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Triaxial loading device for reliability tests of three-axis machine tools

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ABSTRACT

This paper presents a triaxial loading device (TLD), which can apply a triaxial force on the spindle of a three-axis machine tool that is executing a 3-degree-of-freedon feeding motion, aiming at simulating cutting forces applied on the spindle in a machining process. A prototype was fabricated and its kinematics and dynamics were analyzed. An explicit force control system was designed based on a fuzzy proportional-integral (PI) controller, integrating a force and a position feedforward. The effectiveness of the control system was evaluated; results illustrate that the fuzzy PI controller reduces the rising time and overshoots, and the force and the position feedforward eliminate the hysteresis and following errors caused by unknown feeding motions, respectively. Loading experiments were conducted to test the dynamic loading capacity of the TLD. The experimental results illustrate that the device is capable to add a triaxial force, which tracks a reference force with acceptable errors, on a spatially-moving spindle with random trajectories in real time. The TLD can simulate the cutting forces that the spindle encounters in real machining process and provides an efficient and economical loading approach that avoids a costly long-term cutting for the reliability tests of three-axis machine tools.

1. Introduction

Computer numeral control (CNC) machine tools are required to work reliably over a long period of service, as well as to keep the maximum productive output and accuracy [1]. The reliability of CNC machine tools is critical to the production system, because the breakdown of a machine tool can cease the entire production system, and the repair is difficult and expensive due to the high complexity of the machine tool [2].

The reliability of CNC machine tools is usually analyzed by tracing field failure records from workshops of users over a specific period of time [3-5]. However, machine tools perform an abnormally high failure rate during the early failure period, which is the first period of their lives [6], and the reliability in this period is unknown. This is adverse to delivering uninterrupted and on-time service of those machine tools [7]. To eliminate the early failures and provide the reliability characteristics, Wang et al. [6] suggested that suppliers of machine tools are required to conduct ex-factory run-in tests, which simulate the real cutting environment in the field. But these tests considerably waste materials and cutters, and are high-cost and environment-unfriendly. Thus, a loading device that outputs the same force as that generated by real cutting is required to overcome the disadvantages, but related studies have been rarely reported.

The spindle of a three-axis machine tool normally experienced a triaxial cutting force during its feeding motion, therefore, the loading device should have the capacity of applying triaxial force on a moving spindle. A load simulator provides an efficient method to generate desired forces on a moving target. Jiao et al. [8] proposed a velocity synchronizing compensation method for a load simulator to apply a torque on a rotating shaft. The output torque of a loading simulator can be also controlled by adaptive methods proposed by Yao et al. [9, 10]. Truong and Ahn [11] designed a fuzzy PID controller to actuate a load simulator to generate a force on a disturbance generator. Unfortunately, few researches achieve exerting triaxial forces on targets in motion. In addition, studies on multi-axial loading devices have been reported recently. Guo et al. [12] and Nierenberger et al. [13] established material testing machines with multidimensional loading capacity based on Stewart platform. Wang et al. [14] analyzed the stiffness characteristics of a hexaglide parallel loading mechanism. But the objects to be loaded in these studies are all stationary. Therefore, to the best of our knowledge, a loading device that exerts triaxial forces on moving objects have not been reported in related research communities.

A force control system is critical for a loading device to track reference forces. The impedance control and explicit force control provide

