A REVIEW PAPER: THE DYNAMICS, KINEMATICS, DESIGN and CONTROL OF SATELLITE SIMULATORS WITH SPHERICAL AIR BEARING

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A REVIEW PAPER: THE DYNAMICS, KINEMATICS, DESIGN and CONTROL OF SATELLITE SIMULATORS WITH SPHERICAL AIR BEARING

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Abstract Because of the high cost and the long-life requirements of the satellites, they are subjected to various tests on ground before launching. So that all the units assembled to the satellite are tested and checked if they are working properly. The space conditions like near zero friction must be satisfied in the laboratory so that the satellite's orientation controls may be studied. For this reason, different types of simulators are utilized to test these space devices. Spherical air bearing simulators which are often used for checking and validating the attitude control systems are used to simulate only the frictionless space environment where different types of external disturbances are also available. Attitude control systems use different type of actuators that change the orientation of the satellite with the help of the information received from the sensors. In this paper, simulators with spherical air bearing used for testing the attitude control systems available in the literature are examined. Many challenges are encountered that may adversely affect the working conditions during the process from design to manufacturing of the spherical air bearings. Moreover, it is observed that, modeling of the attitude control systems together with the disturbances are also be taken into consideration. So, the required studies from numerical simulations to the ground tests are carefully planned to check the behavior of the attitude control systems. Aim of this study is to make a survey on the dynamic and kinematic analysis, attitude control methods and disturbances on the different types of ground test simulators and various friction models present in the literature. The studies that have contributed to the literature and based on the attitude control systems on simulators, especially in the last 15 years, are examined.

Keywords: *Spherical Air Bearing Simulator, Satellite Attitude Control Systems, Dynamic and Kinematic Equations of Satellite Attitude, Design of Satellite Simulator*

I. INTRODUCTION

Space technology competition between developed countries has increased rapidly with the first satellite launched into space in 1957. Many countries have started to contribute more to technology by launching their artificial satellites to various orbits with the technology developed in the early 2000s. Satellites are one of the strategic technologies for countries due to their duties. Communication satellites, meteorology satellites, navigation satellites, surveillance satellites and space stations are examples of various satellite types. Because satellites have sensitive technologies, some of their parts are very expensive to produce. Hardware and software tests of satellites are carried out on the earth to minimize the errors of their systems before the satellites are launched. Many simulators have been developed to test satellites from the past to the present. One of the most common method used in simulators is air bearings. Air bearings used to simulate a frictionless environment such as in space. Planar system, rotational system and combined system of air bearings are reviewed [1]. In this paper, spherical type of air bearing simulators is investigated. Orifices placed on several region of the spherical air bearing surface are supplied with clean and dry compressed air from the compressor. The air from the orifices creates a thin air film between satellite body and air bearing. Thus, an almost frictionless environment is simulated. The major purpose of simulators is to test attitude control systems (ACS) of satellites [2]. ACS is a model that includes dynamic and kinematic equations of satellites, mathematical models of hardware and external disturbances in space. ACS changes the orientation of the satellite's solar panels to charge its batteries for maximum efficient or to send and receive information to the ground with the aid of using sensor data.

The space environment can be simulated with reducing the undesirable torques by coinciding with the center of rotation of the air bearing and the center of gravity of the satellite body. Some designs need to mass-balance system for reducing offset between the center of rotation of the air bearing and the center of gravity of the satellite body [3–12].

Orientation of simulator is controlled by actuators which can be classified as cold gas thruster, magnetorquer and reaction wheels [13]. Magnetorquers and reaction wheels are generally used in simulator. An important actuator used in spherical air bearing simulators and satellites is reaction wheels. The reaction wheels are driven by a motor change the orientation of the satellite by generating angular momentum. Bearing is needed between reaction wheels and electric motor because of high speed of rotation of mass. Bearing lubrication is an issue that can cause the ACS to not work effectively [14]. Vibration may occur due to lubrication problem and adversely affect the system components [15].

The kinematic and dynamic equations of simulators are mathematical expressions that must be derived to control the system. Dynamics equations of satellite for control consist of angular momentum, Euler's torque equation, disturbance torques, mathematical model of electrical motor, inertia matrices of satellite components, and frictional models of bearing of reaction wheels. Kinematics, in orientation control describe the angular motion of satellite. Quaternion and Euler rotational angles are two major approaches to model kinematic analysis of satellites [13,16–18].

