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An anti-saturation steering law for Three Dimensional Magnetically Suspended Wheel cluster with angle constraint

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ABSTRACT

Three Dimensional Magnetically Suspended Wheel (3-DMSW) is a new kind of inertia actuator for spacecraft attitude control, which can provide a 3 degrees of freedom torque. On account of the constraint characteristics of 3-DMSW such as a small deflection saturation angle of rotor shaft and the saturation of rotor's variable rotational speed, an anti-saturation steering law based on weighted pseudo inverse is proposed for 3-DMSW cluster. A new weight adjustment method is proposed to adjust the weights of shaft deflections dynamically. A specially designed exponential function with current deflection angle and angular velocity information on the exponent position is adopted as the evaluation criterion of current torque output ability of shaft deflection. Thus the torque command can be distributed dynamically with no angle saturation. The weight adjustment method is demonstrated theoretically and the effectiveness of the anti-saturation steering law is validated by conducting several numerical simulations of attitude agile maneuver. Comparing with the 3-DMSW cluster and flywheel cluster using the traditional steering law, the results show that the 3-DMSW cluster using the proposed method makes the process of agile maneuver more rapid and accurate and the saturation angles of 3-DMSW cluster will not be reached.

1. Introduction

With the miniaturization trend of satellites, more micro-satellites are applied to earth observation such as SkySat-1 (America) [1] and SuperView-1 (China) [2], and they make it possible for commercial space companies to fully expand the business in the space market of the world. Among those different kinds of micro-satellites, earth observation micro-satellites are widely developed because of their practical value. Due to the characteristics of small volume and light weight, earth observation micro-satellites need small and effective attitude control systems to meet the requirements of imaging system payload. The attitude actuator which is of superior performance should be capable of providing instantaneous large control torque for attitude agile maneuver and high-precision control torque for attitude stabilization. It is well-known that Flywheel (FW) is widely used for attitude stabilization. Although FW can also be applied to agile maneuver independently [3,4], it seems inefficient because its output torque is usually relatively small. It will reach saturation frequently when attitude maneuver requires a long-term large torque and many other types of actuators are applied to desaturate the rotational speed [5–7]. In order to meet the requirement of agile maneuver, Control Moment Gyro (CMG) is applied to attitude control. CMG is a kind of attitude actuator which can produce a large torque output with a fairly small torque input, by using a moment wheel with a fixed high rotational speed and gimbals which can adjust its direction of space. Single Gimbal Control Moment Gyro (SGCMG) is widely used in large spacecrafts because of the large torque output, fast response and small mechanical complexity [8,9]. Meanwhile, Double Gimbal Control Moment Gyro (DGCMG) is applied to attitude control because of the easy description of singularity and multi-directional torque output [10,11]. Despite the advantages of different kinds of CMGs mentioned above, a high precision control torque output is hard to guarantee and the problem of singularity always exists [12]. To combine the advantages of FW and CMG, they are integrated in one attitude control system to realize a high-precision attitude stability using FWs and a large torque output using CMGs [13–16]. However, it makes the attitude control system heavier and more complex which is not suitable for micro-satellites. Ford and Hall first came up with the concept of Variable Speed Control Moment Gyro (VSCMG), which combines the large torque output feature of CMG and the high-precision torque output feature of FW in one actuator [17]. Double-Gimbal VSCMG (DGVSCMG) is a kind of VSCMG with 2-DOF gimbals, which is capable of generating control torque output in three directions [18,19].

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Nomenclature

$\mathbf{A_i}$	transfer matrix from the *i*th 3-DMSW body coordinate frame to spacecraft body frame
$\mathbf{B}^+$	pseudo inverse of matrix **B**
$\mathbf{B}^\#$	weighted pseudo inverse of matrix **B**
G_b	3-DMSW rotor body coordinate frame
G_f	3-DMSW body coordinate frame
$\mathbf{h}_g$	total angular momentum of the 3-DMSW cluster expressed in spacecraft body frame, kg·m^2/s
$\mathbf{h}_{gi}$	angular momentum of the *i*th 3-DMSW expressed in spacecraft body frame, kg·m^2/s
I	axial moment of inertia of the rotor, kg·m^2
$K_{\alpha i}$, K_{β_i}	unsaturation degree of the *i*th rotor shaft deflection angle
q	attitude quaternion of spacecraft
$\mathbf{R}$	attitude actuator instruction vector
$\mathbf{T}_c$	torque command from attitude controller, N·m
$\mathbf{T}_o$	actual torque output for attitude control, N·m
W_0	coefficient of the weight of *i*th shaft deflection angle
$W_{\alpha i}$, W_{β_i}, $W_{\Omega i}$	weight of the *i*th shaft deflection angle and rotational speed
α_0, β_0	initial deflection angle of rotor shaft, rad
α_i, β_i	deflection angle of the *i*th 3-DMSW rotor shaft, rad
$\dot{\alpha}_i$, $\dot{\beta}_i$	time derivative of the *i*th 3-DMSW rotor shaft deflection angle, rad/s
$\alpha_{\max}$, $\beta_{\max}$	deflection saturation angle of rotor shaft, rad
ε	an adjustable parameter of the weight
Ω_0	initial rotation speed of 3-DMSW rotor, rad/s
Ω_i	rotation speed of the *i*th rotor, rad/s
ω	attitude angular velocity of spacecraft, rad/s
$\omega_{\alpha i}$, ω_{β_i}	deflection angular velocity of the *i*th rotor shaft, rad/s

VSCMG, including DGVSCMG, can work in CMG mode when a large torque is needed, and FW mode when a high-precision torque is needed or CMG mode is approaching singularity [20,21]. Although VSCMG shows many advantages in satellite attitude control, there are many inherent drawbacks such as friction and output disturbance like other inertial actuators. As is known widely, the rotor of FW, CMG or VSCMG is supported by mechanical bearings which have friction of certain value. With the extension of working hours, the performance of bearings will degrade and the friction in the gimbals will increase which bring about output disturbance [22]. It troubled many spacecrafts in the past few decades.

