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MAGNETIC BEARING WHEELS

FOR VERY HIGH POINTING ACCURACY SATELLITE MISSIONS

J.P. Roland
AEROSPATIALE, 78133 Les Mureaux, France

Abstract

Inertia wheels used as actuators in Attitude Control Systems remain the most frequently encountered solution for all types of scientific or military space missions : telecommunications, earth observation ...
The magnetic levitation of the flywheel leads to new performances, which will be highly appreciated for very high pointing accuracy missions in the next decade.
For military and commercial earth observation missions, for optical link telecommunication missions, as well as metallurgical process missions under microgravity conditions, the need in platform stability will become stronger and stronger.
Work in progress on the Magnetic Bearing Reaction Wheel, dedicated to the HELIOS military earth observation satellite is presented. The HELIOS program is very demanding in terms of pointing accuracy. The main features of this wheel and its overall characteristics and performances are given.

Introduction

The prime advantages of Magnetic Bearings are : no wear, no lubrication, and low rotational losses. These properties are particularly appreciated in satellite Momentum Wheels, which have to operate at high rotational speeds in vacuum for long periods of time.

Less obvious but equally important properties, only reached by using Magnetic Bearing, are at first the complete cancellation of any "stiction" effect which creates limit cycle in attitude control when rotor speed is crossing zero, and then no variation with temperature of the very low "frictional" drag torque. The other induced performance is the very low level of microvibrations induced onto the platform.
These attributes, in addition to those hereabove mentioned, make them ideal for use in Reaction Wheels for Very High Pointing Accuracy missions.

The Magnetic Bearing technology has been flight-proven for the first time in the world, as part of the French earth observation SPOT programme. The satellite attitude is actuated by 3 Magnetic Bearing Reaction Wheels (MBRW), contributing to the SPOT pictures sharpness. It should be noticed there is only

one fully redundant wheel on each axis. The SPOT 1 satellite was launched on February the 21st, 1986. Designed for 2 years, it is still in operation. SPOT 2 was launched on January the 20th, 1990.
The ERS 1 (Earth Remote Sensing) satellite, a European Space Agency programme, is also actuated by 3 MBRW. It was launched on July the 17th, 1991. The quality of the first view, transmitted as soon as the 27th of July, is sharper than expected.

Those previous MBRW are based upon 1 Degree Of Freedom (DOF) actively controlled configuration. In this paper, we describe an advanced MBRW concept, based upon a 2 DOF actively controlled configuration, which has been developed in order to improve the initial concept and to lead to an extremely simplified and robust mechanical part.

The development of the 2 axis active wheel was performed under a Research & Development contract awarded by the European Space Agency (ESA). The work was started in 1982 and was completed in 1986.

This configuration is being used for the military earth observation HELIOS programme and for the new generation of SPOT (called SPOT 4) programme. The strong requirements of these programmes involve new MBRW improvements to obtain very low microvibrations.

Principles and Technologies

It is known that we can't realise, in normal conditions, a completely passive contactless magnetostatic bearing that would be stable in the 6 Degrees of Freedom.
There is at least one Degree Of Freedom in which the suspended part is in unstable equilibrium.

Stability is achieved, along passive axis ('axis' means Degree Of Freedom), as many as five, by the use of permanent magnets which create restoring forces. Along active axis, at least one, stability is achieved by actively controlled electro-magnets (called actuators). Those can be associated or not with permanent magnets.

The Magnetic Bearings developed by AEROSPATIALE are of the semi-active type: they utilize permanent magnets. Most Degrees Of Freedom are passively controlled, consistent with the application at hand. This strategy makes for high inherent reliability and low power consumption because it minimizes the amount of electronics and other active required elements.
The actuators also utilize permanent magnets which produce the main part of fluxes in the magnetic circuits. The fluxes created by the coils only modulate the static flux, and by the way increase or decrease the force applied to the bearing part and make it stable. Another advantage is to provide a quasi-linear characteristic of force vs current.

