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TEST BENCH for NANOSATELLITE ATTITUDE DETERMINATION and CONTROL SYSTEM GROUND TESTS

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ABSTRACT

This paper presents recent progress in designing a three degree-of-freedom (3DoF) test bench for CubeSats. Such test benches offer many prospects for ground testing of CubeSats and their subsystems, and first of all Attitude Determination and Control System (ADCS). The difficulty of ground satellite tests is to create conditions simulating space environment with given accuracy while limiting the effects occurred on ground facilities. For nanosatellites, the accuracy of ground tests has to be very high due to reduced capability of actuators and high sensitivity to external forces. The main challenge of this research is to find a design solution allowing a nanosatellite to rotate freely around three axes with minimum disturbances from gravity and friction forces. We propose two ways to deal with these difficulties and avoid any limit in rotational motion. The first one is the active compensation of parasitic moments acting on CubeSat during the tests. The second one consists of an air bearing sphere structure providing a contactless suspension for all possible angular position of the CubeSat. In prospect, both approaches can be used together in one test bench to improve its efficiency. General aspects of the design and initial confirmation of system efficiency are presented.

1 INTRODUCTION

Since CubeSat-class of nanosatellites was started in 1999 it became widespread and a significant trend. Due to low cost and a number of off-the-shelf components, the development of such satellites became common, especially among school and universities. Building a CubeSat takes less time than needed to realize a nanosatellite from scratch. Hence, developers can focus on scientific payload integration and students can lead the project through all stages during their universities years. Despite small sizes and standardized construction, CubeSats are useful to solve wide range of tasks in different fields of space exploration - communication, earth and near-earth space observation, scientific missions.

Passive ADCS can be enough for CubeSats that do not need accurate positioning on its orbit, but the more complex missions require precise ADCS. Traditional ADCS, designed for full-scale satellites, cannot be used for nanosatellite needs due to their sizes, price or power consumption. CubeSat developers have to build ADCS using standard hardware or design their own system. ADCS is a sophisticated system which needs validation testing to prove its operability and verify software compatibility with hardware and other subsystems. This procedure is widely used for full-size satellites, but testing of nanosatellite comes with many difficulties. The efforts required to set up nanosatellite ADCS ground testing are generally comparable to the efforts needed for building a

CubeSat. Although every element of the system can be individually verified before flight and computer simulations can be made, only satellite operation in space environment shows if all components work together correctly. Otherwise, one small mistake often leads to mission failure. Despite a CubeSat is relatively inexpensive, one failure on the orbit is costly in terms of money and time due to payload preparation and launch. After a number of CubeSats loss on the orbit, the necessity of ground testing system for nanosatellite-class ADCS became evident.

Full-scale satellite developers have arrived at the same conclusion when first generation of satellites with complex orientation system was built some fifty years ago. Since then, the technology of ADCS ground testing evolved and became a common procedure for full-size satellites. For correct operation and valid results of the testing, precision of the ADCS test bench has to correlate with the precision of the satellite control system, the capabilities of its actuators and the magnitudes of disturbing torques acting on the satellite on its orbit. Unfortunately, it cannot be simply scaled down. Due to this limitation, test benches designed for full-scale satellites are not efficient for CubeSats.

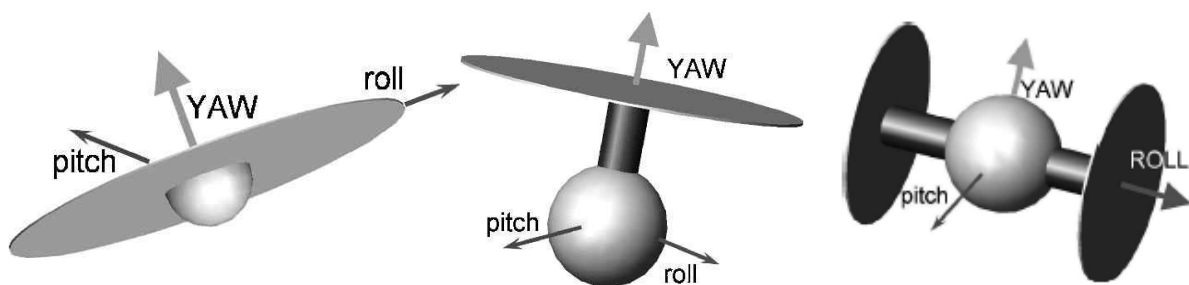


Figure 1. Tabletop, umbrella and “dumbbell” types of air bearing platforms [2]:
a sphere represents an air bearing; a disk represents a table for a payload

The simplest type of test bench use wire suspension. A wire is connected to a satellite (or a stack of ADCS components) through its center of gravity and provides rotation around one axis [1]. Such a wire suspension is simple to build but only one DoF is usually not enough for correct test results. The most widespread and reliable approach to ADCS test bench is using air bearing table, that allows motions with extremely small friction and let satellites freely rotate around at least one axis. Accordingly, three types of air bearing tables can be distinguished [2] – tabletop, umbrella and “dumbbell”, as shown in Fig.1. All types provide full rotation in yaw axis. For tabletop and umbrella configurations, pitch and roll rotation ranges are typically constrained to less than $\pm 90^\circ$. The “dumbbell” table configuration increases free motion in pitch and roll, but limits the range of possible applications. Since dumbbell has two self-balanced ends, testing of separated components is more convenient than testing of an assembled satellite.

