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Dynamic characteristics of piezoelectric six-dimensional heavy force/moment sensor for large-load robotic manipulator

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ABSTRACT

This paper presents research on dynamic characteristics of a piezoelectric six-dimensional heavy force/moment sensor for a large-load robotic manipulator. The theory on dynamic characteristics of the sensor structure is analyzed, and a mathematical model of the sensor dynamics, decoupled into separate vibration modes, is provided. This model is complemented by dynamic mode analysis of the sensor by finite-element modeling (FEM; ANSYS software). A dynamic calibration experiment is designed, and methods and principles for measurements and data analysis are provided. The characteristic dynamic vibration modes of the piezoelectric force/moment sensor are extracted by analyzing experimental data, yielding amplitude frequency and phase frequency curves of the transfer function linking the excitation loads with the output signals of the transducer. The results of the dynamic calibration experiment demonstrate the good dynamic characteristics of the piezoelectric six-dimensional heavy force/moment sensor. The natural frequencies in the three force directions are high, with values close 2000 Hz. This demonstrates the applicability of the presented six-dimensional heavy force/moment sensor to large industrial robotic manipulators.

1. Introduction

Terminal actuating mechanisms for manipulating heavy-loads are common in large industrial robots. They are working in extreme conditions, can realize smart multi-dimensional force-position operation, and have characteristics such as large inertia, multi-degree of freedom, and variable stiffness. The dynamic characteristics in unloaded and loaded state may make lead to inaccuracies and instabilities during dynamic operation. Furthermore, in heavy-load and discontinuous operation, frequency response characteristic is poor, and easily leads to nonlinear responses such as time delays and dead-times. Therefore, six-dimensional force/moment measurement and real-time feedback during operation are fundamental in coordinate and force compliance control for complex equipment, and therefore constitute an indispensable part for intelligent robots [1–3]. Six-dimensional force/moment sensors can simultaneously monitor the full load vector, and thus are the ideal detecting element in such a real-time feedback control system [4–6], thus enabling harmonious operating control of a multi-dimensional complex actuator such as a robotic gripper.

Hitherto, researchers in the world have made many theoretical and applied studies on six-dimensional force/moment sensors for robots. Six-dimensional force/moment sensors based on different principles have been studied and chosen, such as piezoresistive [7], capacitive [8], optical [9], piezomagnetic [10] and piezoelectric [11,12]. Meanwhile, scholars have designed many different structural embodiments, and conducted extensive researches

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on their operational performance. At present, Maltese cross-shape, and Stewart type six dimensional force/torque sensors are mostly researched and applied. Liang et al. [13] presents a novel device for measuring components of forces and moments along and about three orthogonal axes based on E-type membranes compared to conventional sensor based on cross beams, and fabricates a six-dimensional wrist force/torque sensor based on E-type membranes. Wua et al. [14] adopts multi-axis force sensor (MFS) in humanoid robot foot to obtain external forces/moments acted on the foot while in locomotion. The precision and comprehensive performances of MFS originally determined by its elastomer structure are significant essentially for humanoid robots to keep balance by detection of external forces/moments during walking motion. Jia et al. [15] presents a measurement method of six-axis load sharing based on the Stewart platform. The force Jacobin matrix of the Stewart platform, the solution of forward kinematics of the Stewart platform and the deep beam element stiffness matrices are combined in the decoupling algorithm. Although six dimensional force/torque sensors has been intensively studied during the last decade and a large number of papers and books have been published, the existing six dimensional force/torque sensors cannot realize measurement of large range loads (more than 30 kN). They are used to measure low loads on small robotic wrist, rather than large-load robotic manipulator.

