A 3(5) Degree of Freedom Electrodynamic-Bearing Wheel for 3-Axis Spacecraft Attitude Control Applications

U. Bichler, T. Eckardt
TELDIX GmbH, Germany

Abstract

This paper deals with two related types of electrodynamically suspended rotors, acting either as momentum or reaction wheels for spacecraft attitude control purposes. One is of the three-axis active type, the other involves five actively controlled degrees of freedom.

The wheels are of a pancake design with the control forces acting on the outer rim where the main rotor mass is concentrated thus avoiding low structural resonances. The rim is decoupled from the hub by titanium springs. Both wheels provide a vernier gimballing capability enabling three-axis attitude control of spacecraft with one rotating mass only.

A special decoupling tilt control loop design eliminates all gyroscopic effects, such as precessional and nutational oscillations.

The electrodynamic bearing principle is advantageous because main parts of the mass can be concentrated on the outer rim of the rotor contributing to the desired inertia. Force generation is linear involving only very small lags and practically no cross-coupling exist between the orthogonal axes facilitating a control strategy to prevent disturbing unbalanced forces from affecting the stator of the bearing for the use in so-called 'micro-gravity' environment. The wheels are actually in the development phase and in the paper the principles, the design, the control loops and first results are presented.

Introduction

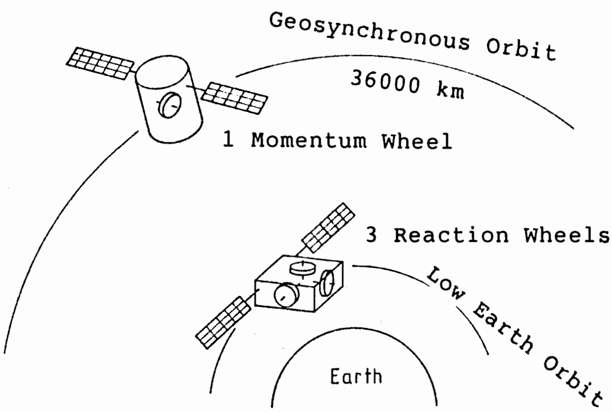


Fig. 1 Satellites with 1 Momentum Wheel or 3 Reaction Wheels

In principle, momentum wheels are gyroscopic actuators designed for compensating periodic disturbing torques which act on geostationary communications satellites. A momentum wheel mounted in a double-gimbal system offers the additional possibility of tilting the satellite with respect to the wheel. Satellites in a low earth orbit are equipped with a set of at least three perpendicular reaction wheels providing attitude control about all three axes.

Almost all momentum and reaction wheels in orbit are equipped with ball bearings but wheels with magnetic bearings offer some special features which are of interest with regard to the increasing attitude performance requirements of modern spacecraft and with environments where only extreme low disturbing accelerations can be tolerated [1].

In magnetic bearings, the achievable speed is not limited by friction and fatigue effects of ball bearings. They provide low friction and no stiction at zero speed, are insensitive to hard vacuum and need no lubricant. If a vernier gimballing capability is implemented an active satellite nutation damping and a three axis attitude control for small roll and yaw angles is enabled with one rotating mass only. Unbalance forces are - as far as no permanent magnets are involved for direct attraction/ repulsion - transmitted to the stator only at an amount which can be kept near zero when a special control law is applied.

Principle

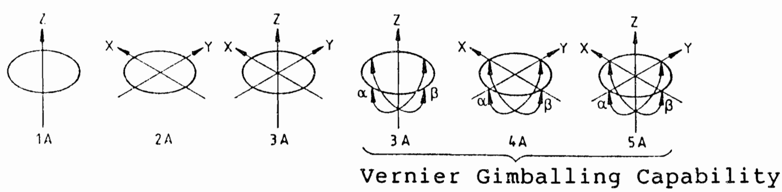


Fig. 2 Different Types of Magnetic Bearings

Several designs of one- and two-active-axis magnetic bearings are known [2,3,4]. They all use a permanent magnet flux which is superimposed for control purposes by a variable coil flux. The disadvantages involved are that the magnets must be very homogeneous to avoid drag torque due to eddy current and hysteresis losses, that the passively stabilized degrees of freedom have a low stiffness and that practically no inherent damping is present. Especially the passive tilt suspension forms a weak spring and leads, together with energy losses in a passive damper, to satellite nutational motion [5,6] requiring additional nutation dampers. The permanent magnets cannot be 'switched' to a lower flux mode in micro-g environments, and unbalance disturbance isolation is only possible by active means.

