiffness matrix; $D$ is modal damping matrix; $f_g$ is generalized gravity; $Q$ is generalized force; $\lambda$ is Lagrange coefficient of constraint equation; $\dot{\bar{\xi}}$ and $\ddot{\bar{\xi}}$ are first or second derivative of generalized coordinate of flexible body; $M$ and $\dot{M}$ are weight matrix and its derivative of flexible body.

**Rigid-Flexible Coupling Dynamics modeling of Parallel Robot**

3-PRS parallel robot’s schematic diagram and 3D model in this article are shown in Fig.2. It consists of a motional platform $S1-S2-S3$, three branches and one static platform $R1-R2-R3$. Connection between motional platform and up-link of every branch connects by spherical pair; connection between static platform and down-link of every branch connects by revolute pair; connection between up and down-link connects by prismatic pair. When three up-links are driven, contact length between up and down-links changes, and then pose of motional platform changes. This motional platform totally has two rotational DOF and one translational DOF.
In ANSYS, each link of robot is flexible. Then define material property, and select element type, performance and mesh parameters. At last, mesh. Based on constraint condition between each link and other modules in ADAMS, external linking points are defined, on which flexible body establishes proper connection with other components. Flow chart of rigid-flexible coupling simulation generated in ANSYS appears below.

After external linking points are defined, it needs compile ANSYS cyclic command and rigidize bearing areas using beam4 element. Then modal neutral files (.mnf files) generate from interface between ADAMS and ANSYS. Reading the .mnf files in ADAMS/View, replacing the up and down-links in rigid multi-body system with flexible ones, Rigid-Flexible Coupling Dynamics Analysis of 3-RPS Parallel Robot occurs.

**Rigid-Flexible Coupling Dynamics simulation of Parallel Robot**

**Displacement change of the end of manipulator.** Taking thread machining working condition of parallel robot as an example, dynamic analysis is preceded for operation process of whole machine. Because kinematical inverse solution is easy to have and positive solution is hard to, we exert point force on the end of manipulator to drive its spiral motion. Next, measure the relative displacement change curve between each up-link and down-link. These curves are just about the input conditions of each prismatic pair. Parallel robot fulfills spiral motion needs those input conditions. Then, convert measured curves into splines. These splines drive the prismatic pairs on each branch and positive solution process of parallel robot is done.

During building dynamic model of parallel robot, it is necessary to exert proper load on the manipulator. Given that in the process of thread machining, the main load bearded is contrary to speed tangential direction, whose value is 3000N.
During the robot loaded works, the load may cause deformation of links on each branch, and the size of deformation produces large influence on machining accuracy of parallel robot. Through analyzing and simulating full rigid body model and rigid-flexible coupling model, displacement curve of the measuring point in the vertical direction and the deformation about two models of spot welding robot are shown as Fig.4.

![Displacements curve](a) Displacements curve) ![Error curve](b) Error curve)

Fig.4 Vertical displacements and error of measuring point

As shown in Fig.4 (a), under the same law of motion and the same size of load, there is deviation between two curves. This deviation is just the displacement variable of measuring point caused by flexibility of links. What’s more, the size of the variable is positive or negative corresponding to different time. Fig.4 (b) displays error curve of the measuring point of two simulated models. Overall, we have:

1. From displacement curve, we found that fluctuation phenomenon of displacement curve measured in rigid-flexible coupling system is much more obvious comparing with that in multi-rigid body system. While, general trend of two curves is accordant.
2. From deviation curve, we found that the robot vibrate severely in initial stage. As motion becomes stable, displacement error in vertical direction at end of manipulator changes periodically, and the size of period is 4.2 seconds.

In the whole working process of robot, maximum vertical displacement error is about 0.2mm, changing up and down zero.

Coordinate of measuring point and its vertical error at three different times are shown below:

| Model                      | Time (s) | Whole rigid body | Rigid-flexible coupling body | Displacements error |
|---------------------------|----------|------------------|------------------------------|---------------------|
| Whole rigid body          | 4.2s     | 437.1712         | 436.9648                     | 0.2064              |
| Rigid-flexible coupling body | 5.9s     | 445.2829         | 445.2941                     | 0.0112              |
|                           | 7.6s     | 453.7524         | 453.9633                     | 0.2109              |

**Stress of up and down-link on each branch.** After rigid-flexible coupling dynamical simulation on flexible link is done, we get the maximum stress of links in whole working process. Maximum stress curve is shown in Fig.5.
From Fig. 5(a), point of maximum stress occurs on root of every down-link at 1.8s, with the value of Von Mises stress is 202.64Mpa, which is smaller than yield limit 282Mpa of link material (carbon steel). So, the link is safe. From Fig. 5(b), stress curve of point 1732 (the point bears maximum stress located on root of down-link) is given. Also, stress fluctuation range of the point is from 70 to 200Mpa, and the size of mean stress is about 135Mpa.

It turns out that present design strength is safe, and position of maximum stress point is unchangeable, though pose of parallel robot and forced direction of links are changing. While, because dynamic stress of down-link is high and oscillates severely, this will leads to stress accumulation and fatigue failure. So, we should conduct further experiment and analysis on root of link, and check whether it is necessary to perfect structures to avoid fatigue failure.

**Summary**

Using ADAMS and ANSYS, we build rigid-flexible coupling dynamic model for 3-RPS parallel robot and carry out simulation analysis. With the help of software, it avoids limitation and improves analysis efficiency and accuracy heavily.

The conclusion is as follows:

1. From rigid-flexible coupling dynamic simulation, we get vertical displacement curve and error curve of measuring point on the end of manipulators. Where, displacement error changes periodically with the size of period is 4.2s and maximum error is 0.2mm.

2. We got the location and changeable curve of maximum stress point during the whole process. As the results show, maximum Von Mises stress point is at root of down-link, whose value is 202.64Mpa smaller than yield limit (282Mpa). However, periodic change of stress may bring about fatigue failure.

3. Using rigid-flexible coupling method to analyze multi-body system, accuracy of dynamic response analysis for components under dynamic load is improved. So, we can simulate actual working conditions for parallel robot more visualized and precisely.

**Reference**

[1] LuYoufang. Dynamics of flexible multi-body systems [M]. Beijing: Higher education press, 1996.

[2] ZhongXin, YangRuqing, XuZhengfei etc. Multi-body system modeling theory and application [J]. Mechanical science and technology, 2002, 21(3):387-389.

[3] HuJunfeng, ZhangXianming, ZhuDachang etc. Flexible parallel robot dynamics modeling [J]. Journal of agricultural machinery, 42(11): 208-213

[4] XingJunwen. MSC. MSC. ADAMS/Flex and AutoFlex training tutorial [M]. Beijing: Science press, 2006.
[5] Zhang Yongde, Wang Yangtao, Wang Monan etc. Unite simulation of flexible body based on ANSYS and ADAMS [J]. Journal of system simulation, 2008, 20(17): 4501-4504.

[6] Wang Dan, Guo Hui, Sun Zhili. Solution and inverse solution of 3-RPS parallel robot pose based on ADAMS [J]. Journal of Northeastern University, 2005, 26(12): 1185-1187.

[7] J.F. Li. Inverse Kinematic and Dynamic Analysis of 3-DOF Parallel Mechanism [J]. Chinese Journal of Mechanical Engineering, 2003, 16(1):54-58.

[8] Wang Xiaoyun, James K M. Dynamic modeling of flexible-link planar parallel platform using a sub-structuring approach [J]. Mechanism and Machine Theory, 2006, 41(6):671-687.