Permanent magnets are operating in the attractive mode, which gives a better passive/active stiffness ratio associated to lower magnetic disturbancies than in the repulsive one. The pole pieces, with one or more teeth, concentrate the flux and produce higher forces and passive stiffnesses.

Fig. 1 illustrates the basic geometries of Magnetic Bearings (MB) of 1 and 2 axis active types.

Fig. 1a shows a 1 axis active MB of the type used in the SPOT Reaction Wheel. It consists of four annular elements, arranged in two axially separated pairs. Each element consists of a radially magnetized permanent magnet ring fitted with cylindrical iron poles on its inner and outer curved surfaces.

This type of MB exerts passive (i.e. permanent magnet induced) restoring forces on the rotor when it is radially displaced (self-centering). In the axial direction, however, it is magnetically unstable.

Fig. 1b shows a 2 axis active MB of the type used in the wheel, described hereafter.
It consists of three annular elements arranged as concentric rings in a common plane. The middle element consists of a ring of axially magnetized permanent magnets sandwiched between flat ferrous pole plates. The inner and outermost elements simply consist of shaped iron rings.

In this type of MB, the rotor experiences a passive stable restoring force when it is axially displaced, but it is unstable radially. The active control has to include two independent electromagnetic coils, i.e. one for each principal radial axis.

Whichever configuration is chosen, the actuator can be separated or integrated with the static Magnetic Bearing. In both configurations, tilting stiffnesses are passive.

The coils receive their excitation signals from electronic servo-loops. The error signals of the latter are derived from the radial displacements of the suspended rotor from its nominal (centered) position.

Fig. 2 shows how the coils are incorporated in the bearing and how they exert the necessary stabilising forces. Only one coil of four is shown.

Using only speed sensors can provide stability of the rotor. In this case the lift-off of the rotor needs a particular sequence, because when the rotor is against the stop, the servo-loop is open.

In a 1 axis active MB, the unbalance rotating forces of the rotor have no effect on the servo-loop (because these forces act principally in the radial direction).

In a 2 axis active MB, a cancellation of the unbalance can be provided by a special law of the servo-loop. This becomes an advantage in applications that call for a very low transmissibility of vibrations to the surrounding spacecraft.

Compared with 1 axis active wheels, the most obvious difference is the more favourable shape : the present wheel is much flatter. It therefore takes up less volume and is much better suited to panel mounting.

The locking system could be much simpler. At the same time, it could be lighter, more robust and considerably easier to adjust.

With regard to manufacturability and serviceability, the 2 axis active concept represents a considerable improvement. Interlocking parts are entirely eliminated. Therefore, the assembly and dismantling of the wheel can be performed more quickly, leading to low costs. For example, the rotor can be simply lifted off the stator, giving access to all parts and making adjustments and eventual repairs very easy.

At last, but not least important, the 2 axis active type of bearing results in a wheel with high momentum/mass ratio. This is due to the fact that the operating speed may cross over the "critical" speed without incurring any vibrations. For this reason, this unit has been considered as a Reaction Wheel, but it can be used as a Momentum Wheel as well.

Design Description

A cross sectional drawing of the developed wheel is given in Fig. 3.

The unit incorporates the following features :

1.-Rotor.

The rotor consists of a heavy rim and a light, web stiffened, central disc portion. The high density magnets of the motor are integrated into the rim. They contribute to the required inertia.

The flat web is only needed to transmit Magnetic Bearing and auxiliary stops forces, not the locking mechanism ones.

2.-Electromechanical suspension.

A 2 axis active Magnetic Bearing-Actuator and displacement sensors levitate the rotor part so as to be completely free of contact with the fixed parts of the wheel.

2.1-Magnetic Bearing-Actuator.

Fig. 4 shows the bearing in somewhat more detail, including a top view. In this concept, the actuators are associated with the static Magnetic Bearing. This feature leads to a very compact design. The permanent magnet ring weighs only 150 grams. Four coils are distributed at intervals of 90 degrees around the inner bearing ring. Slots in the flange avoid leakage in adjacent coils.

