AN OVERVIEW ON AEROSPATIALE MAGNETIC BEARING PRODUCTS FOR SPACECRAFT ATTITUDE CONTROL AND FOR INDUSTRY

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SUMMARY

Since now 25 years, AEROSPATIALE works on the magnetic bearing technology and has been awarded contracts with many customers in order to develop equipment for flight and ground applications.

Two generations of magnetic bearing reaction wheels are already in flight, onboard observation satellites :

- firstly on SPOT and ERS with 15 wheels in flight on 5 satellites,
- secondly on HELIOS spacecraft with 3 wheels in orbit.

Total cumulated flight time is now more than 88 years without any problem.

AEROSPATIALE Magnetic Bearing is based on the use of permanent magnets and on the control of the rotor around a zero force equilibrium point.

A **NEW GENERATION OF MAGNETIC BEARING WHEELS** for space applications is now emerging. The versatility of its basic design leads to a family of reaction and momentum wheels with tailored torque and kinetic momentum, together with **competitive** mass and cost.

Other applications of this technology are presently studied to position and actuate an optical mechanism for space active optics, or to isolate an experiment from space station generated

microvibrations or else to improve different high speed rotating devices.

1. INTRODUCTION

AEROSPATIALE has been developing magnetic bearings for more than 25 years now. Our products were developed with the help of national and international organizations, who provided us with specifications, funding and technological support and allowed us to reach our present technical excellence and to offer performing products to our customers.

The present paper recalls the chronology of Magnetic Bearing history at AEROSPATIALE, explains the inventive principle of the magnetic bearing and its applications in space., It describes how this technology matures through other competitive products.

2. MAGNETIC BEARING HISTORY AT AEROSPATIALE

During the seventies, AEROSPATIALE worked on internal funding and with the help of some customers to develop all the technologies required for space flywheels. They were designed for applications such as:

- Energy storage wheels for COMSAT and INTELSAT. It lasted until 1984 and allowed the realization of mock-ups and drawings of energy storage wheels.

- Momentum and reaction wheels for CNES and ESA/ESTEC, with a 50 Nms and a 150 Nms models.

Proceedings Third International Conference on Spacecraft Guidance, Navigation and Control Systems, ESTEC, Noordwijk, The Netherlands, 26-29 November 1996, ESA SP-381 (February 1997)

In 1978, AEROSPATIALE began the development of the 15 Nms reaction wheel for the SPOT 1 satellite(the French optical observation satellite). The wheel was also chosen for SPOT 2 - SPOT 3 and for the two ERS (European radar observation satellites). All these spacecraft are equipped with only 3 reaction wheels, with redunded electronics, as the magnetic bearing has no single point of failure.

In 1985, AEROSPATIALE began the development of the two axes magnetic bearing, with a first 66 Nms momentum wheel mock-up for ESA/ESTEC. This bearing is the best design to reduce the wheel

microvibrations together with high rotation speed rotors. This technology was selected for the SPOT 4 and HELIOS 1 programs, with 9 flight models of a 40 Nms and 0.45 Nm reaction wheel offering a **very low micro vibration** level. These same wheels will also equip ENVISAT (5 wheels), SPOT 5 (3 wheels), and METOP (3 x 3 wheels).

Presently, a more powerful model is being developed for HELIOS 2 military observation satellite, with a very stringent microvibration specification.

Different devices have been developed to use the magnetic bearing for other applications. We can mention energy storage accumulators for telephone exchanges, test bench actuators for nuclear bars wear studies, X-Ray tubes bearings, tape recorder for satellite, artificial horizon gyroscope wheels, ...