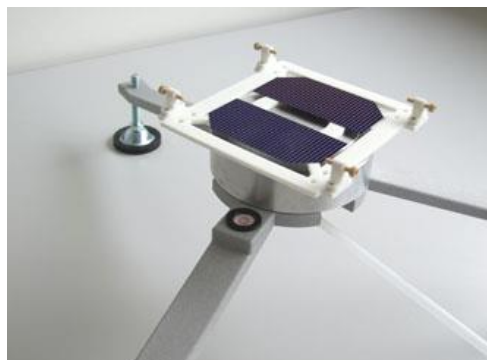


Figure 2. NanoSat Air Bearing Platform with only one vertical rotation axis [4]

Nowadays, there are not many test benches suitable for CubeSats ADCS ground testing. As mentioned above, such test benches have some special features due to CubeSat sizes and have to be specifically designed. One example is an air bearing test bench designed in York University, Canada [3]. This test bed provides 3 DoF (45° for roll and pitch rotations and 360° for yaw) and load capacity up to 9 kg. Another example is the NanoSat Air Bearing platform of Berlin Space Technologies [4]. It is a 1 DoF system suitable for 1-3U CubeSats and capable to simulate magnetic field and to test sun sensors (Fig. 2).

The University Space Center of Montpellier and Nîme (CSU) is working for a few years on developing CubeSats for different purposes and needs a nanosatellite test bench for ADCS ground testing. Since both 1U and 3U CubeSats are designed at CSU, the test bench has to be suitable for 1-3U. According to present-day needs and willing to improve current test bench characteristics, testing platform has to provide 3 unlimited rotational DoF and challenging disturbing torques of less than 10^{-5} Nm. In this paper, possible approaches satisfying those requirements are presented.

2 DESIGN STRATEGY

2.1 Requirements

The requirements to design a CubeSat ADCS test bench are determined by ADCS sensitivity and actuators capabilities. Those characteristics define the maximum value of the test bench disturbing torque which has no tangible influence on the test results. For a realistic simulation, this maximum disturbing torque has to be two orders of magnitude below the maximum control torque available in the spacecraft or one order of magnitude below the total expected external torque on the orbit [5]. According to calculations for the 3U CubeSat Robusta-3a designed at CSU, external torques on the orbit do not exceed 10^{-4} Nm. Additionally, current off-the-shelf CubeSat ADCS system were reviewed to make the test bench suitable for any other satellite of this class. The control torque of the majority of 1-3U CubeSat reaction wheel blocks ranges from 0.6 to 1 mNm. Thus, the order of magnitude of the maximum uncompensated disturbing torque of the test bed shall be 10^{-5} Nm.

Other important test bench requirements are the number of degrees of freedom and the rotation constraints. As mentioned above, all current air bearing test beds have strict limitations in pitch and roll motions. For full-scale satellites, it is not an issue because the real angular velocities on the orbit do not increase 1 deg/s. They have preliminary detumbling mode and active ADCS components operate on quite low angular rates of up to 1.5 deg/s. On the contrary, CubeSats are launched as auxiliary payloads and get rotations up to 20 deg/s and even more after deployment. For example, AAUSAT3 have got rotation velocities of 540 deg/s [5]. A nanosatellite does not have preliminary detumbling and operability of its ADCS at high velocities is very important for mission efficiency and survival of the CubeSat. During tests of ADCS operability in conditions close to the worst case (around 20 deg/s), a test bench with strong constraints on some rotation axes shall reach its limit in a few seconds. Therefore, full 3DoF rotational motions are much recommended for the test bench.

ADCS is a combination of perfectly adjusted actuators, sensors and algorithms. Requirements mentioned above define environment for testing actuators and algorithms, but sensors have to be checked as a part of the system as well. For this reason the test bench has to support sun-, star- and magnetic field simulators, as well as measurement and telemetry systems for feedback and result collection.

2.2 Proposed concepts

Friction forces, gravitational torque and additional moment of inertia are the main factors which have undesirable influences on the results of ADCS ground testing. The most common way to deal with friction forces is using air bearings. Gravitational torque can be limited by precise balancing of the satellite on the test bench. The satellite's center of gravity (CG) and the test bench's center of

rotation are brought together until the parasitic gravitational torque is lower than a maximum admissible value. The most evident way to minimize additional inertia is to design a test platform with minimum mass added to the satellite. These approaches to deal with the disturbing factors underlie the light test bench design based on spherical air bearing structure.

A fundamentally different approach to the minimization of parasitic torques is active compensation. We propose to eliminate the influence of the additional moment of inertia with help of an electric motor. This solution removes the restrictions on the moments of inertia of the test bench and therefore on its mass. In the future, this method of active compensation can be made more complicated and include the compensation of gravitational torque and friction forces.

