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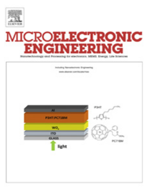

The nanostructured super-oleophobic liquid-floated rotor gyroscope

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ABSTRACT

Liquid-floated rotor gyroscopes can provide high accuracy at small volume and low cost. In rotor gyroscopes, the rotating speed of rotor can significantly affect the detection accuracy. This work presents a new kind of liquid-floated rotor gyroscope using super-oleophobic surface processing, which can improve the performance of driving system. In this work, an unconventional anodization in oxalic-acid electrolyte under high current was employed to fabricate diverse nanostructured alumina surfaces. The top-view SEM image shows the nanowire pyramid structure on the surface of processed sample. Modification of the rough surfaces was achieved by dipping substrates in 0.5 wt% 1H,1H,2H,2H-perfluoro-octadecyltrichlorosilane-in-hexane and then curing then at 120 °C for 1 h. The maximum contact angle (CA) of the aluminum rotor with nanowire pyramid structure was measured to be 156° in average. The oleophobicity of the rotor surface was used to reduce the resistance in the floating liquid. The test results show that, under the normal working state, the rotating speed of super-oleophobic rotor can be reached up to 3200 rpm. While a similar system without the micro-nano composite structure can only reach 2860 rpm. Thus, the nanostructured super-oleophobic alumina surface processing can greatly increase the rotating speed, thereby improving the performance of the gyro system.

1. Introduction

Liquid-floated gyroscopes have the advantages of accurate, stable and impact resistance, however, they usually have large volume and high weight. While scaling down the component, the sensitivity and resolution are also reduced. In order to deal with this problem, the rotating speed of rotor must be increased to maintain adequate Coriolis force [1]. Under the same driving power, a higher rotating speed can be obtained if there is drag reduction treatment on the rotor surface. Therefore, the drag reduction treatment of the rotor surface is one of the important means to improve the performance of liquid-floated rotor gyroscope.

The device presented here is a new kind of liquid-floated rotor gyroscope, which can provide high accuracy at smaller volume and lower cost [2,3]. In this device, the mechanical structure is manufactured by precision machinery processing technology. The rotor in this device is directly driven by stator coils, it is just similar to the structure reported by Shearwood and Damrongsak, even though they may have completely different processes [4,5]. But this work is also different from both theirs, the aluminum alloy rotor of this system is hollow to match the density of floating liquid, and no separate levitation coils are needed. The liquid-floated design of this system can avoid using bearings, signifying that this system can reduce frictional drag while avoiding device damage caused by wear [6]. The whole mechanical system consists of two plexiglass covers, two sets of detecting nodes, two stator rings, a set of driving coils, a stator made of silicon-steel sheets and the hollow aluminum alloy rotor placed in the center of the stator.

In this structure, floating liquid's buoyancy can support the rotor thereby eliminating the mechanical supporting structure [7]. At the same time, the anodized nanoporous alumina nanostructured super-oleophobic surface is employed, which greatly reduced the resistance between the rotor and the floating liquid [8]. Therefore, this design can make the rotor achieve higher speed in the same driving power. In other words, the new design can reduce the power consumption of liquid-floated gyroscope, signifying that the device is more suitable for battery powered applications.

2. System structure and driving mechanism

The mechanical structure of liquid-suspended rotor gyroscope is shown in Fig. 1. It can be seen that the liquid-suspended gyroscope contains the following components: stator, driving coils, stator ring, cover, hollow rotor and capacitance detecting electrodes.

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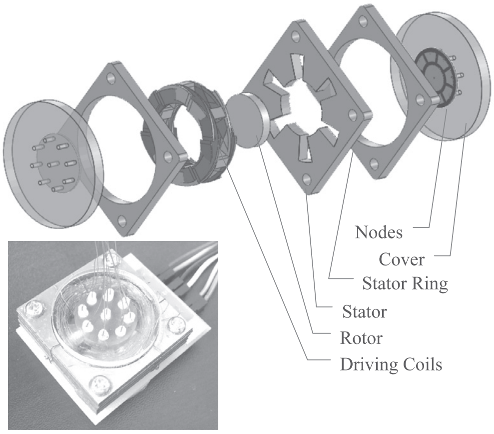

Fig. 1. The structure of liquid-suspended gyroscope.

The stator is composed of a set of stacked silicon steel sheets, it acts as the coil core, and it is also a part of the closed cavity. The closed cavity is filled with a floating liquid to provide buoyancy to the hollow rotor. Alternating driving current flows through the driving coil and produces a rotating magnetic field, which generates eddy currents in the aluminum rotor and drives it.