A system whose dynamics and kinematics are well modeled is convenient to be controlled. The general working principle of the control mechanism is that the actuators ensure the desired torque in the body-fixed frame of platform with the help of the feedback it receives from the sensors and perform this process until the platform reaches the desired orientation.

II. Spherical Air Bearing Simulator

Spherical air bearings are one of the most common simulators used to test and verify control of satellite attitude. They are known in the literature as aero-static bearings [19]. Spherical air bearings consist of two main parts which are inner hemi-sphere and outer hemi-sphere. Inner hemi-sphere (top) and outer hemi-sphere (bottom) are shown in Fig. 2. While the inner hemi-sphere has locomotion in the x-y-z axes, the outer hemi-sphere is stator. The spacecraft to be tested is mounted on the inner hemi-sphere. There are no ACS components and the platform design shown in the Fig. 1.a is mounted on the inner sphere. In Fig. 1.b, the simulator with all system components is shown.

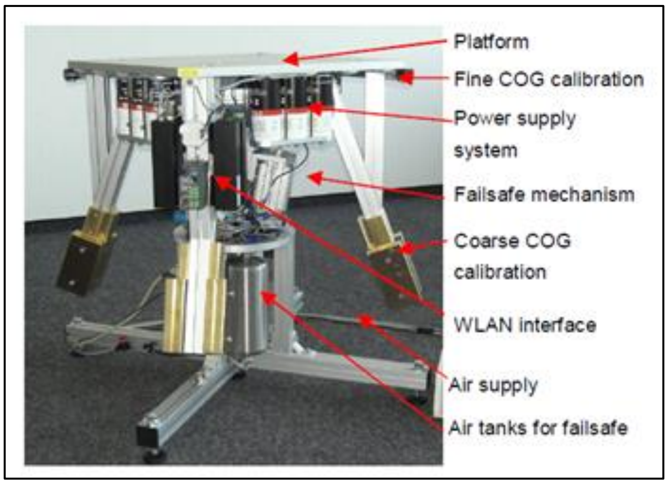

Fig. 1.a. Spherical air bearing platform [20]

Fig. 1.b. Simulator with ACS components and spherical air bearing [21]

ACS verification can be tested because the inner sphere has the ability of rotating about three principal axes like in the space. Whereas the inner sphere has the ability to rotate 360° around the yaw, roll and pitch turns are limited due to mechanical conditions [5,6,20,22]. There are orifices on the outer hemi-sphere surface to supply the inner hemi-sphere. These orifices should be placed symmetrically on the outer hemi-sphere surface to avoid undesirable gravitational torque [23,24]. Orifice can be placed on central of the outer hemi-sphere surface with a single air hole, or orifices can be placed symmetrically on the surface with 5-10 holes. Orifices, air inlet and thin film are shown in Fig. 2. New types of porous air bearing are also available in the market with the developing technologies in the field of metallurgy [25]. Porous air bearing has lots of micropores on the stator structure. The air coming from the compressor is transmitted to the air bearing through these holes. Thus, the air bearing, which is much more stable and minimized disturbances, has been presented to the use of researchers. The outer hemi-sphere is supplied with clean and compressed air from the compressor. Undesired gravitational torques on the simulator are eliminated by coinciding with the center of gravity of the moving body and the center of rotation of the air bearing [26]. Thus, it is possible to simulate the space environment almost frictionlessly.

The thin film is created between the moving structure and the stator to provide an almost frictionless environment. However, the compressed air used to create the thin film occurs the undesired friction torque in the spherical bearing. Inner and outer sphere must be machined precisely in order to supply smooth air flow that is passing over them. Surface quality is usually 0.4 µm. Inner and outer spheres are generally machined from 6061 Aluminum alloy material. Because this material is easy to form and suitable for hard coating [21,27].

