

500'000 rpm rotational speeds thanks to magnetic bearings

Applications with high rotational speeds require outstanding bearing solutions. Air and magnetic bearings are increasingly used in place of ball bearings. When operated in vacuum, magnetic bearings offer the most advantages. A new concept for rotational speeds above 500,000 rpm will provide a durable basis for optical systems and satellite reaction wheels.

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Which bearings for which application? This question is often asked in connection with ultra-high-speed drive systems. On one hand, speed, lifetime, acceleration, temperature and available space confront engineers with arduous challenges, while on the other hand, the requirements cannot be more different: start/stop sequences or continuous operation; operation in vacuum, gas or fluids; cryogenic applications or extreme environment temperatures; strong vibration impact on the bearing versus minimal accepted vibrations by the bearing, such as in satellites, etc.

Above 100,000 rpm on, there is a need for customized bearings

The expected number of units and manufacturing cost also plays a role in the selection of the bearing. Applications with rotational speeds exceeding 100,000 rpm require a customized bearing. The following Table shows the advantages and disadvantages of different types of bearings.

Type of bearing	Advantages	Disadvantages
Ball bearing 	<ul style="list-style-type: none"> ▪ Rigidity/bearing force ▪ Availability ▪ Compactness ▪ Start/stop sequences ▪ Cost 	<ul style="list-style-type: none"> ▪ Vacuum not possible (for high rotational speeds) ▪ Lifetime limitations (especially with very high rotational speeds)
Air bearing 	<ul style="list-style-type: none"> ▪ Lifetime (especially in continuous operation) ▪ Rigidity/bearing force ▪ Compactness 	<ul style="list-style-type: none"> ▪ Vacuum not possible ▪ Limited number of start/stop sequences ▪ Limitation of rotational speed through production tolerances, instability and losses
Magnetic bearing 	<ul style="list-style-type: none"> ▪ Lifetime ▪ Vacuum possible ▪ Active control or rotor dynamic and vibration 	<ul style="list-style-type: none"> ▪ Complexity/size ▪ Speed limitation through reactive power and losses ▪ Cost

Figure 1. Overview of possible bearing solutions for high rotational speeds

Ball bearings

Ball bearings offer advantages regarding rigidity and bearing reaction. Furthermore, they are low cost and compact. On the other hand lifetime and rotational speed are limited due to high mechanical abrasion and losses. In addition, ball bearings do not qualify for operation in vacuum, as the lubricant could evaporate.

Gas bearing

There are different designs of gas bearings, namely static and dynamic gas bearings. Static gas bearings require an external compressed gas supply, whereas in dynamic gas bearings, the gas cushion is generated through its own rotation. This article only considers the latter, as static gas bearings are only used in stationary applications.

There are some commonalities between dynamic gas bearings and ball bearings – the high rigidity and bearing reaction as well as the compact size. Crucial disadvantage is that it is not possible to operate in a vacuum. Compared to ball bearings, the lifetime of gas bearings in continuous operation is theoretically unlimited, but has limitations for applications with many start/stop sequences. At every start, a new gas cushion is built up in a gas bearing. Therefore, below a certain minimum rotational speed, mechanical friction occurs. Furthermore, there are big challenges regarding production tolerances and the design for sufficient stability and low losses.

Magnetic bearing

Similar to the gas bearing, the magnetic bearing increases the lifetime of the drive system to a theoretically unlimited period. It is the only type of bearing suitable for operation in vacuum, since the bearing forces are generated independent from the surrounding atmosphere and are purely electromagnetically with no lubricant needed. Disadvantages are complexity, size, and cost. In addition, current designs only provide solutions for limited rotational speeds of up to 120,000 rpm. The working principle of a magnetic bearing is depicted in Figure 2.