3 TEST BENCH DESIGN with ACTIVE COMPENSATION of DISTURBING FORCES

3.1 Design overview

The proposed test bench structure is based on a gimbal suspension allowing 3DoF motion needed to meet the aforementioned requirements. A simplified gimbal with 3U CubeSat is shown in Fig. 3 (CubeSat model use here and below is taken from [6]) to better describe the concept. The gimbal consists of three holding rings which are connected with each other by air bearings providing contactless rotations.

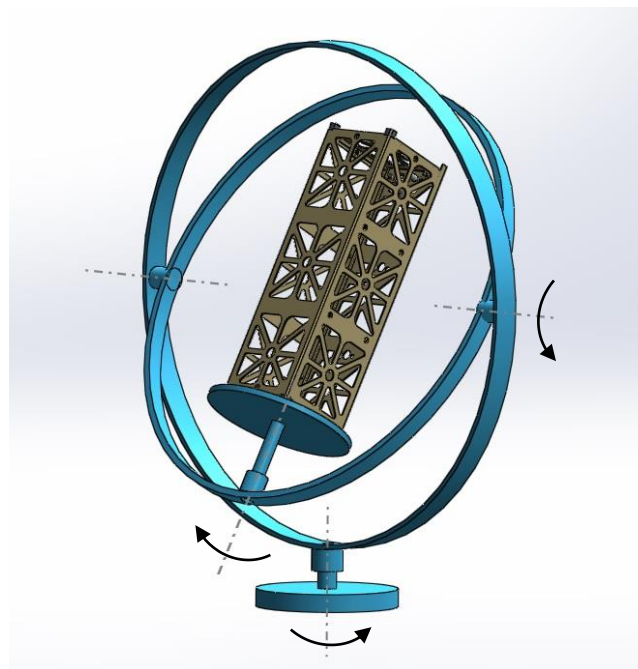


Figure 3. 3U CubeSat on gimbal suspension

As can be seen, the moments of inertia of the holding rings are considerable with respect to moments of inertia of the CubeSat and cannot be neglected.

The principle of compensation of the additional moment of inertia proposed in this paper is based on a sensor and a motor. The sensor shall be able to detect the test bench angular position or acceleration. The motor shall be able to provide required direct and reverse accelerations to the platform. Fig. 4 shows the principle of compensation on the example of a one-axis device.

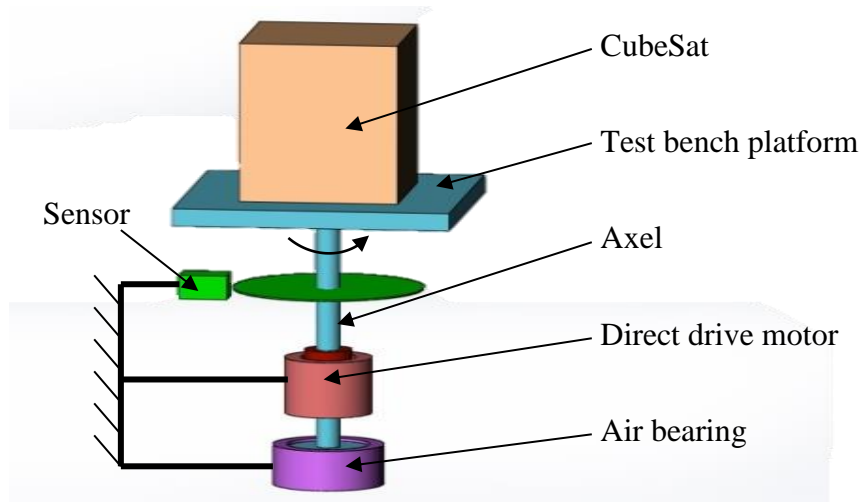


Figure 4. Principle of compensation of the additional moment of inertia of a one-axis platform

There are two types of sensors which potentially can be used in this compensation scheme – a rotary encoder and a Ferraris sensor. A rotary encoder is a widely used and well-known sensor that is able to convert angular position or motion of an axle to digital code. Rotary encoders have wide range of operation characteristics and can be found in different design that helps to easily employ them in any configuration of the platform.

Ferraris sensors are able to directly measure angular acceleration of an axle which removes the need to differentiate an output signal when time derivatives of the position are required. It can usually increase the performance of a highly-dynamic system with control loop [7]. Nevertheless, Ferraris sensors have a disadvantage which could be critical for their use in systems with tight requirements to compact sizes. While Ferraris sensors are small, they require a conductive but non-magnetic disk connected to the rotating object to induce eddy currents. The diameter of this disk influences the accuracy of the measurements. Linear tangential acceleration detected by the sensor increases with distance from the center of rotation. Accordingly, the sensor needs smaller gain to obtain measurements and provides less noise. Diameter of a disk is a result of trade-off between efficiency and size of the sensor.