Due to the advantages of non-contact, non-friction, high precision and long life, Active Magnetic Bearing (AMB) is applied to inertial actuators. With the active vibration control of AMB, the rotor can rotate stably and its vibration can be reduced to infinitely small [23,24]. Three Dimensional Magnetically Suspended Wheel (3-DMSW) is a new kind of inertia attitude actuator based on AMB [25–27]. 3-DMSW has many merits: (1) By applying suitable control methods, 3-DMSW can stably output high-precision radial control torque in 2 degrees of freedom by deflecting the rotor shaft and axial control torque by accelerating and decelerating the rotor [26,27]. (2) 3-DMSW has virtual gimbals and doesn't need real gimbals owing to the application of AMB. As a result, the control of rotor shaft deflection and the control of rotor suspending are highly integrated. (3) 3-DMSW can output a fast response control torque with a high band-width. (4) This innovative actuator can measure the angular rates of spacecraft in 2 degrees of freedom which makes it a good attitude sensor simultaneously [25]. All merits mentioned above create a good application prospect for 3-DMSW in the near future.

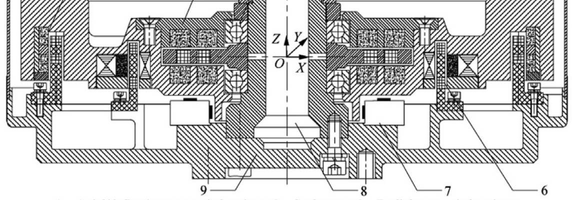
In order to apply 3-DMSW cluster to the attitude control system, a steering law is needed to distribute the torque command properly. The traditional pseudo inverse steering law is proposed to meet the requirement of a minimum power consumption [13]. However, it is not suitable for 3-DMSW because the deflection angle of 3-DMSW rotor shaft is limited [28]. Some steering laws are proposed to avoid singularity at the cost of allowing torque output error. Singularity robust inverse steering law and singular direction avoidance steering law are representative among them [10,29–31]. All of them are proposed to solve the singularity problem of CMG cluster while this problem is not involved in 3-DMSW. Weighted pseudo inverse steering law is successfully applied to VSCMG cluster to avoid singularity. In this kind of steering law, the weight of FW mode can be adjusted dynamically according to the current singularity indicator of the gimbals [20,21,32]. However, it can not be applied to 3-DMSW directly because the problem of small deflection saturation angle of 3-DMSW is not involved in the steering law for VSCMG cluster. So in this paper, an anti-saturation steering law based on weighted pseudo inverse method is proposed. In this steering law, the weight of CMG mode is constructed in a special form of an exponential function in which the unsaturation degree of rotor deflection angle is included. By using this weight adjustment method, the weight of CMG mode can vary dynamically according to the current deflection angle and deflection angular velocity. As a result, the deflection angle of rotor shaft will not reach saturation. This innovative work makes it possible to apply 3-DMSW cluster to the real attitude control system of earth observation micro-satellites.

The remainder of the paper is briefly outlined as follows. In Sec.2, the coordinate frame definition of 3-DMSW is given and the output torque produced by 3-DMSW is presented clearly. In Sec.3, the new anti-saturation weighted pseudo inverse steering law is proposed and the specific formulas of the weight adjustment method are presented to meet the angle constraint of 3-DMSW. In Sec.4, numerical simulations are performed to validate the effectiveness of the anti-saturation steering law which contains a new weight adjustment method specially designed for 3-DMSW cluster, by comparing with the traditional pseudo inverse steering law and the case using flywheels only. Finally, the conclusions are drawn in Sec.5.

2. Basic formulation of 3-DMSW cluster

3-DMSW is mainly composed of axial/deflection magnetic bearings, radial magnetic bearings, displacement sensor, motor, rotor, shaft, base and seal cover if classified by functions which is shown in Fig. 1 [25]. For the convenience of studying the dynamic characteristics, it can be simplified to a machine having a rotor suspended by magnetic bearings as shown in Fig. 2. The non-contact displacement sensor measures the translational motion and the rotational motion of rotor. In order to describe the angular momentum of the 3-DMSW, the coordinate frames shown in Fig. 3 are defined as follows.

1) Body coordinate frame of 3-DMSW G_f ($Ox_f y_f z_f$): The G_f frame is the orientation of the entire 3-DMSW. The origin is located at the mass center of the rotor. The z_f axis lies along the initial symmetrical axis



1—Axial/deflection magnetic bearings; 2—Seal cover; 3—Radial magnetic bearings; 4—Touch down bearings; 5—Rotor; 6—Motor; 7—Displacement sensor; 8—Shaft; 9—Base

Fig. 1. Structure diagram of 3-DMSW.