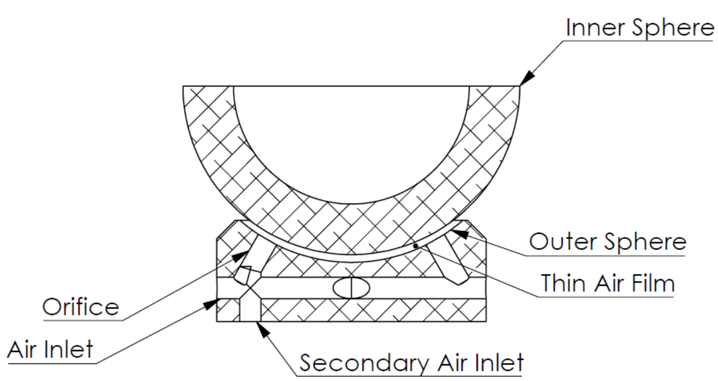

Fig. 2. Section of spherical air bearing

Spherical air bearing simulators generally provide 3-axis rotational motion, but 5-axis degree of freedom simulators have been studied. While the inner hemi-sphere is stationary connected to the ground in 3-axis simulators, pad type air bearing is used in addition to provide the ability to move along x-y planes on the ground. 5-DOF simulators have 2-DOF for translational motion with the help of ped type air-bearing and 3-DOF rotational motion with spherical air bearing. These combinations of motion make the simulator behave like in deep space, so it is referred to as 5-DOF [7,22,28–31]. The working mechanism of 5 DOF simulators is shown in Fig. 3.

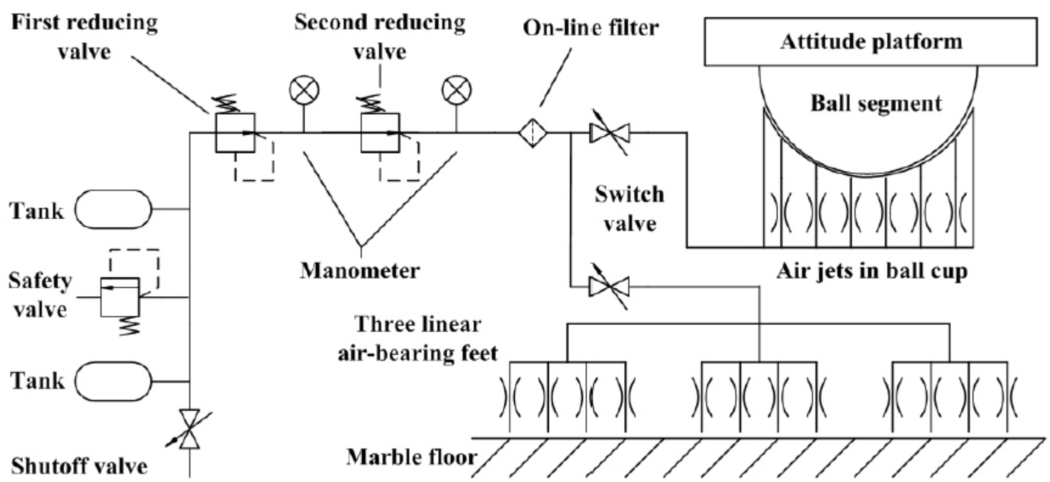

Fig. 3. The working mechanism of 5 DOF simulators [22]

There are also gimbal type simulators that test the ACS without using an air bearing. The biggest disadvantage of these simulators is the friction that occurs in the gimbal connections. Angular momentum of actuators is wasted because of the frictions in the gimbal bearings. Therefore, the mathematical friction models of the simulator should be carefully obtained while designing the controller of the gimbal [32].

Some researchers have developed spherical air bearing simulators to perform verification processes of ACS created for both educational and research purposes [33]. A simulator with automatic mass balance system has been developed at the University of Utah [34,35]. At the Air Force Institute of Technology, studies have been carried out on an attitude model with reaction wheel and fixed thruster actuators [36] and a satellite dynamic and control simulator [37]. An air bearing simulator which only use reaction wheels as actuators have been developed at MIT [38]. At the Virginia Polytechnic Institute and State University, a spherical air bearing simulator with control moment gyro and reaction wheels was studied [39], then hardware upgrading continued on the test setup [40]. At Naval Postgraduate School in 2009, works were performed on the spherical air bearing simulator [4] and the spherical air bearing with Helmholtz cage to provide magnetic field [41]. Spherical air bearing satellite simulators were developed in the Universidad Nacional Autonoma de Mexico in 2005 [42] and 2007 [43]. At Yonsei University, a spherical air bearing with only reaction wheel actuators has been enhanced [44].

Different types of disturbances also occur on spherical air bearing. Disturbances such as static-dynamic unbalance, anisolasticity, material instability, stress-temperature-humidity-evaporation and gravity gradients are occurred on the inner hemi-sphere shown in Fig. 2. There may be disturbances such as air flow in the test room, vibration in the ground, which originate from the environment where the test setup is located. In addition, hardware-induced disturbances such as battery discharge, loose fits in bearing of reaction wheel and electrical wires can also affect the simulator [21].