Magnetic bearings with three and more active axes have the important advantage of the tilt axes controllability offering the vernier gimballing capability [7]. The top magnetic bearing is the five-axis active one, which does not need any permanent magnets in direct attraction or repulsion. This type is perfect, very stiff and controllable in all axes with excellent damping.

Design

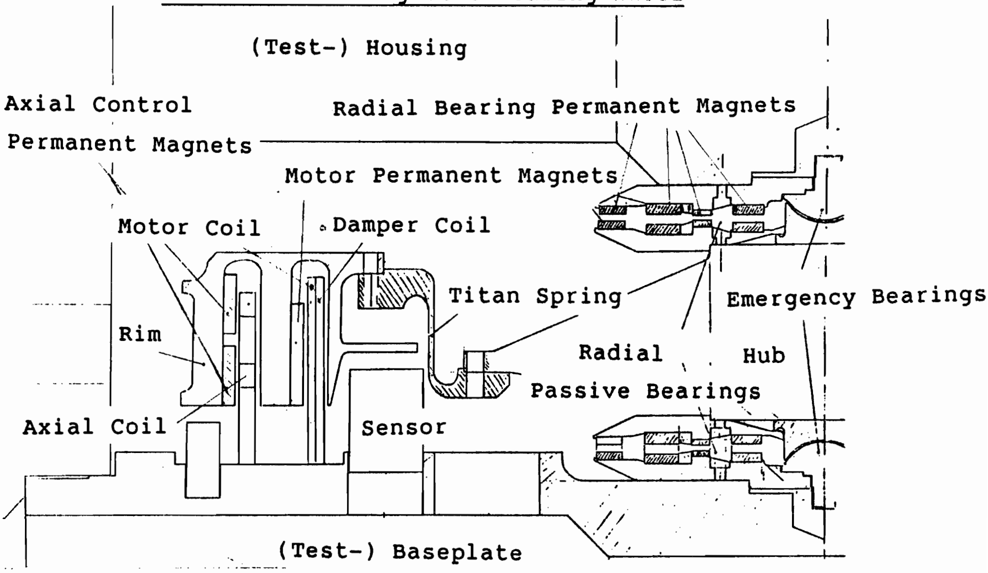
Because of the mentioned features, a modular design of an axial and tilt-controlled bearing with both a passive and an active radial suspension, resulting in 3- and 5-axis active magnetic bearings, was chosen.

Additional overall design requirements have been an easy assembling procedure, a high momentum/mass ratio, obtainable by arranging most of the mass at the outer rim of the rotor, and control force injection and position detection at this location, too, to avoid low resonances between hub and rim.

The magnetic bearing rotor is essentially composed of a rim which is connected to the hub by five titanium springs. Two slots in the rim which are equipped with Neodym-Iron magnets form, together with corresponding air-coils on the stator, the axial/tilt actuators and the drive motor. The hub contains the radial center bearing, either passive or electromagnetically active, and carries the emergency bearings.

The electrodynamic force generation was chosen as best suited for a large diameter and the associated high circumferential speeds, which resulted from the design requirements. The ironless armature coil consists of four 90° segments. The axial forces are provided by applying a similar current to all coils. The tilting torques about the two perpendicular radial axes are yielded by exciting two opposite coils alternatively.