Along each radial axis, a linear actuator consists of two diametrically opposite coils "halves", electrically connected to form an independent electric circuits. It allows us to add or substract flux into the gap according to the sign of the current.

All the control coils are redundant.

2.2-Displacement sensors.

A system of inductive type position sensors measures the radial position of the suspended rotor and provides the necessary error correction signals. This detection is fully redundant.

3.- Electromechanical drive system.

3.1-Drive motor.

The reaction torque is set up by a brushless ironless D.C. multipole motor, integrated into the rim. In spite of this location, a special feature reduces the drag torque (induced by eddy currents).

The permanent magnets of the motor are attached to the rotor rim and thus make a useful contribution to the inertia.

The ironless armature consists of an array of copper windings embedded in an epoxy material for mechanical rigidity and support. By means of a special winding design, the ripple torque developed by the motor has been kept to less than 3% peak-to-peak of the demanded reaction torque.

3.2-Opto-electronic angular detection.

This part is basically a coarse angular encoder and generates information on the angular position of the rotor for motor commutation purposes. It is based on the interrupted light beam principle and uses solid state opto-electronic components as the light source and detection elements. To detect the rotation sign, two detectors are needed.

This design ensures high stability of the transient (instant and duration), at any speed.

All this detection is redundant.

4.- Touchdown bearings.

These provide for a safe landing of the rotor in the event of a failure occurring in the suspension electronic, or loss of power supply while rotating at speed. These ball bearings are dry lubricated. They only provide for radial support because the Magnetic Bearing gives axial support, even in the failed or switched-off condition.

Another function is to avoid peripheral contacts when slew rate is overshooting.

This central auxilary bearing is much more simple than a peripheral one and allows higher touchdown speeds.

5.- Peripheral locking mechanism.

A locking mechanism prevents "rattling" of the rotor in the severe vibration environment experienced during launch. It consists of a number of specially shaped carbon fibre spring plates arranged around the periphery of the rotor, and which can be drawn in by a steel cable so as to force the rotor downwards onto a conical seat.

Once in orbit, the steel cable is cut by a redundant pyrotechnic device, the rotor automatically goes up due to the axial restoring force and the magnetic suspension is then engaged. On ground, locking and unlocking are manually performed.

The load path between the rotor mass and the wheel attachment points to the spacecraft is very short. This allows for high stress during the launch of the satellite without any effects on further performances.

This method of locking is light, strong and reliable. It is also very simple mechanically and very accessible. The touchdown bearings are completely off-loaded when the rotor is locked.

6.- Built-in electronics package.

This performs the control functions associated with the 2 active axes of the Magnetic Bearing. It also performs motor commutation, power conditioning and suspension monitoring functions.

All electrical elements of the wheel are 100% redundant. This includes the electronic package, the Magnetic Bearing coils, the radial position sensors, the optical commutation devices and the pyrotechnics. Only the motor windings are not redundant, but a specific technology has been applied to ensure a very high reliability to those windings.

6.1-Suspension.
For the 2 radial axes, the suspension electronic :

- processes sensor signals,
- provides the requisite transfer function (corrector) giving rotor stability. For small radial displacement, the corrector is sensitive to the speed. This makes it possible to operate the wheel on the ground without dissipating any more power than is required in zero gravity conditions.
  But for large displacements, such as during lift-off, it acts with the position. Thereby, the lift-off is automatically performed as soon as the electronic is switched on.
- delivers current to the actuator, by a linear amplifier with a current servo-loop (current independent of the impedance and b.e.m.f. of the actuator).

6.2-Rotation.

Data from the angular detectors are processed, then commutators of each phase are controlled in accordance to the required sign of the reaction torque. Commutators are fitted with limiters in order to avoid the transient overvoltages.