A. Components of Spherical Air Bearing Simulator

Sensors are one of the significant hardware as feedback control is used. Sensors are used to verify the ACS in both simulators and satellites. The star sensor that can detect by tracking the stars with the help of the images stored in its memory, the sun sensor to detect the direction of the sun, the three-axis magnetometer for the magnetic field measurement and the inertial measurement unit (IMU) sensor that measures the speed and acceleration of the system by using the position change are the types of sensors that can be found in simulators [6,7,10,22,45–56].

Satellites need actuators such as cold-gas thrusters, magnetorquers and reaction wheels to perform their motion in the orbit. Cold-gas thrusters systems contain compressed gas in the tank and valves and piping systems for the transmission of these gases [57]. Since have low-cost, low energy consumption and reliable systems, they may be preferred for getting the satellite into orbit as planned [58–61]. Magnetorquers type of actuators provide magnetic torque for attitude control of satellite with the help of using electrical current that is passing through their coils [62,63]. Reaction wheels placed on the principal axes of the satellite generate angular momentum due to the change in its rotational motion and are used for attitude control according to the law of conservation of angular momentum [17,64]. At least four reaction wheels are generally used in case one of the reaction wheels breaks down for ACS. Therefore, power consumption for torque generation is high and reaction wheels can be added to satellite systems in different configurations [65]. Studies have been conducted to reduce the energy consumption of different systems with reaction wheels [66]. Works have also been done on the dimensions of the reaction wheels and the reduction of energy consumption by improving ACS [67–69]. The angular momentum generated by the reaction wheels is limited due to the motor characteristics. Because of this limit, the reaction wheel cannot change the orientation of the satellite and a saturation event may occur. Momentum dumping should be applied to get rid of the reaction wheel from saturation [70]. As an alternative to reaction wheels, a control moment gyroscope (CMG) is used, and their first studies have started at SKYLAB [71]. There is a 3-axes control study that the tilt mechanism controls two axes by generating angular momentum vectors and the change of wheel speed provides control of third axis [72].

On-board computers are needed to process the data received from the sensors and to drive the actuators. Besides, motor drivers are needed to control the motors. Therefore, control mechanisms including ACS and motor control are used in air bearing simulators [5,22,46,52,72,73]. Various batteries are used to power the system. In order to observe the simulator's behavior, wireless connection components are also used that enable it to connect with the remote desktop [22].

B. Theory of Spherical Air Bearings

It is possible to calculate the pressure distribution of the air coming from the compressor on spherical air bearing surface and numerical calculation of the load capacity [74]. The parameters used in the calculation are shown in Fig. 4. Where h is gap height between sphere and socket, O is orifice, pl is gas plenum, R is radius of bearing sphere, ΔR is concentric radius increment between the bearing sphere and the socket, $R + \Delta R$ is socket radius, R_0 is recess radius, θ is angle between the orifice center line and any point on the bearing sphere with respect to the socket center, θ_0 is angle between the orifice center line and the edge of the recess, θ_1 is angle between the orifice center line and the rim of the socket. Pressure in any point of the spherical air bearing can be obtained by using the Navier-Stokes equation as given in (1) [74].

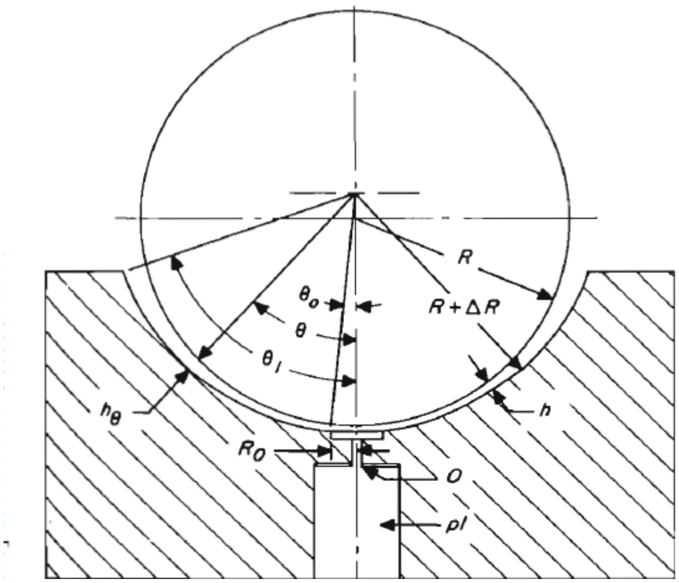

Fig. 4. Section of simplified spherical air bearing with single orifice [74].