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Nomenclature

C_{ij}	rotation center of a spherical joint installed on the moving platform in the i-th limb
D_{ij}	rotation center of a spherical joint installed on the fixed base in the i-th limb
C_i	middle points of C_{i1} and C_{i2}
D_i	middle points of D_{i1} and D_{i2}
L_{ij}	linkage in the i-th limb
L_i	midline of L_{i1} and L_{i2}
H_i	slider on the i-th linear actuation
d	constant distance between two neighboring actuations
r	circumradius of the triangle $\Delta C_1C_2C_3$
$\boldsymbol{x}_p$	position vector of the moving platform
l	length of the linkage L_i
$\boldsymbol{k}_i$	unit vector of $\overrightarrow{D_iC_i}$
d_i	actuation of the i-th slider H_i
$\boldsymbol{a}_i$	initial vector of the i-th slider H_i
$\boldsymbol{s}_i$	unit vector of the i-th slider H_i
$\boldsymbol{v}_p$	velocity vector of the moving platform
$\boldsymbol{a}_p$	acceleration vector of the moving platform
$\boldsymbol{v}_D$	velocity vector of actuations
$\boldsymbol{a}_D$	acceleration vector of actuations
$\boldsymbol{\omega}_i$	angular velocity vector of the linkages L_i
$\boldsymbol{\varepsilon}_i$	angular acceleration vector of the linkage L_i
m_P	mass of the moving platform
m_{D_i}	mass of the i-th slider H_i
m_{L_i}	mass of the i-th linkage L_i
$\boldsymbol{I}^C_{L_i}$	inertia tensor of the i-th linkage L_i with respect to its own linkage coordinate
$\boldsymbol{F}_{ex}$	external force vector applied on the moving platform
$\boldsymbol{g}$	gravitational acceleration vector
$\boldsymbol{\tau}$	actuation force vector
$\boldsymbol{F}_p$	sum of active and inertial forces on the moving platform
$\boldsymbol{F}_{H_i}$	sum of active and inertial forces on the i-th slider H_i
$\boldsymbol{F}_{L_i}$	sum of active and inertial forces on the i-th linkage L_i

two efficient methods [15]. However, trajectories of feeding motions that generate the references in the impedance control [16] are unknown to the load device. Therefore, the explicit force control method is suitable for this application, because it tracks reference forces by feeding back actual forces and forming a close-loop force control system [17]. Since the dynamics of the loading device is nonlinear and the contact environment is unknown, considerable errors and hysteresis happen. Fuzzy logic is effective to deal with the nonlinearity and uncertainty, since fuzzy rules based on the knowledge of experts make the control system independent from the nonlinear dynamics [18]. Ju et al. [19] designed a hybrid fuzzy controller for a rehabilitation robot to control the force along the moving direction. Wang et al. [20] presented a design methodology for stabilization of nonlinear systems using fuzzy models. Cao and Frank [21] proposed fuzzy control system for both continuous and discrete-time nonlinear systems. Moreover, time-variant reference forces and unknown feeding motions introduce disturbances to the control system, but Yuen [22] illustrated to be eliminated by force and position feedforwards. But, few studies have been reported to implement the explicit force control to generate triaxial forces on a moving spindle.

A triaxial loading device (TLD) based on a 3-degree-of-freedom (DOF) parallel mechanism was proposed to generate triaxial forces on a spindle that was performing random 3-DOF feeding motions. An explicit force control system was designed based on a fuzzy proportional-integral (PI) controller, integrating a force and a position feedforward that was predicted by a polynomial prediction filter (PPF). Finally, experiments were conducted to evaluate the control system and validate the loading capacity of the TLD.

The remaining of this paper is organized as follows: Section 2 describes the prototype and coordinates of the TLD. In Section 3, the kinematics and dynamics of the TLD are analyzed. An explicit force control system is designed in Section 4. Section 5 shows control system evaluations and loading experiments, and conclusions are drawn in Section 6.

2. Prototype description and coordinate definition

The TLD, based on a 3-DOF parallel mechanism as shown in Fig. 1(a), consists of a fixed base, a moving platform, and three kinematic limbs with parallelogram structures, each of which is composed of fours spherical joints, two fixed-length linkages and two force sensors. A force sensor (China Academy of Aerospace Aerodynamics, China), which measures uniaxial forces by its S-shaped beam, was installed to measure the forces along each linkage, and data of six force sensors was utilized to calculate the actual force applied on the spindle. The fixed base contains three linear actuations, each of which is composed of a servo motor, a ball screw, a slider and two linear guides; the ball screw converts the rotation of the servo motor to the translation of the slider, whose linearity is guaranteed by two linear guides. Due to the constraints of parallelogram structures, the moving platform has three translational DOFs [23] that are translations along x-, y-, and z-axis, and connects the spindle by a cylindrical connector.