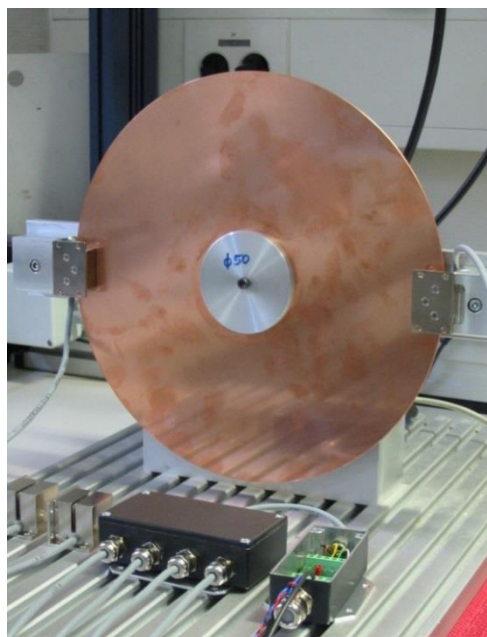


Figure 5. Ferraris sensors with a 500mm diameter eddy current disc

The active compensation system for ADCS test bench requires good accuracy. Noise, as a result of double differentiation of the position signal, may harmfully affect the efficiency of the system. Simulations, presented below, are made to study the feasibility of the active compensation of the additional moment of inertia and to determine the performances of the different types of sensors (rotary encoders and Ferraris sensors).

3.2 SIMULINK model

For preliminary verifications, the active compensation principle was simplified to only one motion axis. This simplification allows checking the approach in the case of a simple system modeling. In prospect, the model shall be improved and extended to three axes with mutual interferences.

The main idea of ground ADCS tests is to simulate behavior of the satellite as if it were in space. In this condition, the ADCS performance can be evaluated realistically. Angular motion of the satellite in space can be described by Eq.1.

$$I_s \bullet \ddot{\theta}_s(t) = \Gamma_e + \Gamma_a \quad (1)$$

where I_s is the moment of inertia of the satellite, $\ddot{\theta}_s$ is the angular acceleration of the satellite, Γ_e and Γ_{rw} are the external torque and the torque produced by the actuators of the satellite ADCS, respectively.

The equation of motion of the satellite and test bench platform can be written as:

$$(I_s + I_p) \bullet \ddot{\theta}_p(t) = \Gamma_e + \Gamma_a + \Gamma_p \quad (2)$$

In Eq. 2, I_p is the moment of inertia of the test bench platform, $\ddot{\theta}_p$ is the angular acceleration of the set composed of the satellite and the platform, Γ_p is a compensation torque produced by the motor on the platform. The influence of the platform moment of inertia is compensated if the satellite motion is close to its motion in space. Feedback is needed to define the influence of the platform on the motion of the system and compensate it. It can be done if Γ_p is equal to the platform's contribution to the left hand side of Eq. 2. However, since there is a feedback loop in the system, the time delay cause by the loop cannot be ignored. Eq. 3 is then used for the compensation torque.

$$\Gamma_p = I_p \bullet \ddot{\theta}_p(t - \tau) \quad (3)$$

$\ddot{\theta}_p(t - \tau)$ is the angular acceleration of the satellite and the platform at time $t - \tau$, τ is the time delay. The total equation modeling the system behavior is found as a combination of Eqs. 1-3:

$$(I_s + I_p) \bullet \ddot{\theta}_p(t) = I_p \bullet \ddot{\theta}_p(t - \tau) + I_s \bullet \ddot{\theta}_s(t) \quad (4)$$

Figure 6 shows the three main parts composing the SIMULINK model of the system – the satellite, the test bench platform and the computer. The satellite behavior is described by Eq. 1 and represented with blue block. The block for motion of the test bench platform with the satellite is based on Eq. 2 and it includes a negative feedback that means the output signal is sent back to change the original signal by a given gain. The output of this block is arranged in two ways – a Ferraris sensor (output called Acceleration in Fig. 6) or a rotary encoder (output Position in Fig. 6). Only one type of sensor can be used in modeling at one time. The computer and drive block includes a switch allowing choosing the type of sensor. In case of the encoder, double differentiation is required. It is made in the computer block. The computer is a controller which takes the signal from the sensor, transforms it according to Eq. 3 and sends the resulting compensation torque back to the test bench platform. Moreover, the computer block emulates time delay in the system which is due to the negative feedback.