1970	Beginning of R & D on Magnetic Bearings at AEROSPATIALE
1973	First patent on Magnetic Bearings
1973-1979	Development contracts on Magnetic Bearings Systems leading to the delivery of 15 equipment for customers such as CNES, COMSAT, ESTEC, INTELSAT
1980	Industrial development of Magnetic Bearing Wheels for observation satellites
February 1986	First flight on SPOT 1 (3 wheels) launched by ARIANE Flight n° 16 Follow on series with SPOT 2, SPOT 3, ERS 1, ERS 2 (3 wheels each) 15 one-axis controlled wheels launched and operating without any problem
July 1995	Flight of the first two-axes controlled reaction wheel on HELIOS 1A (3 wheels) Follow-on series with SPOT 4 , HELIOS 1B, ENVISAT, and probably SPOT 5 and METOP (24 wheels)
1998	Qualification and delivery of AEROSPATIALE NEW GENERATION MAGNETIC BEARING WHEEL

Fig 1 MAGNETIC BEARING WHEELS HISTORY

SPOT 1	Launched 02/86	3 WHEELS	x 94608)	
SPOT 2	Launched 01/90	3 WHEELS	x 60288)	
ERS 1	Launched 07/91	3 WHEELS	x 47184)	769968 h
SPOT 3	Launched 09/93	3 WHEELS	x 28252)	
ERS 2	Launched 04/95	3 WHEELS	x 14304)	
HELIOS	Launched 07/95	3 WHEELS	x 12120)	

CUMULATED FLIGHT WITHOUT FAILURE > 88 YEARS

Fig 2 FLIGHT RECORD (11/96)

4. AEROSPATIALE MAGNETIC BEARING

AEROSPATIALE magnetic bearing principle is based on the use of permanent magnets which provide within the bearing :

- **a permanent field of force,**
- **an unstable equilibrium which is controlled by a servo loop.**

The reader will find sketches on figures 3.1 and 3.2. They show the different parts of a typical bearing :

The magnet ④, is located on the rotating par ⑧, for this particular design. It generates a magnetic field, which can be materialized through its flux lines. Those flux lines follow a specific path from Northern to Southern pole of the magnet, which is constrained along the iron parts.

Those iron parts ②, ③, ⑤, ⑥ constitute the favorite mean to curve a magnetic flux. Our particular skill is to design those parts in order to create the useful stiffness of the magnetic bearing. Then, it is the shape of the iron teeth, on both parts of the air gaps, which give our bearings all their characteristics and qualities.

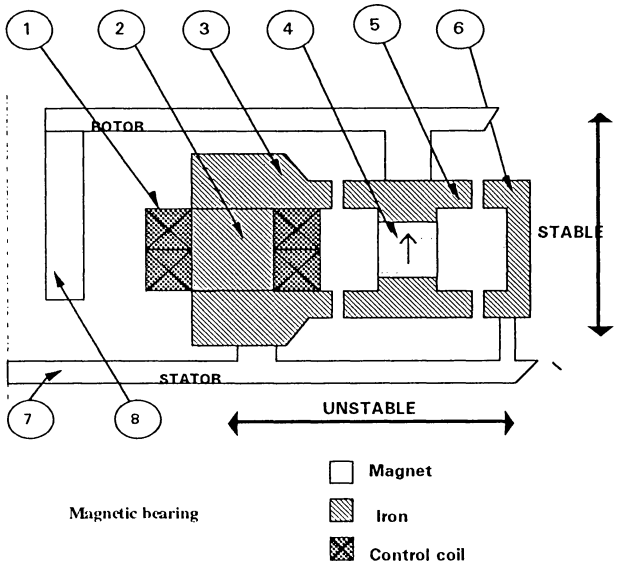
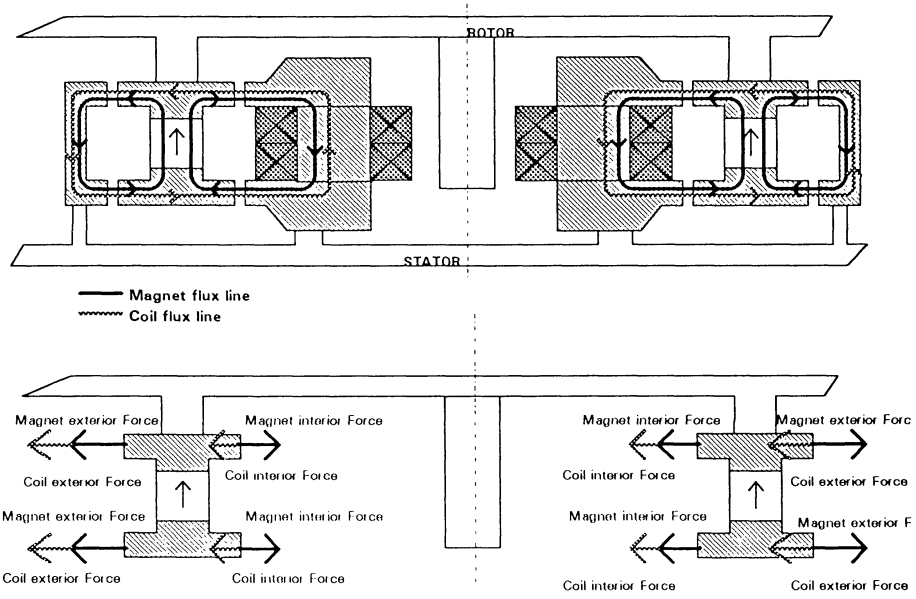