3 Axis Active Magnetic Bearing Wheel



5 Axis Active Magnetic Bearing Wheel

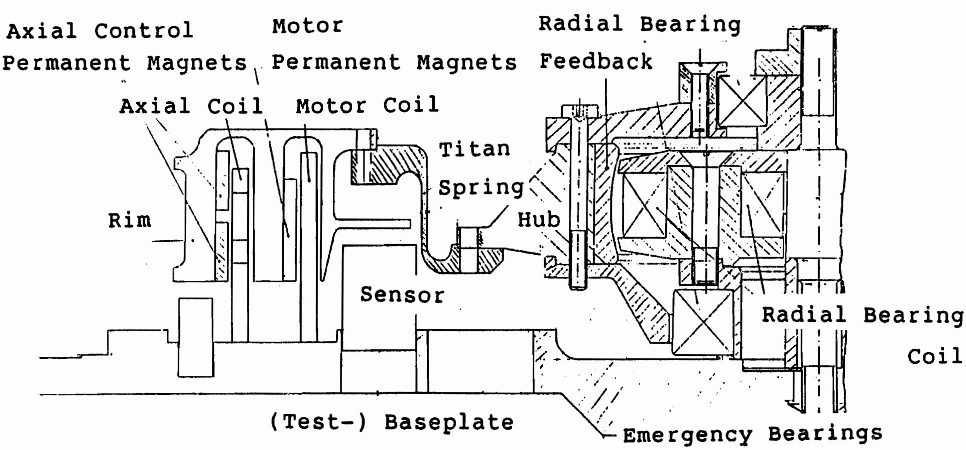


Fig. 3 Schematic Diagrams of the Magnetic Bearings

Redundancy is assured because only three coils are necessary to produce the desired forces and torques.
The radial bearing of the 3-axis wheel consists of two sets of concentric permanent magnet rings. The axial stiffness is, of course, unstable, the tilt stiffness has been designed to zero around the neutral position. For the radial bearing of the 5-axis active system, the electromagnetic force generation principle was chosen because of the small circumference in the hub.
Any deviation from the nominal rotor position is detected in a redundant way by a set of four position sensors, each located besides a stator coil, and - using three control loops - balanced by forces generated in the coils. The sensors are of the eddy current type and invole only very small lags.
The connection of the rim with the hub is achieved by titanium springs, which provide the decoupling of the different strains of rim and spokes due to centrifugal forces and temperatures by means of radial weakness of a single spoke, but a high stiffness in all directions against relative motion of hub and rim.
The task of the emergency bearing is to provide a nondisturbing landing of the (spinning) rotor in the cases of a failure in the suspension electronics or in the power supply and with externally applied forces or torques exceeding the active stiffness capability within the given mechanical limits. The emergency bearing in the 5-axis active system consists of two ball bearings the locating of which is determined by circumferential speed limits and some considerations concerning gyro- and centrifugal effects. In the three-axis active system a spherical surface sliding bearing will be tested.
The drive motor is of the brushless, ironless d.c. type which allows an excellent controllability of torque while providing high efficiency. It is located in the outer rim because in this position the mass distribution between rotor and stator is advantageous. The ironless armature consists of a three- phase stranded winding embedded in an epoxy material to avoid radial destabilizing forces as well as cogging torques caused by armature slots. The commutation is performed using three reflex light barriers which are also utilized to detect the sense of rotation.
In the 3-axis bearing, a special short-circuited winding is

introduced into the motor slot which uses the motor magnets to damp radial oscillations. The rotational drag is negligable if a sufficient uniformity of the induced voltage per magnet can be achieved.

Both types of magnetic bearings have been built and the 5-axis configuration has already been tested statically and up to 7000 rpm. The main data of the 5-axis bearing are:

Diameter	:	0.3	m	Height	:	0.1	m
Rotormass	:	6.65	kg	Total Mass	:	10	kg *
Max. Speed	:	14000	rpm	Nom. Speed	:	10000	rpm
Inertia	:	0.1	kgm^2	Momentum	:	100	Nms
Axial Gain	:	55	N/mm	Tilt Gain	:	3000	Nm/rad
Gimballing Angle	:	± 1.5	°	Slew Rate	:	17	°/s **
Motor Torque	:	± 0.35	Nm				