Improvements for Very High Pointing Accuracy

All the potentialities of the Magnetic Bearing had not been exploited with the first technological model, developed for ESA.

For Very High Pointing Accuracy missions, improvements of some components of the Magnetic Bearing Wheel have been developed, in order to decrease the overall mechanical noise transmitted to the satellite platform.

The Fig. 5 shows the microvibration noise generation inside a Magnetic Bearing Wheel.

This noise could be expressed either in torque unit or in force unit related to the orthogonal distance between the application point and the satellite center of mass.

The microvibration contributors, in order of magnitude, are

- the static unbalance error. This is the most important contributor. It creates a rotating force at the rotor speed.
- the dynamic unbalance error. Due to the flat shape of the rotor, it is of minor importance. It creates a rotating torque at the rotor speed.

- the ripple torque of the motor is also of minor importance if the motor is designed for. It creates high frequency spectrum noise, depending on the number of commutations per round.
- the noise, generated inside the magnetic bearing control-loop, is quite neglegible.

There is obviously no tribologic noise, as encountered in Ball Bearing (races and balls noise), producing non-integer harmonics of the rotor speed.

For the first generation, due to the tight schedule, only mechanical type improvements have been implemented:

- high quality grade of rotor balancing (static and dynamic), using signal processing methods
- rotor assembly design ensuring a long-term stability of the mass distribution
- reduction of the ripple torque of the motor

The Fig. 6 shows the microvibrations, generated by the mechanically improved MBRW. The noise is expressed in N as a force, taking into account a lever arm of 1 meter.

For the next generation, improvements are foreseen, concerning the electronic part as

- optimization of the control laws of the magnetic bearing, including tracking notch filters
- electronic offset counteracting the mechanichal disturbances due to the static unbalance. The unbalance is continously estimated by observing parameters inside the servo-loops and computed with constant laws.

Taking into account these improvements, the equivalent rotor unbalance will reach values as low as 0.1 μm for a rotor of 7 kg. The improved model is under R&D development.

Characteristics/Performances of the HELIOS-SPOT4 Model

The main characteristics of the unit are

Momentum Capacity	: ±40 Nms
at maximum speed of	: ±2500 rpm
Reaction Torque	: ±0.45 Nm
Slew rate	: 0.08 rd/s
Mass	
Stator	: 7.4 kg
including electronics	: 2.0 kg
Rotor	: 7.1 kg
Total	: 14.5 kg

Dimensions

Diameter	: 355 mm
Height	: 135 mm

Power consumption

Magnetic suspension (whatever speed or torque) from -25°C to +65°C (-13°F to +149°F)	:10 W
Motor drive (at full speed and torque)	: 140 W

Environmental Capability

Temperature range	:-25°C to 65°C (-13°F to +149°F)
Vibrations (when locked)	
Sine •from 5 to 20 Hz	: 11 mm peak
from 20 to 100 Hz	: 20 g peak
Random (20-2000 Hz)	: 20 g rms

Drive Motor

Phases	: 4
Poles	: 48
Ripple torque (peak-peak)	: 3%

Magnetic Bearing

Diameter	: 165 mm
Magnetic Gap	: 0.8 mm
Mechanical Gap	: 0.2 mm
Axial stiffness	: 140 N/mm
Radial stiffness	: 480 N/mm
Tilting stiffness	: 470 N•m/rd
Active Force Constant	: 106 N/A
Friction torque @ 2500 rpm (proportional to the speed)	: 2.10^{-3} N•m

Development Programmes

The development of the new 40 Nms 2 axis active MBRW, which is designed for both HELIOS and SPOT4 programmes, started in 1989 and is still in progress. The HELIOS satellite will be launched in 1992. Three Reaction Wheels with high torque (0.45 N.m) allow fast maneuvers of the platform.

Other space applications of the magnetic suspension are foreseen, for areas in which classical technologies with ball bearings are not well fitted. Some are already under development :

- Large Momentum or Reaction Wheel for space stations (200 to 1000 Nms), especially suitable if microgravity experiments are performed on the spacecraft.