Fig 3.1



Coil and magnet flux lines and forces

WHEN CURRENTS CIRCULATE, RADIAL FORCES ARE INDUCED

Fig 3.2

Together, permanent magnets and the iron circuit generate a field of forces and torques, which keeps the rotating parts within the teeth of the stator (the static rigidity on the stable axes) while creating an attraction (or a repulsion) towards both sides of the air gaps stator (the cause for the unstability). Attraction forces within the air gaps are shown at the bottom of figure 3.2. Without any external force and with a null coil current, those attraction forces are equal somewhere close to the middle of the air gaps, and they define a point of equilibrium.

The coil ① is used to restore stability within the bearing. Its electrically generated magnetic flux modulates the permanent flux of the magnet, so that the rotor may be positioned in the central part of the air gaps. Position sensors and an electronic control loop command the current in the coil to that effect.

The goal of the control loop is to stabilize the rotor in position, so that it levitates. In fact, the rotor is stabilized on the unstable equilibrium point, so that no significant force needs to be exerted on it. In consequence, no significant electric current is required to keep the rotor in position, even in a 1 g environment, as long as the air gap and the bearing stiffness are compatible with the external force. Due to this property, all our space wheels may be operated on ground, without any additional ground equipment.

5. THE PRESENT APPLICATIONS IN SPACE

AEROSPATIALE MAGNETIC BEARING WHEELS

CHARACTERISTICS	SPOT 1 reaction	SPOT 4 reaction	SPACEBUS momentum NG A series	SPACEBUS reaction NG B series	SPACEBUS reaction NG A series
Kinetic Momentum Nms	15	40	60	12	20
Torque Nm	0,2	0,45	0.075	0.075	0.15
Rotor Speed rpm	2 400	2 400	10 300	10 300	6000
Constant speed power including motor power W	14 1	50 24	12 2	12 2	10.5 1.5
Max. torque power including motor power W	115 64	190 140	120 80	120 80	120 80
Mass kg	8,4 + WDE	17 + WDE	8.2 (WDE included)	6 (WDE included)	7.4 (WDE included)
Onboard satellites (* when in flight)	3 x SPOT 1* 3 x SPOT 2* 3 x SPOT 3* 3 x ERS 1* 3 x ERS 2*	3 x Hélios 1A* 3 x Hélios 1B 3 x SPOT 4 6 x ENVISAT 6 x SPOT 5	SPACEBUS 3000B	SPACEBUS 3000B	SPACEBUS

Table 4. Aerospatiale Magnetic Bearing Wheels

The SPOT 1 Type Magnetic Bearing Wheel

To date, 15 models of this first generation of magnetic wheel, the first to be flown on the SPOT spacecraft, has been manufactured. Their magnetic bearing is a one active axis type with its unstable axis along the rotation axis of the wheel. An active electromagnetic control allows the axial positioning of the wheel.

