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Research article

Research on the parallel load sharing principle of a novel self-decoupled piezoelectric six-dimensional force sensor

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ABSTRACT

This paper presents a novel integrated piezoelectric six-dimensional force sensor which can realize dynamic measurement of multi-dimensional space load. Firstly, the composition of the sensor, the spatial layout of force-sensitive components, and measurement principle are analyzed and designed. There is no interference of piezoelectric six-dimensional force sensor in theoretical analysis. Based on the principle of actual work and deformation compatibility coherence, this paper deduces the parallel load sharing principle of the piezoelectric six-dimensional force sensor. The main effect factors which affect the load sharing ratio are obtained. The finite element model of the piezoelectric six-dimensional force sensor is established. In order to verify the load sharing principle of the sensor, a load sharing test device of piezoelectric force sensor is designed and fabricated. The load sharing experimental platform is set up. The experimental results are in accordance with the theoretical analysis and simulation results. The experiments show that the multi-dimensional and heavy force measurement can be realized by the parallel arrangement of the load sharing ring and the force sensitive element in the novel integrated piezoelectric six-dimensional force sensor. The ideal load sharing effect of the sensor can be achieved by appropriate size parameters. This paper has an important guide for the design of the force measuring device according to the load sharing mode.

1. Introduction

Six-dimensional force sensor is superior to single-dimensional force sensor for its ability to measure all the force information in space simultaneously, including three-dimensional force and three-dimensional torque. It has been a challenging issue to accurately and efficiently measure six-dimensional force/torque of heavy-loads in some fields. Super large heavy equipment (large forging machine, large operation machine, shield machine, large welding positioner, ultra large machine, et al.) has characteristics of heavy load, large inertia, multi degree of freedom, multi dimensional load [1–3]. The full load feedback in the manufacturing process is an indispensable part of the automated manufacturing. Force feedback is very important for large heavy manufacturing equipment, which determines multi-equipment control coordination and force adaptation capacity in equipment operation. Sensing and measuring device has been an important part of the control system. Six-dimensional force sensors can realize the space force and torque measurement [4,5]. As a kind of multi-dimensional force sensor, six-dimensional force sensor can realize multi-degree of freedom force feedback and force compliance control of operation equipment. At present, there are mainly two measuring ways for the six-dimensional force sensor. One is traditional strain six-dimensional force sensor; the other is piezoelectric six-dimensional force sensor.

During load measurement, not only the steady state force needs to be measured, but also real-time changes of multi dimensional force need to be investigated in the changing external conditions. Traditional six-dimensional force sensors [6–8] which adopt resistance strain as force sensing element have advantages of high precision, good stability, wide range and miniaturization,et al. In this aspect, six-dimensional force sensor based on Stewart structure can realize the large range load measurement. Gaillet and Reboulet [9] firstly applied the Stewart platform to parallel six-axis force sensor. Zhao et al. [10] developed a pre-stressed six-axis force sensor based on the Stewart platform. Lu et al. [11] made research on statics and stiffness analysis of a novel six-component force/torque sensor with 3-RPPS compliant parallel structure. Ranganath et al. [12], Yao [13], Hou et al. [14], Wang and Yin [15], Jin et al. [16] developed different six-dimensional force sensors based on Stewart platform, and established their static models and

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Nomenclature

A_b	Cross-sectional area of load sharing ring
h_b	Height of load sharing ring
E_b	Elastic modulus of load sharing ring
G_b	Shear modulus of load sharing ring
du_b	Axial micro deformation of load sharing ring
$d\nu_b$	Horizontal micro deformation of load sharing ring
ε_b	Axial deformation displacement of load sharing ring
ν_b	Horizontal deformation displacement of load sharing ring
F_{zb}	Axial load of load sharing ring
F_{xb}	Horizontal load of load sharing ring
h_a	Height of upper cover
λ_b	Shear non-uniformity coefficient of load sharing ring
I_{yb}	Inertia moment of load sharing ring
I_{zb}	Polar inertia moment of load sharing ring
ρ_b	Curvature radius of load sharing ring
θ_b	Allowable bending angle of load sharing ring
φ_b	Allowable torsion angle of load sharing ring
M_{yb}	Torque of load sharing ring
M_{zb}	Moment of load sharing ring
m	Ratio of inner and outer diameter
$\eta_{Fx}(\eta_{Fy})$	Load sharing ratio in horizontal direction
$\eta_{Mx}(\eta_{My})$	Load sharing ratio in torque direction
C	Thickness of load sharing ring (r_{b1}- r_{b2})
A_c	Cross-sectional area of quartz crystal group
h_c	Height of quartz crystal group
E_c	Elastic modulus of quartz crystal group
G_c	Shear modulus of quartz crystal group
du_c	Axial micro deformation of quartz group
$d\nu_c$	Horizontal micro deformation of quartz crystal group
ε_c	Axial deformation displacement of quartz crystal group
ν_c	Horizontal deformation displacement of quartz crystal group
F_{zc}	Axial load of quartz crystal group
F_{xc}	Horizontal of quartz crystal group
h_d	Height of lower cover
λ_c	Shear non-uniformity coefficient of quartz crystal group
I_{yc}	Inertia moment of quartz crystal group
I_{zc}	Polar inertia moment of quartz crystal group
ρ_b	Curvature radius of quartz crystal group
θ_c	Allowable bending angle of quartz crystal group
φ_c	Allowable torsion angle of quartz crystal group
M_{yc}	Torque of quartz crystal group
M_{zc}	Moment of quartz crystal group
μ	Poisson's ratio
η_{Fz}	Load sharing ratio in axial direction
η_{Mz}	Load sharing ratio in moment direction