Angular Momentum Cross Component: 5.3 Nms

* : Preliminary value obtained from laboratory model with test-baseplate, protecting housing and breadboard electronics

** : Short time.

Control

The elements of the axial and tilt control loops of the nonrotating wheel are shown in Fig. 4. The plant consists of a double integration with the mass/ transverse inertia of the rotor as integration constant. The actuator consists of a current-controlled amplifier and the electrodynamic force generation system. The actuator and also the position sensor can be modeled as first order lags. The controller must provide at least one 90° phase shift to achieve stability. In the case of the passive radial bearing, an unstable spring feedback is introduced into the plant. As controller also a simple PD-type can be used, but the stability conditions become more severe in this case. By means of a superimposed zero-power controller, the system becomes selfadjusting into the axial position of minimum (zero) bearing current. If a high static stiffness is required, an integrator term can be added, the controller is then of the PID-Type. Of course, a PID- and a Zero-power controller cannot be used simultaneously in this configuration.

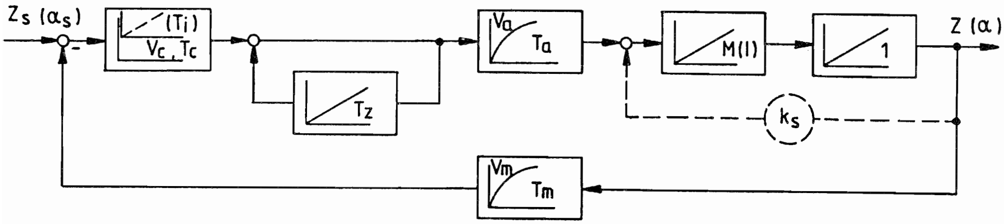


Fig. 4 Block Diagram of the Axial and Tilt Control Loop
Dashed Elements: only with the 3-Axis Active Bearing

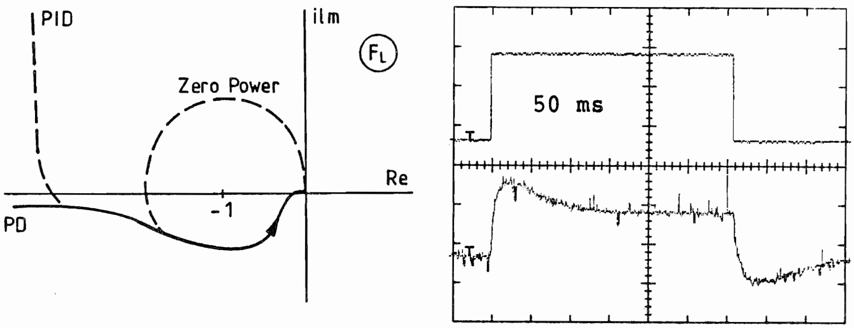


Fig. 5 Nyquist Plots and Step Response of the Axial Loop

The radial control loop of the 5-axis active bearing is principally the same as that of the axial loop of the passive radial bearing. The difference lies in two nonlinear dependencies of the operating point: the destabilizing feedback is proportional to the square of the bearing current while the actuator gain is inverse square proportional to the radial elongation of the rotor. These nonlinearities can be defused with the help of a linearizing network or a bias current. In the radial loop, a PD-controller or a PID-controller can be used. Fig. 6 shows the stability region for the controller parameter which is moving and size-varying with the operating point.

If the controller is provided with a variable parameter set, the active stiffness of the radial loop can be changed while keeping an optimal damping. A stiff controller can be used at normal operation. In zero-gravity conditions where no strong external forces are applied, a very smooth operating parameter set can be chosen which keeps the average rotor position without transmitting high-frequency sensor disturbances, generated by the rotor spinning about its center of gravity, to the stator.

