CIRP Annals - Manufacturing Technology xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

CIRP Annals - Manufacturing Technology

journal homepage: http://ees.elsevier.com/cirp/default.asp

Magnetically levitated six degree of freedom rotary table

Xiaodong Lu (2)[a,*], Mark Dyck[a,b], Yusuf Altintas (1)[b]

[a] *Precision Mechatronic Laboratory, Department of Mechanical Engineering, The University of British Columbia, Vancouver, BC V6T 1Z4, Canada*
[b] *Manufacturing Automation Laboratory, Department of Mechanical Engineering, The University of British Columbia, Vancouver, BC V6T 1Z4, Canada*

ARTICLE INFO

Keywords:
Magnetic bearing
Actuator
Mechatronic

ABSTRACT

This paper presents a novel six degree of freedom magnetically levitated rotary table. Benefits of magnetic levitation include frictionless movement allowing for high precision movements, and real-time correcting capability of 6-axis motion errors. The 6DOF actuator includes a circular Halbach magnet array attached to the underside of the moving table and a printed flat coil installed on the stator. The forces are generated by current through stationary coils interacting with the field from permanent magnet array. Position feedback is achieved using four capacitive probes and four optical encoders. The table has been manufactured and controllers for each axis have been designed. Movement has been demonstrated with position resolution of 55 nm (RMS).

© 2015 CIRP.

1. Introduction

The process of micromachining involves positioning the part relative to the tool with micron level accuracy [1]. Generally, the parts being machined are only a few millimeters in size [2] with features that are between 1 μm and 500 μm in size, and cutting forces that are at most several Newtons [3]. Because of the high positioning accuracy required in micromachining, machine tool design has several key challenges such as stiffness, static friction and bearing errors.

One common configuration for micro-milling machines is several single degree of freedom (DOF) stages stacked in series to achieve multiple degrees of freedom [4]. In order to achieve micron level positioning the stages are often designed to minimize friction, as in [5], by using air bearings. Errors can arise from friction, motor-coupling and backlash, which make micron precision difficult to achieve. Direct drive linear motors are often used to actuate the stages [1] which helps eliminate backlash and motor coupling errors. However, when single DOF stages are attached in series, mover inertia is increased, particularly near the start of the kinematic chain. Stacked stages also lead to increased error as the geometric errors of each stage are cumulative [6].

In order to achieve sub-micron positioning on the end effector, each single DOF stage needs to be rigid, necessitating larger, stiffer structures which lead to more moving mass. Such stages require larger forces to overcome static friction and increased inertia. Static friction forces may be orders of magnitude larger than micro-machining cutting forces. It is desired to minimize the static friction and design actuators with closed loop control that have a wide frequency bandwidth and high stiffness against disturbance.

Micro milling machines often use ball-bearings to constrain unwanted degrees of freedom. This creates a fundamental limitation to precision as ball bearing accuracy is affected by ball roundness errors. Any imperfections in ball sphericity cause bearing errors on the same order as the required positioning accuracy [7]. One way to avoid the effects of ball roundness errors is to use air bearings. However, it is difficult to achieve the required stiffness using air bearings under varying machining loads. Therefore, an ideal machine would have no static friction, no ball bearings, high stiffness and no stacked stages.

One solution which achieves these requirements is to use active magnetic levitation that actuates the moving stage in multiple degrees of freedom directly without intervening machine elements or bearings. Such technology has been demonstrated for six DOF planar motion in [8,9]. This allows for frictionless and non-contact movement with six DOF over a large positioning range in the planar axes (x, y). For rotary motion, existing magnetic bearings are mainly based on reluctance actuators for suspension [10]. An integrated bearing-motor concept was proposed in [11] using a circular Halbach magnet array and 6 toroidal coil winding for artificial pump propellers. This paper presents the design, prototype, and experimental results of a six DOF magnetically-levitated rotary table based on circular a Halbach magnet array, 4 sets of printed flat coil winding, and a 6-DOF metrology using capacitive sensors and optical encoders. The benefits of a six DOF table are zero friction, being free of contact-bearing errors, and compact design.