A4 phases brushless torque motor creates the required reaction torque, which causes the rotation of the rotor (the kinetic momentum).

The design is dual redundant, to allow the functioning after any first failure. The electronic and electrotechnical parts are all dual redundant, except for the motor coils, who are specially protected.

The SPOT 4 Type Magnetic Bearing Wheel

For this second generation, AEROSPATIALE designed a product with higher torque and kinetic momentum, and providing a greater growth potential in dynamic control, especially to reduce its microvibrations.

The magnetic bearing is here a two active axes type, with two radial unstable axes. This disposition allows a better radial control of the wheel, and hence, has been chosen to better control the rotor unbalances. Two control loops allow the radial positioning of the wheel.

Otherwise, its technology is the same for the two types of wheels.

NEW GENERATION WHEEL

SPACEBUS Momentum and Reaction Wheels

This New Generation Wheel has been designed to match the requirements of modern satellites, in terms of performances, quality and efficiency. It uses the main basic designs as the other wheels, with a two active axes type bearing and a brushless torque motor. Except for the dimensions and characteristical figures, the main technological differences lay in the high rotation speed of the rotor, the 3 phased torque motor, a digital electronics, the absence of any redundancy and a newly designed locking device (with a form memory alloy actuator).

Its basic characteristics are shown on table 4, and correspond to the needs of geostationary telecommunication satellites, either for the momentum or for the reaction wheels and they are convenient for all different types of attitude control. In fact, this wheel is being designed to easily be adapted to any customer's needs. Its **evolutive** elements are shown in table 5 and are the rotor rim size and diameter (to adjust the required kinetic momentum with the allowed rotation speed) and the torque motor magnets height (to adjust the required torque with the max. allowed current). The rotor diameter may be reduced from 350 mm (A series) to less than 300 mm (B series) for the low momentum wheels.

One of the most remarkable features of this wheel is its overall design. It has been made to fulfill a technical mission, but the search for economies was always present. The result is a very competitive wheel, with all the required performance and a reasonable price. AEROSPATIALE is investing important amounts of money and energy to make this product a great industrial success and a "best-seller" in its category.

Other Magnetic Bearing application

The magnetic bearing is a very powerful technology. Its use for space wheels is efficient, but its potential has to be exploited for other useful application, like the following examples:

- **Space Station Orientation Platform**, able to combine the precise positioning of an experiment while filtering the microvibration
- **Active Optics Actuator**, able to finely position and actuate (1 or several mobile axes) a mobile subassembly within a telescope.
- **High Speed Rotating Axis**, for pumps, compressors, gyroscopes, etc.. to guide without friction and wear the rotating axis.

AEROSPATIALE has studied different magnetic bearing designs to have a suitable design to all these different applications. They have 1 active axis, or 2, or even 4 or 5, depending on the specific requirements. Their stiffnesses are important to precisely position the rotor, or very low to filter mechanical vibrations. AEROSPATIALE has all the required skills to design the bearing you need, or to adapt an existing design to your problem.