The dynamic performance of six-dimensional force/moment sensors strongly influences the performance of robotic systems. In case of poor sensor dynamic performance, rapid variations of the forces/moments to be measured would not be reflected in time, leading to abnormal function of the robotic system. By now, there is no general standard for dynamic performance indexes of six-dimensional force/moment sensors. Many researchers in the world have made researches on dynamic characteristic of six-dimensional force/moment sensor [16–20]. However, most force/moment sensors adopt resistant force-sensing elements. For large strain, it has a larger nonlinearity and weaker output signal. The frequency response is low, requiring dynamic compensation. Piezoelectric six-dimensional force/moment sensing is a dynamic force measurement principle applying piezoelectric crystals or poled ceramics as force-sensing elements. There is little published research on piezoelectric six-dimensional force/moment sensors [11,12], let alone on their dynamic performances.

Therefore, this paper presents research on the dynamic characteristics of a piezoelectric six-dimensional heavy force/moment sensor for a large-load robotic manipulator gripper. A mathematic model of the piezoelectric six-dimensional heavy force/moment sensor is provided and decoupled. The theory on dynamic characteristic of piezoelectric six-dimensional heavy force/moment sensor is analyzed and researched. This model is complemented by dynamic mode analysis of the sensor by finite-element modeling. A dynamic calibration experiment is designed, and methods and principles for measurements and data analysis are provided. Finally, an application test of the piezoelectric six-dimensional heavy force/moment sensor on a large-load manipulator gripper is designed and made.

2. Structure model and measuring principle

In this paper, piezoelectric quartz crystal is selected as force-sensing element to realize spatial six-dimensional force/moment dynamic measurement by comparing with other force-sensing elements' operational performances. Piezoelectric force/torque sensors choosing piezoelectric quartz as force–electric transition element are quasi-static and dynamic transducers. The sensor has the advantages of good static stiffness, high sensitivity, and high resolution [19], good static linearity, small hysteresis and repeatability error. Another favorable characteristic of piezoelectric sensors is their high inherent frequency (200 kHz), making them especially suitable for dynamic measurement. To date, piezoelectricity is the only measuring technology that can satisfy the requirement of such a high resonance frequency.

Fig. 1 shows the structure of our piezoelectric six-dimensional heavy force/moment sensor. Its elastic structure is composed of a top cover, piezoelectric quartz crystals, a baseplate, preload bolts and a wire slot. Here the four group's piezoelectric quartz crystals are evenly distributed on upper surface of baseplate, in a square arrangement. The top cover, piezoelectric quartz crystals, and the baseplate are fixed together with preload bolts. In order to measure horizontal force, the piezoelectric quartz crystals must be compressed by preload bolts. Moreover, preload also compensates the fitting clearance of the sensor, allowing more reliable measurements. Magnitude of preload exerted on piezoelectric quartz crystals is determined by measuring range of the sensor. The preload value for each piezoelectric quartz crystals should be uniform, and the best range is between 10 kN and 15 kN.

The force signals of piezoelectric quartz crystals (x° crystals and y° crystals) are produced, when spatial force is applied on top cover of the sensor. Six-dimensional force/moment can be measured, as long as the supporting points are no less than three. Considering the symmetry of the structure and simplify the decoupling algorithm, four groups piezoelectric quartz are used. Fig. 2 shows a schematic diagram of the measuring principle with a four-point supporting structure. Six force and moment values (F_x, F_y,

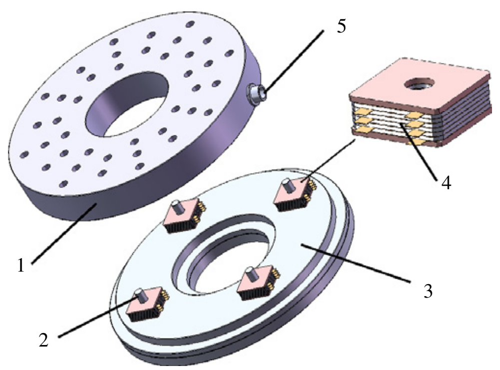

Fig. 1. Mechanical structure of piezoelectric six-dimensional heavy force/moment sensor. (1) Top cover, (2) preload bolt, (3) baseplate, (4) piezoelectric quartz crystal, and (5) wire slot.