$$p = \left\{ {p_1}^2 + {p_0}^2 \left[1 - \left(\frac{p_1}{p_0} \right)^2 \right] \frac{\varphi(\varepsilon,\theta)}{\varphi(\varepsilon,\theta_0)} \right\}^{1/2} \tag{1}$$

Where p is pressure, p_0 is pressure in recess, p_1 is exit pressure, and

$$\varphi(\varepsilon,\theta) = \frac{\varepsilon^2(1-\varepsilon^2)\cos\theta}{(1-\varepsilon\ \cos\theta)^2}\left[3-\varepsilon^2-\frac{\varepsilon}{2}\cos\theta\,(5-\varepsilon^2)\right] - \varepsilon(\varepsilon^2+3)\ln\left(\frac{1-\varepsilon\cos\theta}{\sin\theta}\right) + (3\varepsilon^2+1)\ln\tan{}^{\theta}\!/_{2}$$

Similarly, load capacity of spherical air bed can be obtained as in (2) [74].

$$W = \pi R^2 \left\{ \int_{\theta_0}^{\theta_1} \left[{p_1}^2 + {p_0}^2 \left[1 - \left(\frac{p_1}{p_0} \right)^2 \right] \frac{\varphi(\varepsilon,\theta)}{\varphi(\varepsilon,\theta_0)} \right]^{1/2} \times \sin\theta\cos\theta\, d\theta + p_0 \left(\frac{R_0}{R} \right)^2 - p_1 \right\} \tag{2}$$

III. Dynamic and Kinematic Equations

In order to design a good controller on air bearing simulator, rigid body mechanics and dynamics must be studied. There are guiding books on these issues [13,16–18]. Euler's moment equations are shown in (3) [75]. Assuming that subscript x, y and z are principal axis of inertia of body frame.

$$M_x = I_x\dot{\omega}_x + \omega_y\omega_z(I_z - I_y) \tag{3a}$$
$$M_y = I_y\dot{\omega}_y + \omega_x\omega_z(I_x - I_z) \tag{3b}$$
$$M_z = I_z\dot{\omega}_z + \omega_x\omega_y(I_y - I_x) \tag{3c}$$

Where I is moment of inertia, $\dot{\omega}$ is angular acceleration of body on principal axis, and ω is angular speed of body on principal axis.

The result in (4) is obtained by deriving Euler's moment equation and Newton's 3rd Law together [76,77]. For the reasons explained in previous chapters, (4) was obtained by using the reaction wheel and magnetorquer as the actuators.

$$\boldsymbol{I} \cdot \dot{\boldsymbol{\omega}}_{IE/_B} = \boldsymbol{T_d} + \boldsymbol{T_m} - \boldsymbol{\omega}_{IE/_B} \times \left(\boldsymbol{I} \cdot \boldsymbol{\omega}_{IE/_B} + \boldsymbol{h_w}\right) - \boldsymbol{T_w} \tag{4}$$

Where I is diagonal inertia matrix of satellite, $\dot{\boldsymbol{\omega}}$ is angular acceleration vector of satellite relative to inertial frame, $\boldsymbol{T_d}$ is external disturbance torques vector, $\boldsymbol{T_m}$ is magnetic torque vector of magnetorquers, $\boldsymbol{\omega}$ is angular speed vector of satellite relative to inertial frame, $\boldsymbol{h_w}$ is angular momentum vector of reaction wheel, and $\boldsymbol{T_w}$ is torques vector of reaction wheel.

