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Kinematics simulation and application for machine tool based on multi-body system theory

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Abstract: Based on the multi-body kinematics principle, the topological structure and restriction relation among parts of machine tool and 3-D multi-body model are constructed, the kinematics simulation system of machine tool is developed. The designer can observe the movement and machining course of the whole machine tool and understand accurately the kinematics parameters of components such as position, velocity and acceleration. Also the designer can estimate the pose of components in the virtual circumstance and forecast accurately and correct problems which may appear during the design before the prototype is manufactured to assure the feasibility of design scheme, shorten period of product design and reduce product cost. The simulation system is used during the design of CK1416 high speed and precision numerical control lathe. The curves of ball screw angular velocity and carriage displacement agree well with the results of theoretical calculation and the constructed model is correct.

Key words: mutil-body kinematics; virtual prototyping; machine tool; kinematics simulation

With the high-speed development of production and science and technology, the machining industry is developing in the direction of high-speed, high-efficiency, high-precision and automatization. In order to quicken development speed of new machine tools, improve the quality and reduce cost, the kinematics and dynamics simulation of the machine tool must be considered during the design for machine tool. In this paper, the kinematics simulation system of the machine tool is realized based on the principle of multi-body system. The simulation process provides the scientific basis for machine tool design. The designer can not only observe the 3-D dynamic display and movement course of the whole machine tool in the virtual circumstance , but also forecast accurately and correct problems which may appear during the design before the prototype is manufactured. The feasibility of the design scheme is also increased.

1 Analysis Principle of Kinematics Based on Multi-Body System Theory

The multi-body system theory is the basis of the virtual prototyping technology. The virtual prototyping technology is a synthetic application technology which is based on advanced modeling technology, multi-domain simulation technology, information management technology, interactive consumer interface technology and virtual reality technology. Recently, the virtual prototyping technology has been widely used in product design, manufacturing, testing and analysis, etc[1,2]. The software of automatic dynamic analysis of mechanical system based on virtual prototyping has been developed by the theory of multi-body system dynamics. In this software we can use interactive graphics environment, unit store, restriction-base and force-base to establish full-parameter mechanical system geometry model. Its solver uses the Lagrange method of multi-rigid-body system to establish dynamics equation of system. The characteristics of static, kinematics and dynamics for virtual mechanical system are analyzed through this dynamics equation. Finally we get the curve of displacement, velocity, acceleration and counterforce.

Cartesian coordinate of the center of mass for rigid body i and Euler angle or generalized Euler angle of rigid body are regarded as generalized coordinates, namely $\boldsymbol{q}_i = \{x, y, z, \psi, \theta, \varphi\}_i^{\mathrm{T}}$, $\boldsymbol{q} = \{\boldsymbol{q}_1^{\mathrm{T}}, \boldsymbol{q}_2^{\mathrm{T}}, \cdots, \boldsymbol{q}_n^{\mathrm{T}}\}^{\mathrm{T}}$. During the kinematics analysis process, we only need to establish and solve the restriction equation[3,4] (initial position $\boldsymbol{q}_0$ has been known):

$$\boldsymbol{\Phi}(\boldsymbol{q}, t_n) = 0 \tag{1}$$

where $\boldsymbol{\Phi}$ is the algebraic equation column matrix of restriction, $\boldsymbol{\Phi} = \{\boldsymbol{\Phi}_1, \boldsymbol{\Phi}_2, \cdots, \boldsymbol{\Phi}_n\}^{\mathrm{T}}$; $\boldsymbol{q}$ is the generalized coordinate column matrix of the system.

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At time t_n, its position is calculated by Newton-Raphson iteration:

$$\left.\frac{\partial \boldsymbol{\Phi}}{\partial \boldsymbol{q}}\right|_j \Delta q_j = -\boldsymbol{\Phi}(q_j,\ t_n) \tag{2}$$

where $\Delta q_j = q_{j+1} - q_j$, j denotes the j-th iteration.