2. Electromechanical configuration

Fig. 1 shows the assembled magnetic levitation rotary table, which includes a mover and a stator. The mover frame is made of an aluminum honeycomb panel cut into a 30 cm diameter disk. The underside of the mover consists of 94 magnetization segments arranged circumferentially in Halbach magnet array patterns. On

* Corresponding author.
E-mail address: xdlu@mech.ubc.ca (X. Lu).

http://dx.doi.org/10.1016/j.cirp.2015.04.107
0007-8506/© 2015 CIRP.

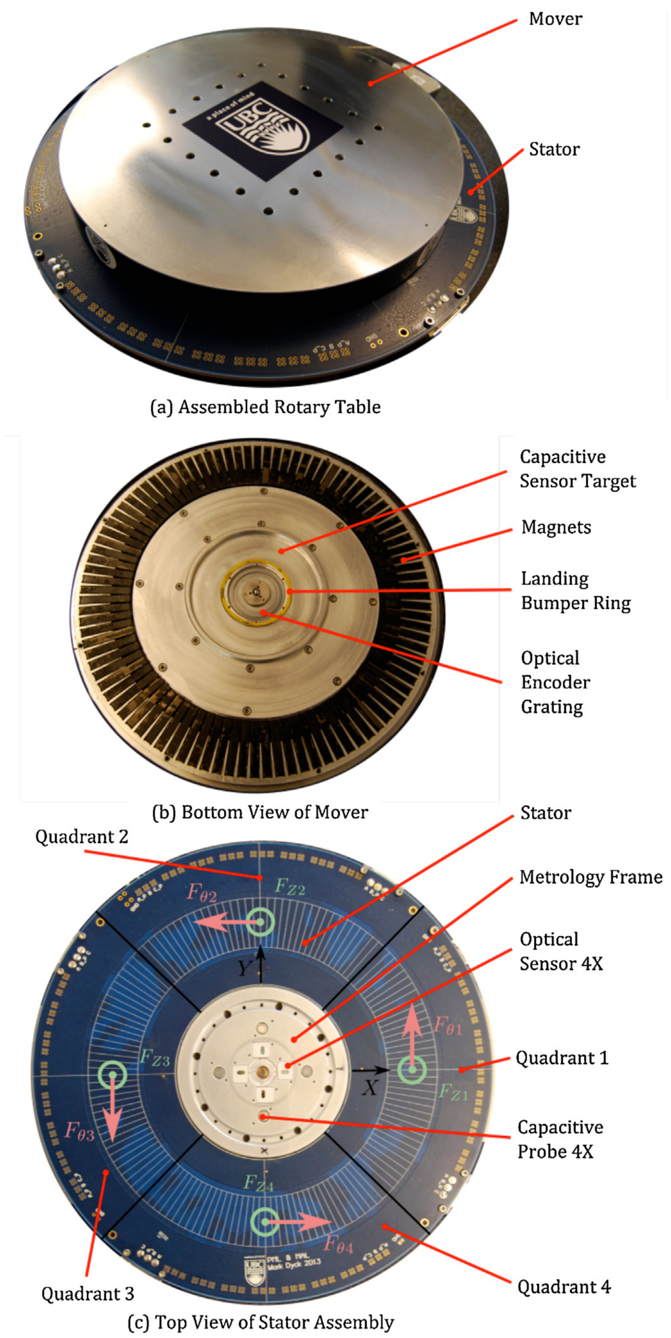

Fig. 1. Rotary table overview.

the bottom center of the mover there is an aluminum plate which serves as the capacitive sensor target, landing pad and optical grating mount. The top of the table has a 25 mm × 25 mm spaced hole pattern which has M4 rivet nuts installed to allow for work piece mounting. The stator, which is made using printed circuit board (PCB) technology, has a hole in the center where the position sensors, landing area and sensor protection system are mounted. The stator is supported from the underside by a circular piece of engineered quartz, which is used for its stiffness, thermal stability and electrical insulation properties. There are four capacitive probes and four optical sensors mounted in the center hub which provide position feedback for the servo control system. The ring on the bottom of the mover fits into the groove in the stator. This ring prevents damage from occurring to the sensors in the event of an emergency stop or uncontrolled landing.