- Kinetic Energy Storage Wheel (associated with self-balancing device)
- optical devices such as scanning mirror or telescope pointing

By another way, the development of ERS 2 satellite, including 3 "one-axis" MBRW of 15 Nms and 0.2 Nm, began in 1990. Launching is scheduled for 1994.

Conclusions

The Magnetic Bearing Wheels that we have described are believed to be among the most advanced of their kind in existence today. It marks a significant step forward in the state-of-the-art of magnetic suspension devices, as well as a substantial advancement in the technology of actuators for space applications.

This Magnetic Bearing concept is very well suited for using in Reaction Wheels, in which application they enable significant improvements in attitude control system accuracy to be achieved. Magnetic Bearing Wheels won't take the place of Ball Bearing Wheels for standard applications. They will be used for High Pointing Accuracy missions. They are also competitive to control very large platforms.

The magnetic bearing part of the wheel, being a compact and self-contained sub-assembly, could easily be incorporated into other devices, like optical devices such as scanning mirror or telescope pointing.

References

[1] PENTLICKI C.J., POUBEAU P. : Magnetic Bearings Momentum Wheel. AIAA/CASI 6th Communication Satellite System Conference, Montreal April 1976.

[2] POUBEAU P. :Development of a satellite flywheel family operating on "one active axis" Magnetic Bearings. 11th Aerospace Mechanism Symposium, Goddard Space Flight Center April 1977.

[3] ANSTETT P.,SOULIAC M.,ROUYER C.,GAUTHIER M. : SPOT the very first satellite to use Magnetic Bearing Wheels. 33rd IAF Congres September 1982 (paper 82.331).

[4] GAUTHIER M. & ROUYER C. : Semi-active Magnetic Bearings for space application. 2nd European Space Mechanisms & Tribology Symposium, October 1985.