Solving the first derivative and the second derivative of restriction equation, we can get instant velocity and acceleration at t_n:

$$\left(\frac{\partial \boldsymbol{\Phi}}{\partial \boldsymbol{q}}\right)\dot{\boldsymbol{q}} = -\frac{\partial \boldsymbol{\Phi}}{\partial t} \tag{3}$$

$$\left(\frac{\partial \boldsymbol{\Phi}}{\partial \boldsymbol{q}}\right)\ddot{\boldsymbol{q}} = -\left\{\frac{\partial^2 \boldsymbol{\Phi}}{\partial t^2} + \sum_{k=1}^{n}\sum_{l=1}^{n}\frac{\partial^2 \boldsymbol{\Phi}}{\partial q_k \partial q_l}\dot{q}_k\dot{q}_l + \frac{\partial}{\partial t}\left(\frac{\partial \boldsymbol{\Phi}}{\partial \boldsymbol{q}}\right)\dot{\boldsymbol{q}} + \frac{\partial}{\partial \boldsymbol{q}}\left(\frac{\partial \boldsymbol{\Phi}}{\partial t}\right)\dot{\boldsymbol{q}}\right\} \tag{4}$$

From the Lagrange equation with multiplier, we get instant restriction counterforce at t_n:

$$\left(\frac{\partial \boldsymbol{\Phi}}{\partial \boldsymbol{q}}\right)^{\mathrm{T}}\boldsymbol{\lambda} = \left[-\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\partial T}{\partial \dot{\boldsymbol{q}}}\right)^{\mathrm{T}} + \left(\frac{\partial T}{\partial \boldsymbol{q}}\right)^{\mathrm{T}} + \boldsymbol{Q}\right] \tag{5}$$

where $\boldsymbol{\lambda}$ is the restriction counterforce and force column matrix, T is the system energy, and $\boldsymbol{Q}$ is the generalized force column matrix.

Fig. 1 shows the flowchart of kinematics simulation analysis for virtual prototyping based on multi-body system theory.

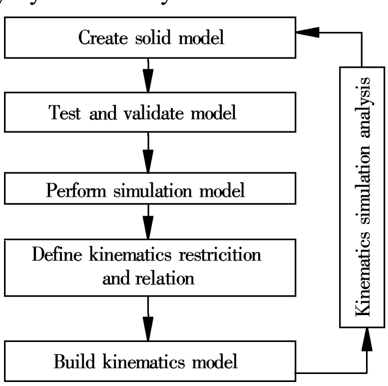

Fig.1 Flowchart of kinematics simulation analysis

2 Application Examples

The 3-D model of machine tool used in the analysis consists of machine tool body, upper-carriage subassembly, lower-carriage subassembly, main arbor subassembly and trail rack, etc. Fig.2 shows the 3-D analysis model. Fig.3 gives the topological structure and restriction among parts of machine tool in modeling of multi-body system. The main shaft B1 and machine tool body B0 are connected by revolute joint H1; the bearings B5, B6 and ball screw B7 are connected by revolute joint H7 and H8, respectively; the bearings chock B2, B3 and machine tool body B0, main shaft B1 and workpiece B4, bearings chock B2, B3 and bearings B5, B6, ball screw B7 and motor shaft B9, carriage B8 and knift rest B10 are connected by fixed joint H2, H3, H4, H5, H6, H10, H11, respectively; the ball screw B7 and carriage B9 are connected by screw joint H9; the carriage B8 and machine tool body B0 are connected by translational joint H12.