MAGNETIC BEARING WHEEL ADAPTABLE ELEMENTS

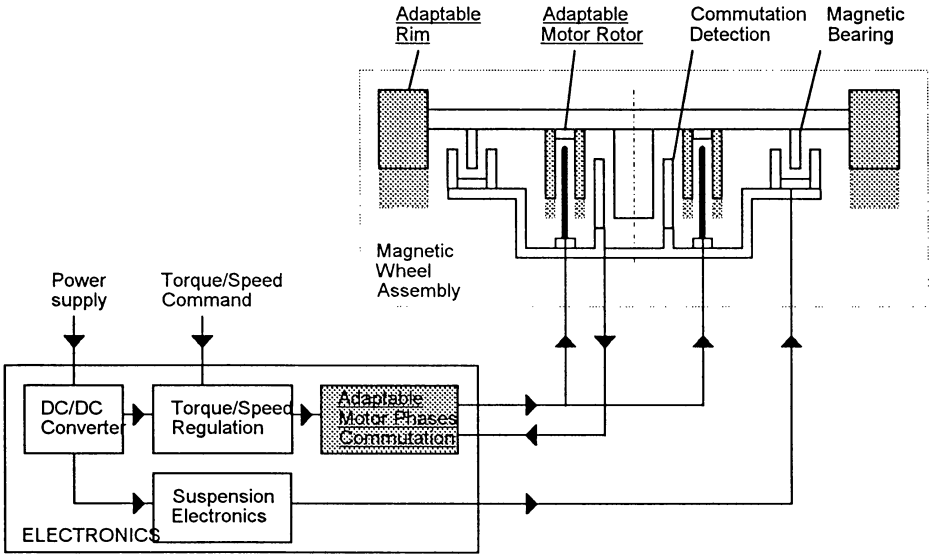


Table 5. SPACEBUS Momentum Wheel Adaptable Elements

AEROSPATIALE MAGNETIC BEARING WHEELS

GENERATION		1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
SPOT 1	SPOT 1 - 2 - 3	♀♀♀	♀♀♀ ■			♀♀♀ ■				■									
	ERS 1 - 2						♀♀♀	■		♀♀♀		■							
SPOT 4	SPOT 4- HELIOS 1					----	-----	-----	-----	-----	♀♀♀	♀♀♀ ■	♀♀♀	□	□				
	ENVISAT												♀♀♀ ♀♀♀			□			
	SPOT 5*																♀♀♀		□
	METOP *															♀♀♀	♀♀♀	♀♀♀	□
HELIOS 2	HELIOS 2											---◊--	------	---◊--	------	♀♀♀	♀♀♀	□	
NEW GENERATION WHEEL	SPACEBUS* PROTEUS*												------	---◊--	---◊--	♀♀♀ ♀♀♀	♀♀♀ ♀♀♀	♀♀♀ ♀♀♀	♀♀♀ ♀♀♀

*Expected order
⇧ Flight items
■ Date of launch
◊ Test Model
□ Expected date of launch

Table 6. AEROSPATIALE Magnetic Bearing Wheels production

MAGNETIC BEARINGS FOR ROTATING MACHINES

APPLICATIONS		STIFFNESS			CURRENT ROTATION SPEED	ROTOR MASS
		X	Y	Z		
Gyroscope	MB 11-02				24000 rpm	
Mini Pump	MB 11-03					
Reaction Engine		200 N/mm	200 N/mm	700 N/mm		0.35 kg
Simulator	MB 11-03				90000 rpm	
X-Ray tube	MB 24-01					
Chopper	MB 24-02	200 N/mm	200 N/mm	40 N/mm	36000 rpm	1.5 kg
Compressor	MB 24-04					
Vibration Simulator for Nuclear Application	MB 12-01	200 N/mm	200 N/mm	150 N/mm	36000 rpm	1.5 kg
Turbomolecular Pump	MB 25-03	2000 N/mm	2000 N/mm	400 N/mm	42000 rpm	2.5 kg
Wheel Energy Storage	MB 11-01	100 N/mm	100 N/mm	10000 N/mm	12000 rpm	360 kg

X, Y, Z passive or active axes

Table 7. Magnetic Bearings for Rotating Machines

CONCLUSION

This rapid survey of AEROSPATIALE products shows how efficient magnetic bearings are for different applications. It may be used either for increased reliability and reduced micro vibration on satellites or for particular industrial uses with competitive characteristics.

Our industrial teams now are well trained either to manufacture existing products or to study and define new ones to fit specific needs.

They just have realized an industrial revolution, by designing **our NEW GENERATION MAGNETIC BEARING WHEEL**: this product has been conceived with a design-to-cost point of view and with a customer-oriented philosophy. The result is a low cost, low weight wheel, robust to vibration and high temperatures and easily adaptable to a large scope of requirements.