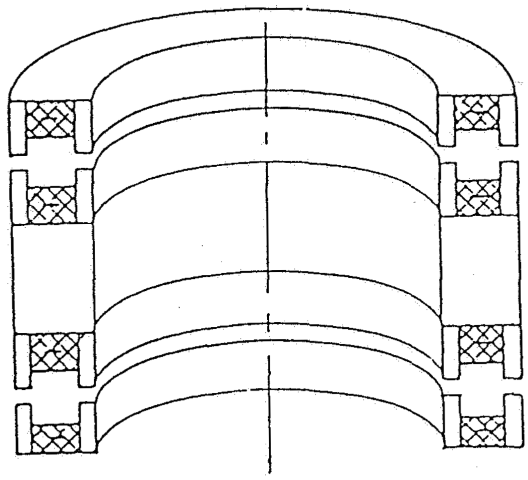

Fig. 1 a – 1 Axis Active
Magnetic Bearing

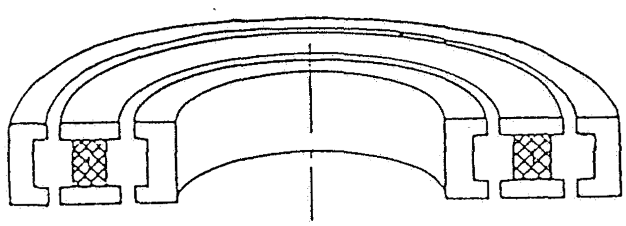

Fig. 1 b – 2 Axis Active
Magnetic Bearing

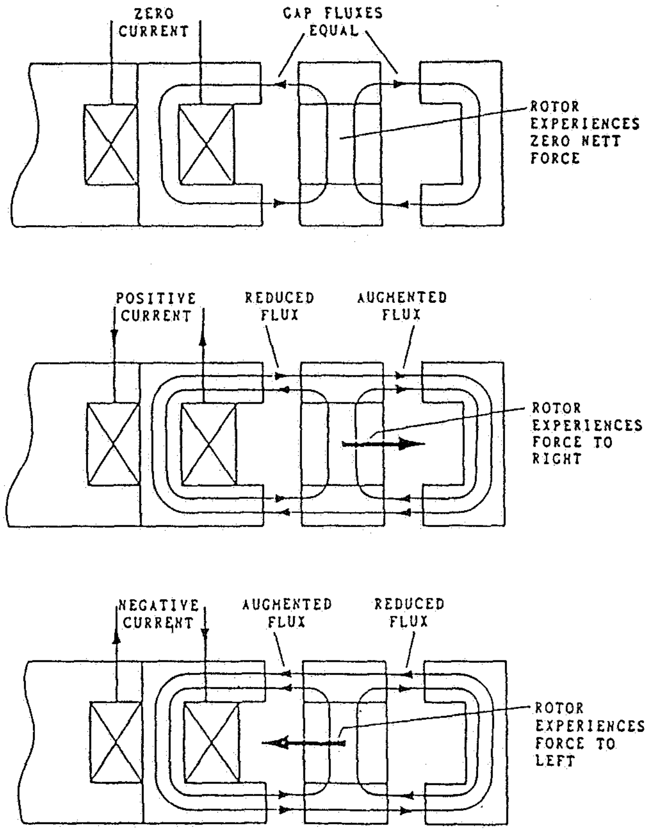