The floating liquid is 3# industrial white oil, a kind of petroleum product, the main components of which are aromatic hydrocarbons. The density of 3# industrial white oil is around 880 kg/m^3, and the kinematic viscosity ranges from 2.9 to 3.5 mm^2/s at 40 °C. The 3# industrial white oil also has good electrical insulation and chemical stability. It is quite suitable to be used in the liquid-suspended gyroscope.

In the gyroscope driving control system, there is a micro-controller unit (MCU). The MCU can speed-up the rotor smoothly during system startup, and keep the rotor rotating uniformly at the user-set speed. To realize the closed-loop controlling, the rotor's actual rotating speed is obtained by the speed detection circuit.

When the control system is connected to a personal computer via a USB cable, the detailed operating status of the system can also be viewed through the gyroscope control program. The block diagram of driving control system is shown in Fig. 2.

The system uses the differential Sine Pulse Width Modulation (SPWM) driving waveform to keep the driving torque smooth. Assume the stator plane is the x–o–y plane and the direction perpendicular to the stator plane is z axis, the direction is from lower side to upper side. Ignore the magnetic coupling between different phase driving coils, and according to the vector superposition principle, when a single coil is powered up or serval coils are powered up together, the total magnetic moment can be expressed as follows:

$$\begin{aligned} \vec{P}_{single} &= i\vec{S} \\ \vec{P}_{total} &= \sum_{n=0}^{N-1} i_n\vec{S}_n \end{aligned} \tag{1}$$

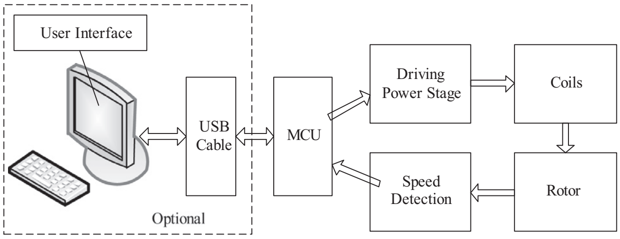

Fig. 2. The block diagram of gyroscope driving system.

In which, i is the driving current, $\vec{S}$ is the cross-sectional area of driving coil, its direction follows the right-hand screw, N is the number of driving coils.

The driving coils' magnetic moment and the rotor's magnetic field generate a torque. In the previously described orthogonal Cartesian coordinate system, the value of magnetic torque can be expressed as:

$$\vec{M} = \vec{P} \times \vec{B} \tag{2}$$

Since the value of magnetic induction intensity $\vec{B}$ is determined by the rotor, here it can be considered as a constant, then the driving torque is only related to the magnetic moment generated by the driving coils. When several driving coils are energized at the same time, the generated magnetic moment is larger, but the power consumption is also higher.

In order to reduce the computational workload, we estimate the driving torque through the finite element analysis method [9]. In the condition where the rotor diameter is 15 mm, the driving coil ampere-turns is 100, the numerical simulation results show that, the average torque of 6 phase 12 coil structure can reach 506.8076 μN * m.

When the system is balanced, the driving torque and drag torque are equal in value, and the output power of a drive system can be described by the following formula:

$$P_{drive} = \vec{M} \cdot \vec{\omega} \tag{3}$$

In which, $\vec{M}$ is total driving torque, and $\vec{\omega}$ is the angular velocity of rotor.

For a particular drive system, the maximum output power is limited. Therefore, the rotating speed of the rotor can be improved by reducing the drag torque [10].

3. Theory of drag reduction

The gyroscope structure can be considered as a variation of hydrodynamic bearing, and the load is very light. According to Spikes' work, if one surface of the bearing is a slipping surface, the frictional resistance can be significantly reduced [11,12].

Fig. 3 shows the simplified sectional view of the gyroscope. Slightly different from Spikes' work, there is no need to entrain fluid into the bearing. In this system, the outer surface of the hollow rotor is processed to be an oleophobic surface, which presents slipping characteristics in the floating liquid – 3# industrial white oil. While the inner surface of the closed cavity is not processed, it is still an ordinary non-slipping surface.

The drag reduction characteristics of oleophobic surface are generally explained using Navier's model [13]. According to the formula of wall slipping, the relationship of boundary slip velocity and shear stress can be described as:

$$u_s = L_s \cdot \left.\frac{\partial u}{\partial y}\right|_{wall} \tag{4}$$

In which, u_s is the slip velocity, L_s is the slip length while $\left.\frac{\partial u}{\partial y}\right|_{wall}$ is the surface shear strain rate. Slipping wall reduces the shear forces between the wall surface and the fluid, which reduces the frictional

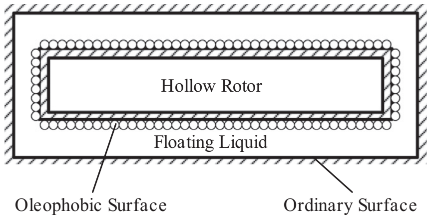

Fig. 3. The simplified sectional view of the gyroscope.