The stator PCB is an 18 layer printed circuit board where the internal layers are 210 μm thick and the outer layers are 70 μm thick. The total thickness of the board is ~4.8 mm with insulating glass fiber layers. The diameter of the board is ~370 mm.

The circumference of the coils (stator) is divided into quadrants and each quadrant's current can be independently controlled. The coil currents in each quadrant can create two independent forces acting on the mover, one in the tangential (θ) direction and one in the levitation (z) direction. As a result, we can generate a total of eight uncoupled forces, as shown in Fig. 1(c). These eight forces allow the table to be controlled in 6 DOF.

3. Actuator analysis

The actuation of the table is based on the Lorentz force which arises from the interaction between a magnetic field generated by the permanent magnet on the mover and a moving charge or current in the stator. The direction of the force is orthogonal to the direction of both the current and magnetic field. The force is acting on the location of coils carrying the current. In order to create a sinusoidally varying magnetic field, a Halbach array is mounted on the underside of the table. A Halbach array is chosen over a simpler arrangement because it creates a stronger magnetic field at the bottom side of the mover. The cross section of a Halbach array is shown in Fig. 2. Force generation using this method has been modified from [8] to reflect the rotary table topology.

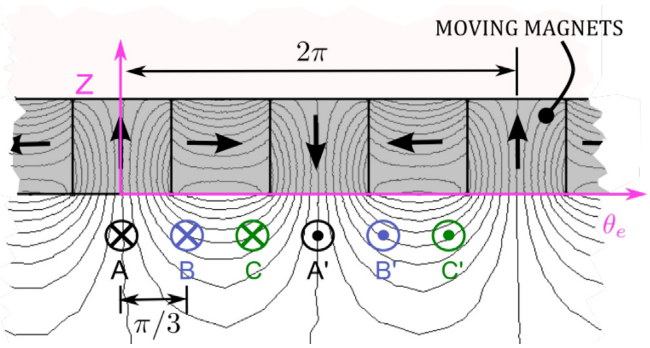

Fig. 2. Cross section of Halbach array and coils schematic.

The electrical angle θ_e is related to the mechanical angle of the mover θ_m by the number of Halbach arrays N used to complete the circle:

$$\theta_e = \theta_m N. \tag{1}$$

The magnetic field on the underside of the Halbach array can be approximated as follows:

$$\begin{aligned} B_\theta(\theta_e, Z) &= -B_r \sin(\theta_e) e^{\frac{ZN}{r}} \\ B_Z(\theta_e, Z) &= B_r \cos(\theta_e) e^{\frac{ZN}{r}} \end{aligned} \tag{2}$$

where r is the radius from the center of the circular Halbach arrays and B_r is the magnetic field amplitude. A constant current through a coil would create a rotating force vector as the magnets move relative to the coils. In order to produce a usable and controllable actuating force at a coil trace A, the excitation current in coil trace A is commutated as:

$$I_A(\theta_e, Z) = I_Z sin(\theta_e) e^{-\frac{ZN}{r}} + I_\theta cos(\theta_e) e^{-\frac{ZN}{r}}, \tag{3}$$

where I_z and I_θ are intermediate variables representing the desired forces in directions Z and θ, respectively. The resulting θ-direction force on coil trace A can be calculated as:

$$F_{A,\theta}(\theta_e) = I_A B_Z l = I_Z B_r sin(\theta_e) cos(\theta_e) l + I_\theta B_r cos(\theta_e)^2 l, \tag{4}$$

where the first term has a mean force of zero while the second term has a usable mean force.

Similarly, the Z-direction force on coil trace Z is

$$F_{A,z}(\theta_e) = -I_A B_\theta l = I_Z B_r \sin(\theta_e)^2 l + I_\theta B_r \sin(\theta_e) \cos(\theta_e) l \tag{5}$$

Please cite this article in press as: Lu X, et al. Magnetically levitated six degree of freedom rotary table. CIRP Annals - Manufacturing Technology (2015), http://dx.doi.org/10.1016/j.cirp.2015.04.107

Download English Version:

https://daneshyari.com/en/article/10673398

Download Persian Version:

https://daneshyari.com/article/10673398

Daneshyari.com