optimized their structure parameters. However, since the upper platform is supported by the six limbs, it is difficult to avoid the over constraints under large pre-tightening forces and instability structure which may result large over stress easily. In addition, since a large pre-tightening force is needed for the connection of the standard force sensor, the effective measuring capability of standard force sensor is quite low. However, traditional strain six-dimensional force sensors have disadvantages of complex decoupling, large volume, and the lack of dynamic characteristics which require dynamic compensation. And then, traditional strain force sensors are not suitable for dynamic measurement.

Compared with traditional strain force sensors, piezoelectric six-dimensional force sensor is a new kind of inelastic type electric quantity sensor, which is the only one to realize dynamic measurement [17]. Piezoelectric materials used for force measurement can be divided into three kinds of piezoelectric quartz crystals, piezoelectric ceramics (PZT), and new organic polymer piezoelectric materials (PVDF film) [18]. Piezoelectric ceramics are often used as actuators. The PVDF film which can only withstand single dimensional compression stress is used to measure the impact load. The quartz crystal has good static and dynamic characteristics. It has high sensitivity, high resolution, good stability, superior frequency response and transient response,et al. Piezoelectric quartz sensor can accurately measure the force from quasi-static to high dynamic force. So we choose piezoelectric quartz crystals as force sensing element. Liu [19] presented a novel parallel piezoelectric six-axis force/torque sensor. Two different arrangements of the eight group piezoelectric quartz crystals for the sensor were put forward. Their mathematic models were derived, the finite element model of sensor was established, and the output charge sensitivity, coupling interference and the natural frequency of the sensor were analyzed by ANSYS software. Ren [20] made research on the force vector measurement model based on the piezoelectric sensor. The force vector measurement is the confirming of the magnitude, direction and the action point, which could be transformed the measurements of the three forces and torques according to the force equivalent principle. However, these methods are involved in both the force and torque measurement, and the coupling is more serious.

Usually, quartz wafers are arranged in the sensor. However, the size of the quartz wafer must be limited due to the overall size of the sensor. At present, the largest size quartz wafer is 30mm × 30mm, and its bearing capacity is about 117kN. The load in heavy equipment manufacturing process may reach hundreds of tons. Whereas, the piezoelectric quartz is not feasible to directly bear all the loads. The indirect measurement method by using parallel load sharing principle has to be adopted, in order to measure six-dimensional and heavy force. The load sharing principle is the key technology and difficult technology to realize the heavy force measurement. There are few reports on the piezoelectric six dimensional force sensors and its load sharing principle. It is urgent to make research on piezoelectric six dimensional heavy force sensors for the dynamic measurement of heavy equipments. Liu [21] made researches on principle of parallel load sharing for six-dimensional heavy force/torque sensor with four point supporting structure, facing to solve dynamic measurement problem on six-dimensional time-varying heavy load in extremely manufacturing process. The load sharing ratios are analyzed and calculated in vertical and horizontal directions. The mapping relationship between six-dimensional heavy force/torque value to be measured and output force value is built. Li [22] presented a novel parallel spoke piezoelectric 6-DOF heavy force/torque sensor by using adjustable load sharing devices. Load sharing principle on parallel spoke piezoelectric 6-DOF heavy force/torque sensor is researched in vertical, horizontal, moment, and torque directions. Related theoretical structural models are constructed, interpreted, and modified. Jia [23] researched the measurement method of six-axis load sharing based on the Stewart platform. The force