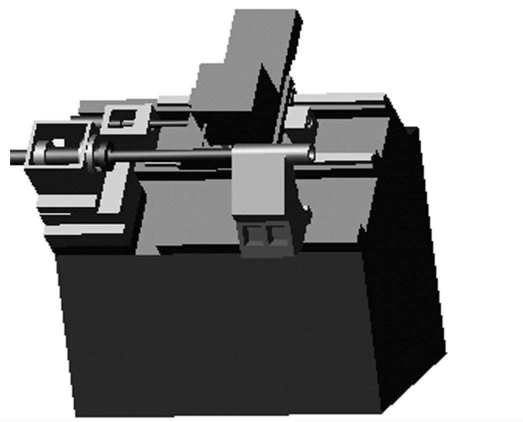

Fig.2 3-D analysis model

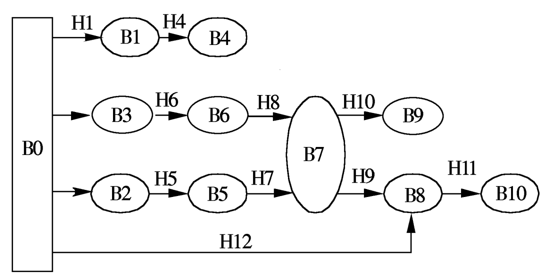

Fig.3 Topological structure and restriction among parts of machine tool

The primary technology parameters of machine tool is provided by Nanjing Numerical Control Machine Tool Ltd. Maximal turning length is 300 mm, longitudinal carriage maximum stroke is 330 mm, transverse carriage maximum stroke is 150 mm, the range of main shaft speed is 40 to 8 000 r/min, maximum torque of main shaft is 44.6 N · m. The feed velocity of both X axis and Z axis is 18 m/min, and the rated feed force is 6 400 N.

3 Simulation Result and Analysis

The time domain curve of ball screw angular velocity and the curve of carriage displacement are shown in Fig.4 and Fig.5[5], respectively. From Fig.4 we can know that the maximal angular velocity of ball screw is 314 rad/s in a period time. The ball screw accelerated at the beginning 0.01 s interval and then it runs at the invariable angular velocity. As it reaches definite position, the ball screw runs reversely at certain angular velocity. The carriage moves back and forth on the machine tool body along with cosine function under the ball screw driving. Fig.5 shows the process of carriage moving. This movement process was consistent with real process and the movement value was consistent with that of above. These results validated correctness of movement process.

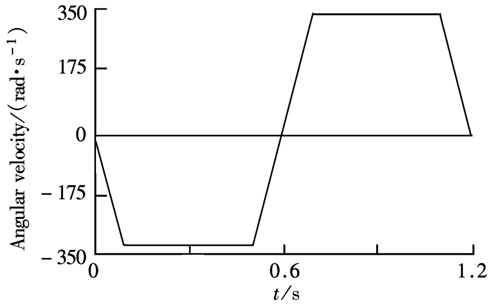

Fig.4 Curve of ball screw angular velocity

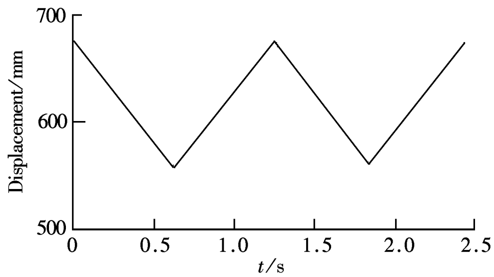

Fig.5 Curve of carriage displacement

4 Conclusion

Kinematics simulation is a new application field in electromechanical engineering. By the movement analysis, we can understand the movement rules of machine tool and forecast all kinds of possibility in the movement process. So it can provide a scientific basis for designing electromechanical products.

It is illustrative and vivid to apply kinematics simulation based on visual prototyping in the process of product design. We can accurately understand the parts and assembly kinematics parameters of a machinery product. We can also know the motion state of parts, the reliability of mechanism movement and reasons for failure of mechanism movement. Based on all these merits, the design quality of the product will be improved and development period of product will be shortened. This method has been used in kinematics simulation of the high speed and precision numerical control machine tool and perfect effects have been obtained.

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基于多体系统理论的机床运动学仿真与应用研究

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摘要: 从多体系统运动学理论的角度, 构建了机床各部件之间的拓扑结构和约束关系, 建立了三维多体模型, 开发了运动学仿真系统. 设计者可在虚拟环境下观察到整个机床的运动加工过程, 准确了解零部件的位置、速度和加速度等运动参数, 判断零部件的姿态, 并可在样机试制前对设计中可能出现的问题作出精确的预测和改进, 保证设计方案的可行性, 缩短产品的研制周期和降低成本. 该仿真系统用于 CK1416 高速高精度数控车床的设计, 所得到的滚珠丝杆角速度曲线、拖板位移曲线与理论结果一致, 从而证明了模型的正确性.

关键词: 多体运动学; 虚拟样机; 机床; 运动仿真

中图分类号: TP391.9