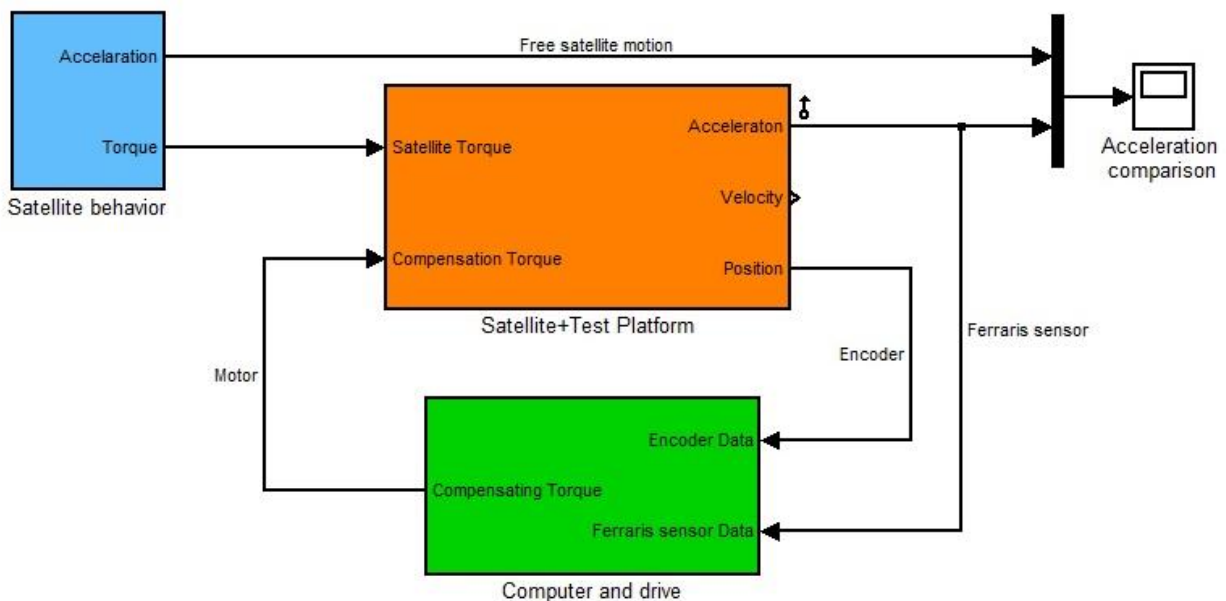


Figure 6. Block diagram of the SIMULINK model of the test bench with active compensation

According to Eq. 4, the behavior of the system depends on the time delay value and on the value of the moment of inertia of the platform. These values were varied in modeling to define how they affect the performance of the system. The time delay depends on the capabilities of the computer and drive. Up-to-date technologies of robotic systems make possible operation frequency of up to 20 kHz which means delay of $5 \cdot 10^{-5}$ s [8].

3.3 Results and discussion

In the first steps of the system study, when some assumptions are made, results have to be parameterized. General character of the system behavior is more important for early analysis. Bode plots help to analyze stability of the system without reference to input signal and to find the range of frequencies where the compensation principle can be efficient. Furthermore, the inertia moment of the platform can be characterized with respect to the satellite to make the results independent from particular numerical values.

The model includes the following parameters:

- Ratio of moments of inertia of the platform and the satellite (I_p / I_s) from 0.5 to 2;
- Time delay values ranging from $5 \cdot 10^{-5}$ to 10^{-4} s;

Fig. 7 and Fig. 8 illustrate results obtained with the SIMULINK modeling.