As seen in (4), the satellite's net torque matrix can be defined as $\boldsymbol{T} = \boldsymbol{T_d} + \boldsymbol{T_m} - \boldsymbol{T_w}$. Therefore, we can write the dynamic equation of the satellite as seen in (5).

$$\dot{\omega}_x = \frac{T_x - (I_y - I_z)\omega_z\omega_y + h_{wz}\omega_y - h_{wy}\omega_z}{I_x} \tag{5a}$$

$$\dot{\omega}_y = \frac{T_y - (I_z - I_x)\omega_x\omega_z + h_{wx}\omega_z - h_{wz}\omega_x}{I_y} \tag{5b}$$

$$\dot{\omega}_z = \frac{T_z - (I_x - I_y)\omega_y\omega_x + h_{wy}\omega_x - h_{wx}\omega_y}{I_z} \tag{5c}$$

In satellite kinematics, rotational sequences can be defined by using rotational matrix with Euler angles or Quaternion method. Firstly, directional cosine matrix (rotational matrix) is derived in (6) where ψ, θ, and φ Euler angles respectively yaw, pitch and roll [75].

$$[A_{321}] = [A_{\psi\theta\varphi}] = \begin{bmatrix} c\theta c\psi & c\theta s\psi & -s\theta \\ -c\varphi s\psi + s\varphi s\theta c\psi & c\varphi c\psi + s\varphi s\theta s\psi & s\varphi c\theta \\ s\varphi s\psi + c\varphi s\theta c\psi & -s\varphi c\psi + c\varphi s\theta s\psi & c\varphi c\theta \end{bmatrix} \tag{6}$$

Although Quaternion Method is complex, it is generally using in attitude representation. Because rotational matrix with Euler angles has singularity [78] for some conditions that is known as gimbal-lock [79] in the literature. Kinematic differential matrix equation can be obtained by using Quaternion Method given in (7). Therefore, dynamic equations can be calculated with the help of obtaining desired angular rate of velocity from Quaternion Method.

$$\begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \\ \dot{q}_3 \\ \dot{q}_4 \end{bmatrix} = \frac{1}{2} \begin{bmatrix} q_4 & -q_3 & q_2 & q_1 \\ q_3 & q_4 & -q_1 & q_2 \\ -q_2 & q_1 & q_4 & q_3 \\ -q_1 & -q_2 & -q_3 & q_4 \end{bmatrix} \begin{bmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \\ 0 \end{bmatrix} = \frac{1}{2} \begin{bmatrix} 0 & \omega_3 & -\omega_2 & \omega_1 \\ -\omega_3 & 0 & \omega_1 & \omega_2 \\ \omega_2 & -\omega_1 & 0 & \omega_3 \\ -\omega_1 & -\omega_2 & -\omega_3 & 0 \end{bmatrix} \begin{bmatrix} q_1 \\ q_2 \\ q_3 \\ q_4 \end{bmatrix} \tag{7}$$

IV. Friction Models

Friction is a phenomenon that exists in all mechanical systems and has a high effect on performance. In order to model a mechanical system correctly, the effect of friction on the system must be investigated and compensation techniques must be known. There are static and dynamic model methods used for modeling friction [80].

Although an almost frictionless environment is created with the thin film between the air bearing and the spacecraft model, friction occurs in the reaction wheel bearing due to mechanical components. Modeling of friction in bearings used in reaction wheels has been investigated in many works and included in the simulation. Coulomb friction model, viscous friction model, Stribeck's model or Dahl model can be used in the friction modeling of the reaction wheel, which is generally used with ball bearings [72,81–88]. These models are generally developed with the help of parameters taken from the experimental setup. There are also ball bearing friction estimation models for systems with no experimental setup and simulation studies [89].

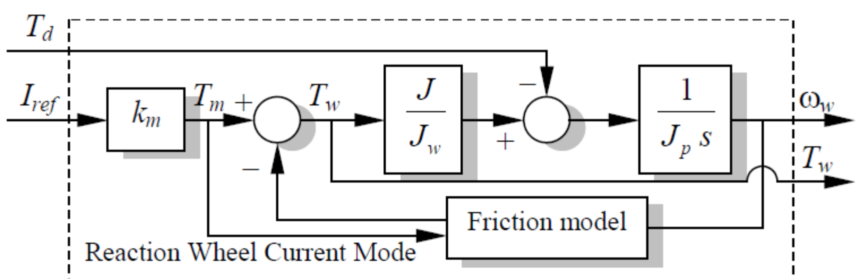

Fig. 5. Current mode control with reaction wheel [86,90].