Fig 2 – 2 Axis Active Bearing principle

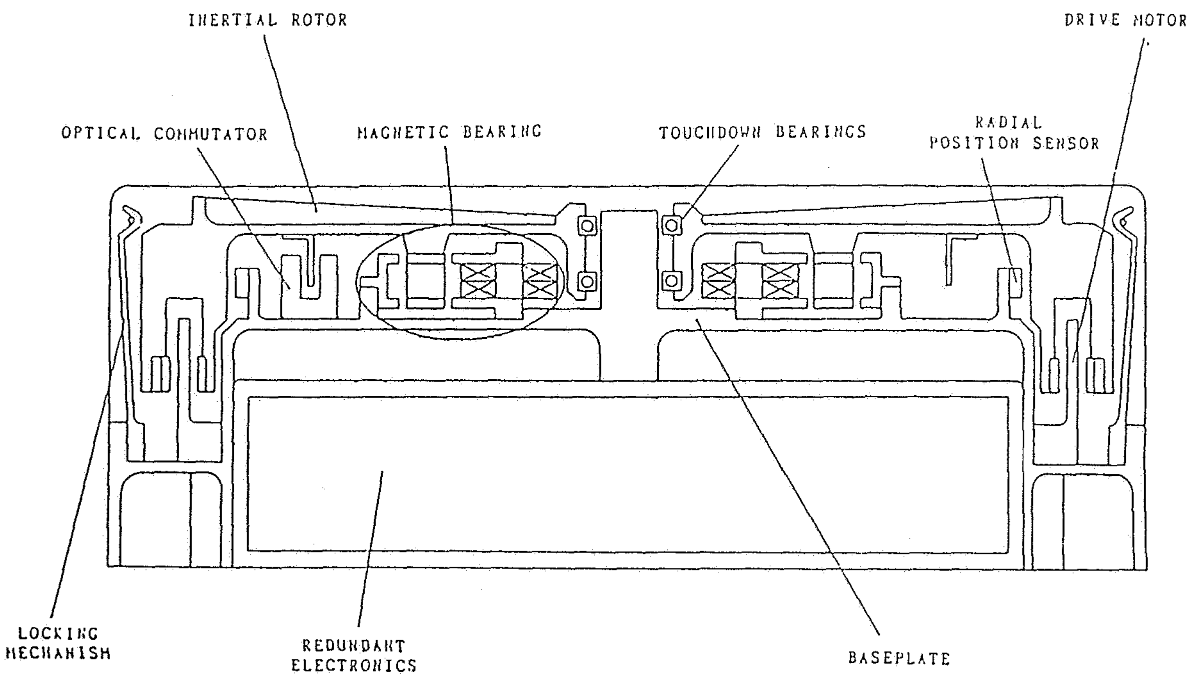

Fig 3 – Cross sectionnal view of the 2 axis active wheel

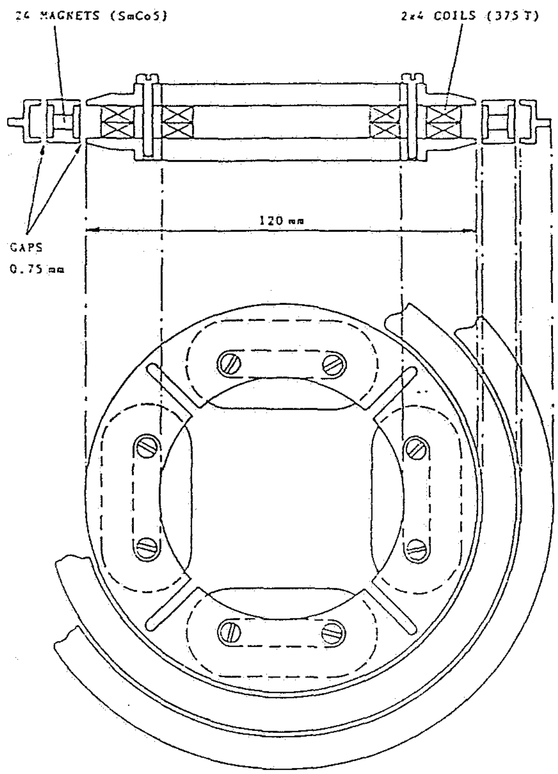

Fig 4 Top view of the bearing