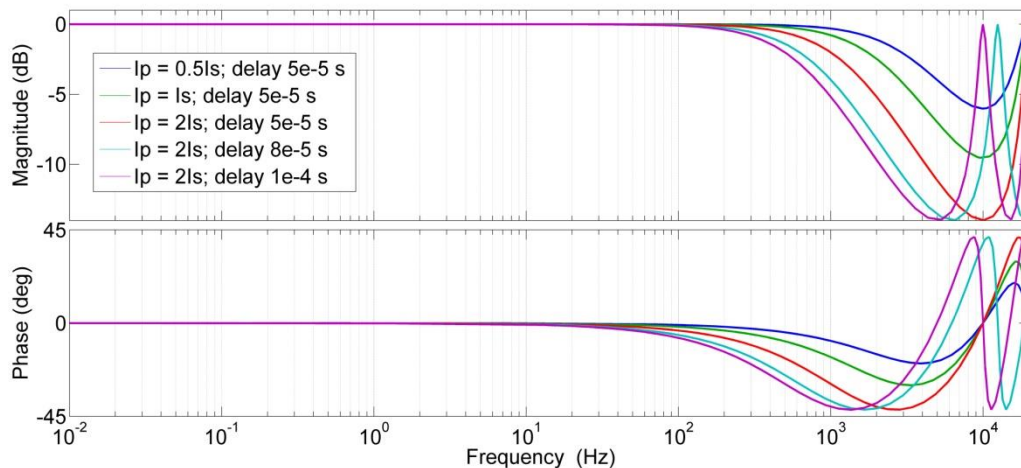


Figure 7. Bode plots of the model with Ferraris sensor

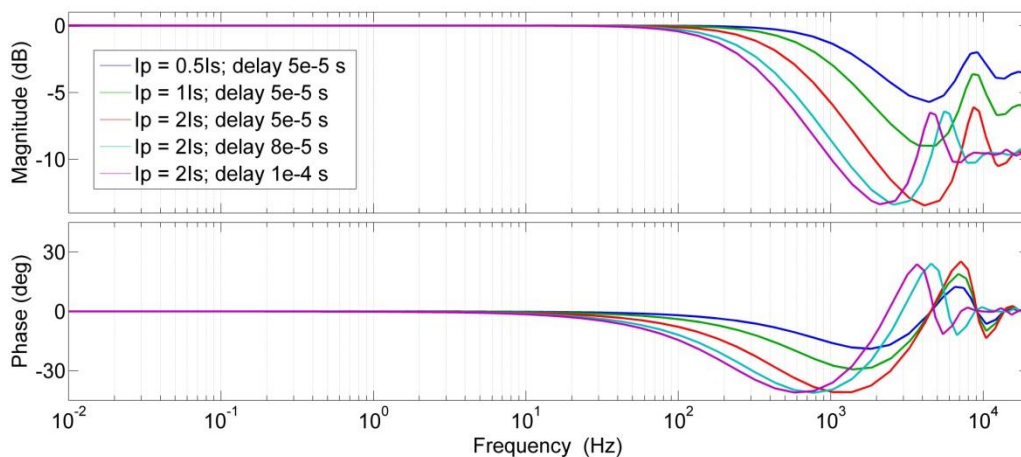


Figure 8. Bode plots of the model with rotary encoder

The system is considered stable and the compensation is considered efficient when the gain of the system and its phase shift stay equal to zero. As can be seen in Fig. 7 and Fig. 8, the maximum of magnitude and phase shift increase and plots move slightly to the left when the compensated moment of inertia grows (first three lines of the plots). The time delay in the system has an influence only on the frequency of stability loss. Thus, the zone of effective compensation shortens when inertia of the platform and time delay (or only one of them) increase.

It is important that the zone of effective compensation includes all frequencies of CubeSat ADSC. Otherwise vibrations of the satellite seen by the sensor can lead to malfunction of the compensation system. Average frequency of ADSC operation is 10 Hz. Additionally, the reaction wheels have to be taken into account. The maximum speed of reaction wheels for CubeSats is 6500 rpm that is approximately equal to 110 Hz. Figures 7 and 8 show that this compensation system, with a Ferraris sensor or with an encoder, cannot provide stable operation at frequencies higher than 40 Hz at delay $5 \cdot 10^{-5}$ s. This result is already acceptable and it shows feasibility of the compensation principle. But the compensation system has to be improved to perfectly satisfy all requirements.

The results obtained from the modeling shall be validated by practical experiment to prove correctness. The design of an experimental setup for validation of the compensation system is shown in Fig. 9. This setup is a 1 DoF equivalent of the satellite test bench with compensation

system. It provides a contactless rotation around axle and motion can be corrected by direct drive motor mounted together with air bearing in the base rotation stage [9]. The CubeSat is replaced with the simple shape rotating body with known mass and moments of inertia. Fig. 9 shows a Ferraris sensor, but a rotary encoder also can be used.

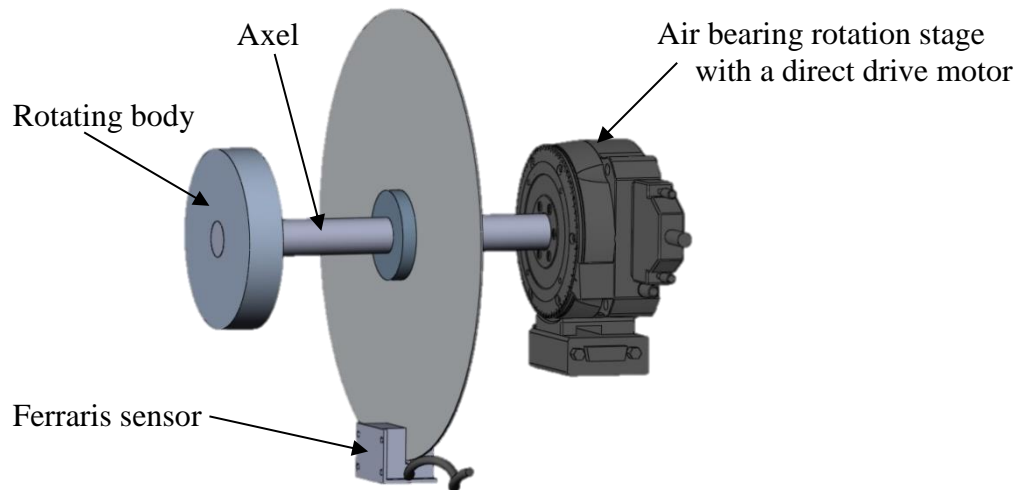


Figure 9. Validation experimental setup for the compensation system

Mass and moments of inertia of the axle and all elements connected to it shall be known with required accuracy before experimental tests. The moment of inertia of the rotating body shall be comparable with the moment of inertia of other rotating parts or smaller. The value of the initial impulse is also important for a correct analysis of the obtained results and shall be known. Hence, the first impulse to the system shall be given by the motor to know its value accurately. Once the axle is rotating, the sensor gets information about motion and sends it to the computer. The computer calculates the required compensation torque according to the algorithm presented above. The motor of the rotary stage applies the torque to the axle with respect to data received from the computer. Information about motion, obtained from the sensor, shall be compared with theoretical computation of free motion of the rotating body without influence of the other test bed elements. Equal results tell that the compensation system operates correctly and efficiently. As a double check, measurement of motion with compensation can be also compared with measurement of motion without compensation.

Summarizing results of the work presented above, the next steps to improve the compensation system are clearly:

- Include filters to reduce frequencies of vibration detected by sensors;
- Design a control scheme for the compensation system;
- Build the experimental test bed and check efficiency of the compensation system;
- Include in the system a component of the compensation torque, which is able to deal with a friction force, to avoid using air bearing.