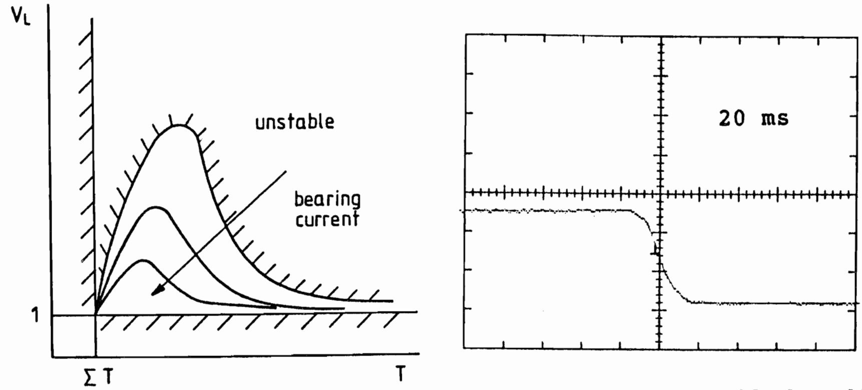


Fig. 6 Stability Area and Step Response PD-controlled Radial Loop

When the wheel is rotating, additional gyro-couplings between the tilt axes of the wheel arise which are proportional to the speed and which enable the precessional and nutational oscillations. The highest nutational frequency of a flat rotor is about twice the speed - a tilt controller, which copes with these frequencies, must be of high bandwidth and therefore causes an increased power demand in the actuator due to noise. One possibility to overcome this problem may be the introduction of a gyro-decoupling network, as depicted in Fig. 7. If the decoupling parameter matches the plant parameter, the resulting plant at all speeds is the same as that of the wheel standing still. In the step responses in Fig. 8 it can be clearly seen that the cross coupling between the tilt axes is removed and the damping is improved.