Driving of reaction wheels can be performed with techniques such as current control mode, speed control mode and torque control mode according to the design of ACS. In the control of the reaction wheel with the current mode, it is necessary to successfully transmit the current to the motor. A current control and friction model block diagram is given in Fig. 5. In speed control, a feedback control is used with the help of the sensors in the motor to reduce the error and the error is tried to be minimized. In other words, errors caused by friction in the reaction wheel are eliminated with the data received from the motor's sensor. However, current control is also used, as speed control is electronically complex and there are delays. Dynamic Model Compensator is used to reduce the error of ACS using the current control method [81,86]. In addition, current control method and speed control method were compared [54]. It is also important to compensate for friction in models that use an alternative instead of an air bearing [32].

V. Control Methods

There are many methods to control the satellite's orientation dynamics. Each method has its own advantages and disadvantages. PID (Proportional–Integral–Derivative), LQR (Linear–Quadratic Regulator), Fuzzy Logic, Nonlinear Lyapunov Control, SMC (Sliding Mode Control) and H-infinity methods are frequently used in ACS design. ACS designs vary according to the objectives of the studies. While a controller is designed to reduce energy consumption in some studies, a controller is designed for the best trajectory control in others. Similarly, it has other purposes such as minimizing the effect of disturbances on the system, generating the desired angular momentum of the reaction wheels as soon as possible, and minimizing the vibration caused by the hardware.

While the satellite is moving in its orbit, the control system must control its required orientation, at the same time, it must also be stable. Lyapunov control method is used in ACS designs due to the fact that satellite dynamic equations are non-linear. The purpose of Lyapunov based controllers is to minimize the error of the non-linear Lyapunov function [39,91–100].

The purpose of PID controllers is to correct the error between the reference value and the actual value. PID controllers are simpler to apply to studies as they are not operationally complex. If stability is not important for applications, it is possible to design a robust system with PID. The disadvantage of the PID controller is that the plant must be well defined. In some applications, the controller is improved by applying an additional control method to the PID controller. PD applications in ACS designs have also been presented to the literature [26,51,52,54,72,101–105].

The SMC method allows for a robust design despite uncertainties. However, this may make the actuators reach saturation more easily. A low-pass filter or integral actuation can be used to overcome this [106–111].

The LQR optimizes the orientation performance by using the torque generated by the actuators effectively, minimizing the error in the yaw-pitch-roll axes. LQR is a type of controller developed for linear systems. Since the satellite's dynamic equation is non-linear, it must be linearized using various methods (e.g., MPC). Moreover, Riccatti equation can solve gains of LQR [112]. The requirement for mathematical equations can be remarked as the disadvantage of this method [102,103,110,113–115].

There are sets with various control rule base and membership functions in the Fuzzy Logic Controller. Researcher knowledge and experience are required for these pre-created sets for control. Fuzzy Logic Control is useful because attitude dynamic equations are non-linear, and the mathematical model is complex. Hybrid studies have also been designed using the Fuzzy Logic Controller with another control method [51,55,116–120].

H-Infinity control providing both robust performance and stabilization, has complex mathematical equations. However, a stable controller is designed by solving its mathematical equations. H-Infinity control is useful when system has disturbances, actuator noises, aggressive motion (that cause saturation for actuators) and uncertainties [77,121–125].

It should be noted that almost all the studies in this section include an acceptable controller design. References should be carefully examined for the control method aimed to be studied. Only simulation results are investigated in some studies, and the results of both simulation and ACS designs on the experimental system is examined in some studies.

VI. Conclusion

Spherical air bearing simulators, which have a key role in testing and verifying ACS, are important ground test platforms. In this paper, many issues from the design to the control of spherical air bearing simulators used for testing ACS are reviewed in detail. Each of the subjects presented under four main headings: the introduction to the simulators, the dynamic and kinematic equations of the simulators, the friction models needed in the simulators, and the control of the simulators.

Spherical air bearing simulators consist of two main parts and these systems are used to best model the space environment. In addition to the mechanical parts, these simulators have various components such as sensors and actuators for modeling the satellite as in the space. In order to ensure the proper testing of the spherical air bearing, its theory must be well known before design. Moreover, dynamic and kinematic equations of spacecraft must also be known to test ACS in the simulators. Friction should also be added to the model for adding the reaction wheel bearings frictions in satellites. For the best attitude control, designing a robust and stable controller is important because of the external disturbances available in the space. Each one of these studies require expertise in the fields of materials, machinery, electrical-electronics and aviation. In this paper, important sources that have guided to this study and the current papers available in the literature for spherical air bearing simulators are examined. By this way, many important aspects needed for the design and control of the spherical air bearing simulators are searched and included in the paper.

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