4 LIGHT TEST BENCH DESIGN with NO COMPENSATION

4.1 Concept

Air bearings are well-known means to create contactless suspension for satellite ADCS tests. Such bearings deal well with friction force and do not need any particular operating conditions while their counterparts – magnetic bearings – have some special needs. Passive magnetic bearings operate at low temperature because of the superconductors included in their structure. Active

magnetic bearings work at standard conditions, but they are usually massive, bulky and require a complicated and heavy controller. Moreover, the generated magnetic field is an issue since it can interact with the satellite body and ADCS actuators and obstructs the magnetic field simulation. This effect can be prevented, but it demands additional efforts and expenses.

Unfortunately, air bearings have restrictions in freedom of motion. The fluid film of the bearing is achieved by supplying an air flow through the bearing face and into the bearing gap [10]. This fluid film holds the load and provides contactless motion. The obtained motion depends on the shape of bearing face. Flat bearings offer planar motions while spherical bearings allow rotational motions. Motion ranges are limited by the area of the fluid film. A spherical air bearing is usually a puck with a spherical cap cut out and the sliding part is a hemisphere. In this case, contactless performance is available only within the area of the spherical cap which means pitch and roll rotation limitations around $\pm 45^\circ$. These limitations can be slightly pushed if the sliding part is almost a full sphere and a payload is placed on a table above (umbrella air bearing platform type mentioned above – Fig. 1). But this configuration leads to difficulties with stability of the motion because the center of gravity of such a structure is usually above its center of rotation. It yields to limited tilt angles or inconvenient requirements to placing the payload. As a result, developers of the air bearing platforms have to choose between restrictions of motion and problematic payload placing.

A solution could be found if the payload is placed at the center of the sphere gliding on air bearing. This concept was tried at Los Angeles/California Institute of Technology where a hollow spherical bearing with all hardware mounted internally was designed [2]. This system provides $\pm 180^\circ$ but reported tests include only single-axis rotations [11].



Figure 10. Experimental hollow air bearing platform in University of California, Los Angeles/California Institute of Technology model spacecraft spheres [11]

The system shown on Fig. 10 was developed for experimental work with control of multiple spacecrafts. Designed for this purpose, the air-levitated spheres contain only a microcontroller, sensors, batteries and a flywheel, but not a full satellite. The sphere able to hold a CubeSat inside would be bulky and heavy. The design presented below in the present paper is based on the advantage of hollow air bearing but without a massive structure. We propose a design where few spots form spherical surface and all unnecessary segments of the sphere are eliminated (Fig. 11).

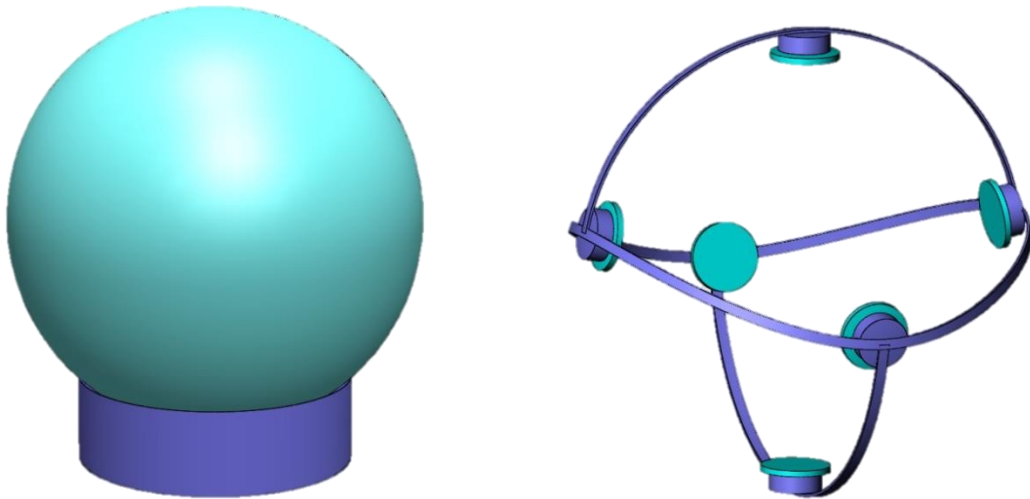


Figure 11. Drawing of hollow air bearing and spherical structure of the same diameter formed by several small air bearings

One of the main requirements to the test bench is 3 DoF unconstrained rotations. Hollow air bearings fit this requirement due to the continuous surface of the ball which allows “contact” with bearing puck in every configuration (Fig. 11, left). But the same spherical surface also can be formed with several small air bearings with one common center of rotation (Fig. 11, right). In the latter case, it can be easily seen that the moving part of the structure is much smaller and lighter than that of the full sphere. Size and mass of this part is critical for the ADCS test bench because it leads to unwanted moment of inertia.

When sliding spherical caps are placed opposite bearing pucks, dynamics of the structure is similar to a hollow bearing. Nevertheless, the frame with bearing pucks needs to be movable to follow a trajectory of the fictitious inner sphere. Although it yields additional mass, the external part of the structure is independent from the CubeSat mounted on the test bench and therefore makes no influence on results of the tests.