The i-th limb ($i=1,2,3$), as shown in Fig. 1(b), has four spherical joints whose rotation centers are C_{i1}, C_{i2}, D_{i1} and D_{i2}. A fixed coordinate $\boldsymbol{O}_b=\{x_b,y_b,z_b\}$ is established at the midpoint of the middle linear actuation. The x-axis is along its sliding direction, and the z-axis is parallel to a normal vector of the fixed base. A moving coordinate $\boldsymbol{O}_p=\{x_p,y_p,z_p\}$ is located at the center of the equilateral triangle $\Delta C_1C_2C_3$ with a circumradius of r. The x-axis coincides with the straight line C_1O_p, and the z-axis is perpendicular to the moving platform. The y-axes of two coordinates can be both derived by right-hand rules.

3. Kinematics and dynamics

3.1. Kinematics

Combining the inertia of a parallelogram $C_{i1}C_{i2}D_{i2}D_{i1}$, two linkages in i-th limb are simplified to a fixed-length linkage D_iC_i with the same length. Based on the closed-loop $O_bO_pC_iD_i$, the constrain equations can be written as

$$\boldsymbol{x}_p+\boldsymbol{c}_i-d_i\boldsymbol{s}_i-\boldsymbol{a}_i=l\boldsymbol{k}_i,\ i=1,2,3 \tag{1}$$

where $\boldsymbol{c}_i=\overrightarrow{O_pC_i}$, and $\boldsymbol{x}_p=\overrightarrow{O_bO_p}=[x_p,y_p,z_p]^T$. Based on the design, $\boldsymbol{a}_1=[0,0,0]^T$, $\boldsymbol{a}_2=[0,d,0]^T$, and $\boldsymbol{a}_3=[0,-d,0]^T$; $\boldsymbol{s}_2=\boldsymbol{s}_3=[1,0,0]^T$, and $\boldsymbol{s}_1=[-1,0,0]^T$. Introducing $\boldsymbol{h}_i=\boldsymbol{x}_p+\boldsymbol{c}_i-\boldsymbol{a}_i$, solving the Eq. (1) derives the solutions of the i-th actuation as $d_i=\boldsymbol{h}_i^T\boldsymbol{s}_i\pm\sqrt{(\boldsymbol{h}_i^T\boldsymbol{s}_i)^2-(\boldsymbol{h}_i^2-l^2)}$. For each position of the moving platform, the position of each actuation has two solutions. The geometric constraint of each limb was defined as $|d_i|>|\boldsymbol{c}_i^T\boldsymbol{s}_i|$ to keep the motion continuity of the moving platform. Denoting $\overrightarrow{O_bD_i}=d_i\boldsymbol{s}_i+\boldsymbol{a}_i=[x_{D_i},y_{D_i},0]^T$, the x_{D_i}can be derived as

$$\begin{cases} x_{D_1}=x_p-r-\sqrt{l^2-z_p^2-y_p^2} \\ x_{D_2}=x_p+r/2+\sqrt{l^2-z_p^2-\left(y_p-\sqrt{3}r/2+d\right)^2} \\ x_{D_3}=x_p+r/2+\sqrt{l^2-z_p^2-\left(y_p+\sqrt{3}r/2-d\right)^2} \end{cases} \tag{2}$$

Eq. (2) presents the inverse kinematics of the TLD, where $y_{D_1}=0$, $y_{D_2}=d$, and $y_{D_3}=-d$ are known by its design. Referring to Eq. (2), its forward kinematics can be expressed as

$$\begin{cases} x_p=\dfrac{(4x_{D_1}+x_{D_2}+x_{D_3}+2\sqrt{3}d)r+2x_{D_1}^2-x_{D_2}^2-x_{D_3}^2-2d^2}{6r+4x_{D_1}-2x_{D_2}-2x_{D_3}} \\ y_p=\dfrac{(x_{D_2}-x_p-r/2)^2-(x_{D_3}-x_p-r/2)^2}{4(\sqrt{3}r/2-d)} \\ z_p=\sqrt{l^2-y_p^2-(x_p-r-x_{D_1})^2} \end{cases} \tag{3}$$