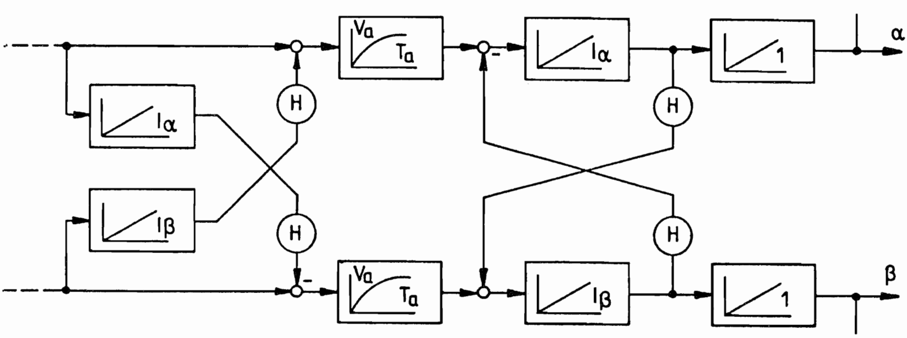


Fig. 7 Block Diagram of the Gyro-coupling and -decoupling

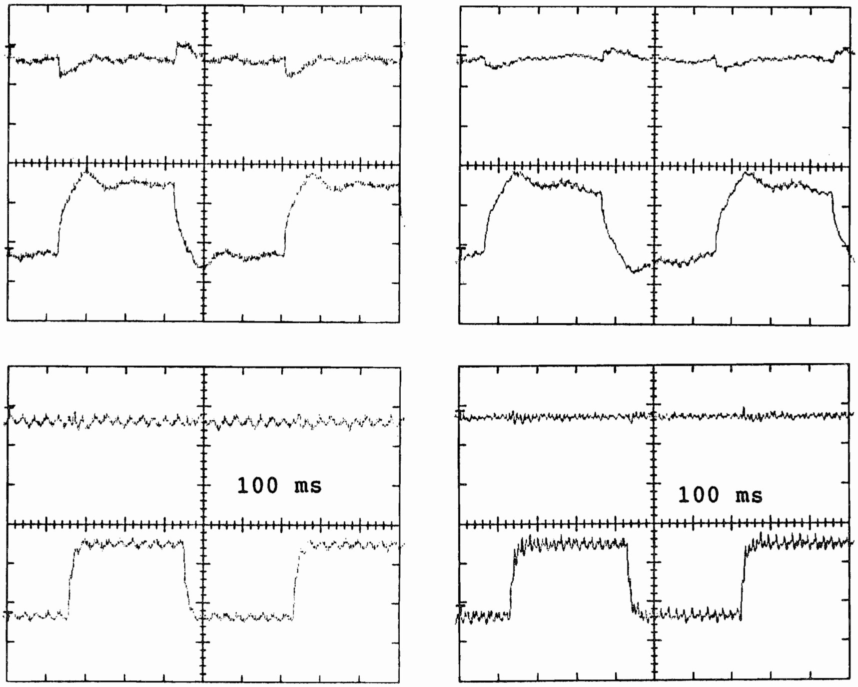


Fig. 8 Step Responses of the Tilt Axis at Different Speed
a: without decoupling, b: with decoupling

The influence of such a decoupling on the overall satellites stability must be considered separately.

Conclusion

Two magnetic bearing wheels of low profile design have been built, a 3-axis active version and a 5-axis active one. Both provide a vernier gimballing capability due to electrodynamically controlled tilt axes. This is of interest with respect to the increasing attitude control requirements of modern spacecraft. With the use of four sensors and four bearing coils, redundancy is built in inherently. The wheels are actually in the test phase and the five degree of freedom wheel has been already stable levitated and rotated up to 7000 rpm. A special tilt control loop design eliminates all gyroscopic couplings and improves the dynamic performance of the active gimballing. Using a control loop with variable active stiffness, the wheel can be switched in a smooth mode preventing unbalance disturbances from affecting the satellite.

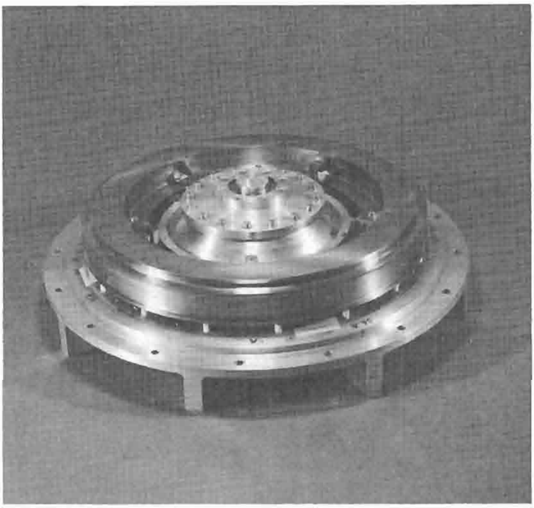


Fig. 9 The 5-Axis Magnetic Bearing

References

1. Ball Bearing Versus Magnetic Bearing Reaction and Momentum Wheels as Momentum Actuators. W. Auer, AIAA 'Global Technology 2000', Baltimore 1980.
2. Satellite Momentum and Reaction Wheels with Magnetic Bearings. J-P. Baudry, P. Poubeau, A. Robinson
3. An Advanced Low Cost 2 Axis Active Magnetic Bearing. Flywheel. M. Gauthier, A. Robinson, J.P. Roland, H. Vaillant. Third European Space Mechanisms & Tribology Symposium Madrid 1987.
4. A Flat Magnetic Bearing Reaction Wheel. C. Murakami, A. Nakajima, S. Shingu, Y. Shimamoto 14. International Symposium on Space Technology and Science Tokio 1984.
5. Magnetic Bearing Design for High Speed Momentum Wheels. T. Lange, First European Space Mechanisms & Tribology Neuchatel, Schweiz Oct. 1983.
6. Impact of Magnetic Bearing Rotor Design on Satellite Nutational Stability. G. Heimbold, AIAA Guidance and Control Conference, San Diego 1982.
7. Magnetic Bearing Momentum Wheels with Magnetic Gimballing Capability For 3-Axis Active Attitude Control and Energy Storage. R.S. Sindlinger, AOCS Conference, Noordwijk, Oct. 1977

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