4.2 Design

The external frame with air bearing pucks has to spin freely and follow inner part with the CubeSat mounted on it. Motion of the satellite is a key point of the tests and shall not be predicted but only observed. The positioning of the bearing pucks has to be corrected rapidly based on the current position of the satellite. For these purposes, a tracking system is required. Optical sensors offer speed and accurate coordinates of the object within a small delay. Delay in the feedback control of the tracking system is not a critical point. Indeed, narrow relative motions of the inner and external parts of the test bench without correction is available due to different sizes of spherical caps and bearing pucks, as shown in the right side of Fig. 11.

Suspension of the external frame is realized by gimbals as shown in Fig. 12. Thin and rigid ring sections in the gimbal provide 4 DoF that helps to avoid possible constraints of the motion. Moreover, the slim design of the gimbals leaves space to place the simulators needed for full imitation of space environment.

This design of the test bench presupposes precise balancing of the CubeSat with the holding frame and the spherical caps attached to it. The geometrical center of the inner sphere defines the center of rotation and it has to be perfectly coincidental with its CG. Inaccuracy in the balancing yields a disturbing gravitational torque acting on the satellite. Value of the acceptable inaccuracy will be defined such that the resulting torque does not exceed 10^{-5} Nm. Precise balancing is a challenging task, which has to be solved in a next step of this work.

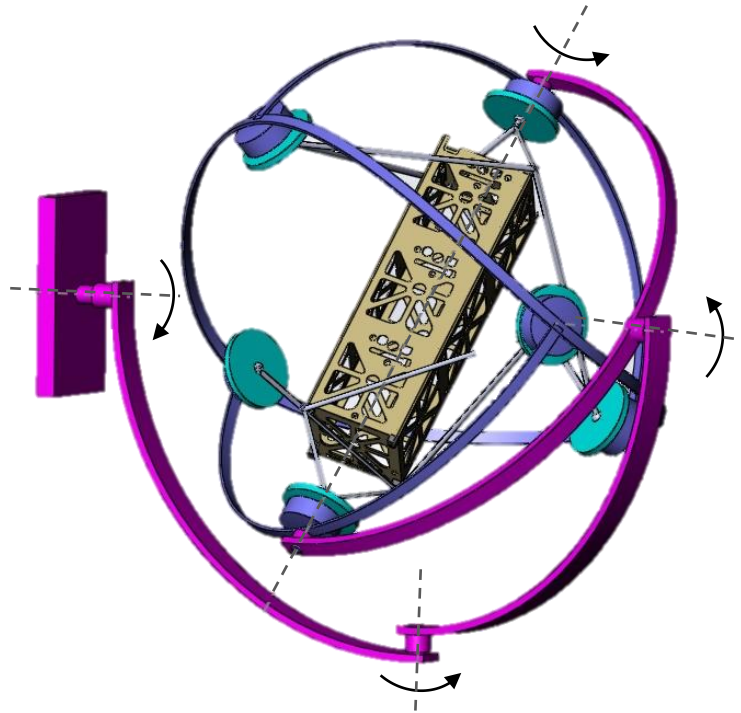


Figure 12. Overall view of the test bench based on spherical air bearing structure

4.3 Further works

The realization of the light test bench with no compensation and infinite rotation angles is a complicated work that was never made before. In this paper, the concept of such a test bench is proposed and the critical points of its design are identified.

The balancing of the inner part of the test bench with the payload has to be done. The efficiency and accuracy of the test bench will depend on the:

- Coincidence of center of rotation and CG;
- Stiffness and thermal stability of the holding frame connected to the CubeSat.

The design of the holding structure has to be approved with strength analysis. This structure design is expected to result from a tradeoff between mass, strength and stiffness.

Many indefinite characteristics of the air bearings have to be found from tests. Usual applications of spherical air bearings do not involve their use in positions different from the vertical, when the puck is under the sphere. But, in our use, the bearings can be located with every possible tilt angle. Air bearing capability, friction and stiffness could highly change with tilt angle and the corresponding relationships need to be defined from tests.

The tracking system for the external frame has to be designed. It shall include sensors measuring the spherical cap positions, simple motors to actuate the gimbal and algorithms to control the tracking. As mentioned above, this system does not need high accuracy or speed.

Verification of the test bench is as important as its development. The CubeSat developers have to know the conditions of the testing and influences on the nanosatellite. All disturbing torques, produced by the test bench, have to be estimated in theory and checked by verification tests:

- Gravitational torque;
- Residual friction in air bearings;
- Aerodynamic friction;
- Average parasitic torque of the test bench.

5 CONCLUSION

In this paper, two approaches to the problem of nanosatellite test bench design are proposed. This work was started recently and this paper introduces the first results as well as the intended next steps. The results show that the test bench with compensation is a promising way to design CubeSat test beds. But the light test bench design looks more feasible on short time. It is a completely new approach to use air bearings for satellite ground testing. In our future works, the mathematical model of the compensation will be expanded to 3 DoF and both designs could be integrated together into a single system.

6 ACKNOWLEDGMENTS

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