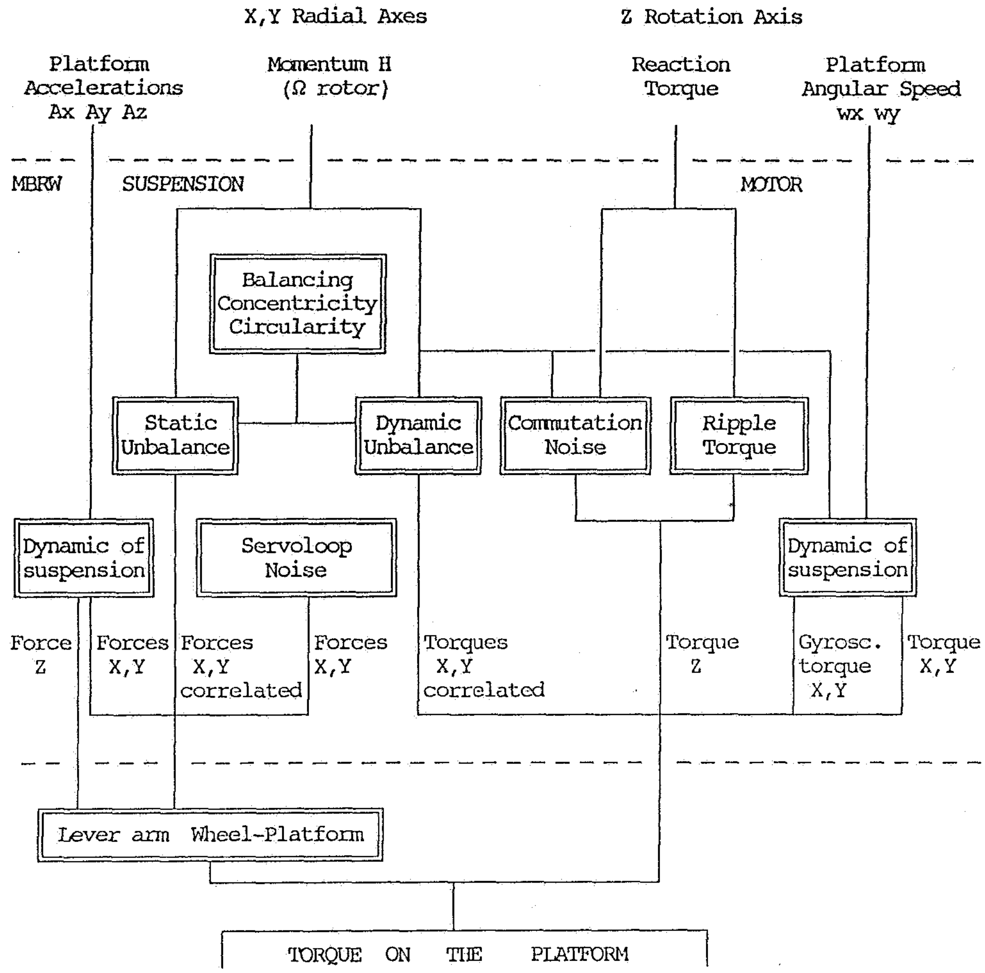

Fig 5 – Noise sources in a Magnetic Bearing Wheel

MICROVIBRATION LEVEL

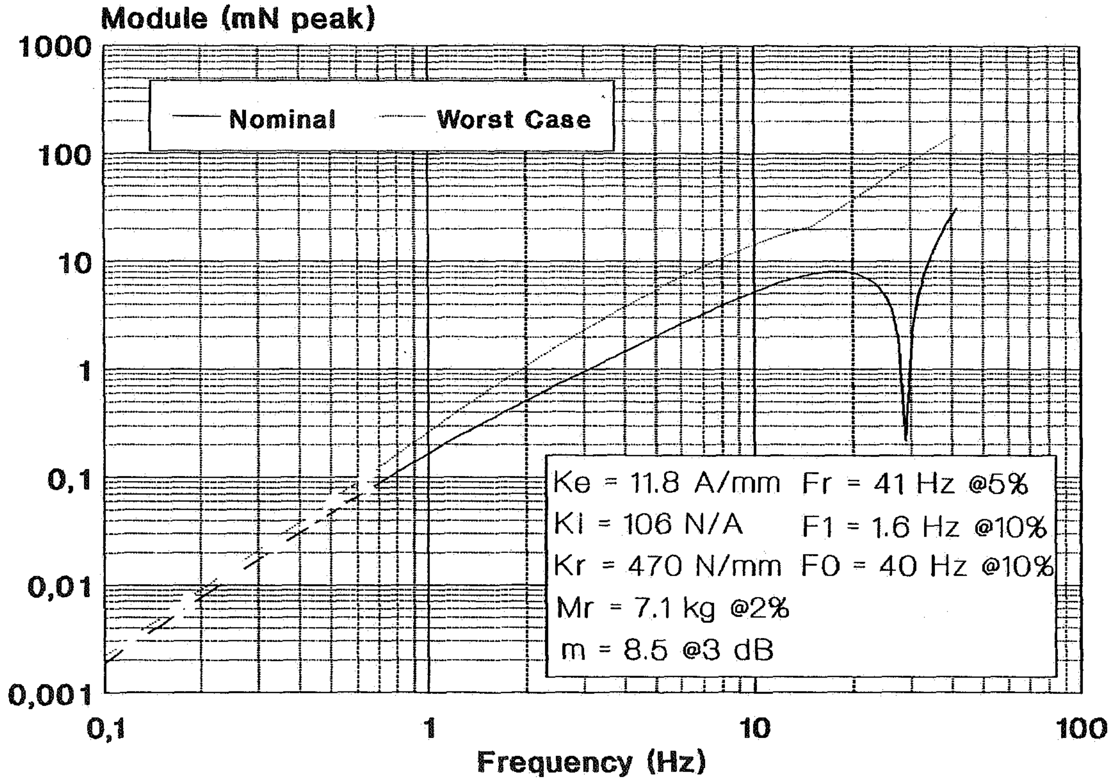

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Fig 6 –