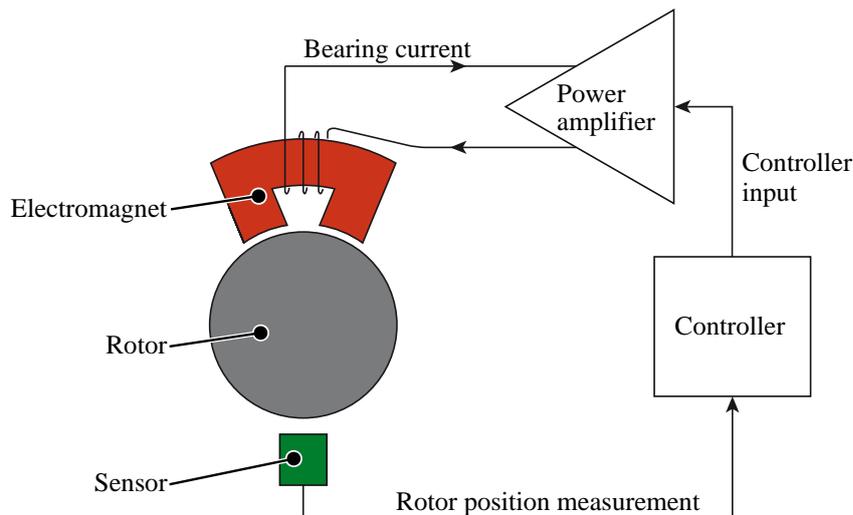


Figure 2. Functional principle of an active magnetic bearing

Application examples for magnetic bearings

- Optical systems with high rotational speeds such as a beam chopper: These applications are operated in a vacuum or helium atmosphere to minimize air friction losses, and to protect the optic from pollution. The disadvantages of magnetic bearings regarding space requirements and complexity are not critical, as the whole optical system is much bigger and more complex than the bearing itself.
- Reaction wheels for satellites: Reaction wheels are used in satellites to control and stabilize the attitude in the space. They are moved to the desired position by rotational speed regulation. As satellites depend on light components, reaction wheels are often designed with the aim to reduce weight by increasing the rotational speed. Furthermore, they should generate the lowest

possible vibrations suitable for the operation in full or partial vacuum. Therefore, the magnetic bearing turns out to be the optimal solution for this application.

- Special centrifuges and further physical test environments, such as the mechanical acceleration of particles.

New development for high rotational speeds

Most magnetic bearings are based on reluctance forces. A magnetic flux in the air gap between the stator and rotor generates these forces, whereas the flux is regulated by stator currents. In this magnetic bearing type, the rotational speed is limited due to increasing eddy current losses in the rotor and stator iron; a limited actuator bandwidth; and a high reactive power demand. Therefore, magnetic bearings have only been successful up to rotational speeds of a maximum of 120,000.

To overcome these rotational speed limits, a collaboration between the Power Electronics Systems Laboratory (PES) of ETH Zurich and Celeroton, has researched a new magnetic bearing concept. The new bearing enables rotational speeds of 500,000 rpm and more, which represents to the knowledge of the author, the world record for a magnetically levitated drive system.

The bearing is based on Lorentz forces instead of reluctance forces. A winding, which lies in the air gap between the rotor magnets and the stator iron, generates these forces – electric current in the winding regulates them. The magnetic field of the permanent magnet can also be used for the generation of the torque, which enables a short design for a bearingless motor. The working principle of such a motor is shown in Figure 3.

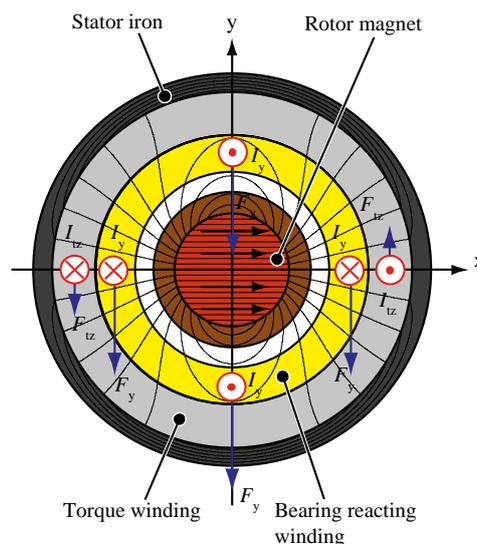


Figure 3. Working principle for the generation of forces (F_x , F_y) and torque (F_{tz}) of a bearingless motor with air gap winding.

Application example: Reaction wheel

The above mentioned reaction wheels for satellites are usually operated with ball bearings. However, there are some magnetically levitated models as well. These magnetic bearings are primarily used in large satellites due to the comparatively low maximum rotational speed. For compact satellites one must depend on reaction wheels with higher rotational speeds to increase the parameter of the reaction wheel – the angular momentum – proportionally to the weight.

Reaction wheels have been typically operated between 5,000 to 10,000 rpm, either due to the required lifetime or the maximum rotational speed. With the new magnetic bearing design, a rotational speed of above 200,000 rpm is theoretically possible, and thus the weight can be drastically minimized. With this new technology, a significant increase in rotational speeds in full and partial vacuum can now be realized.

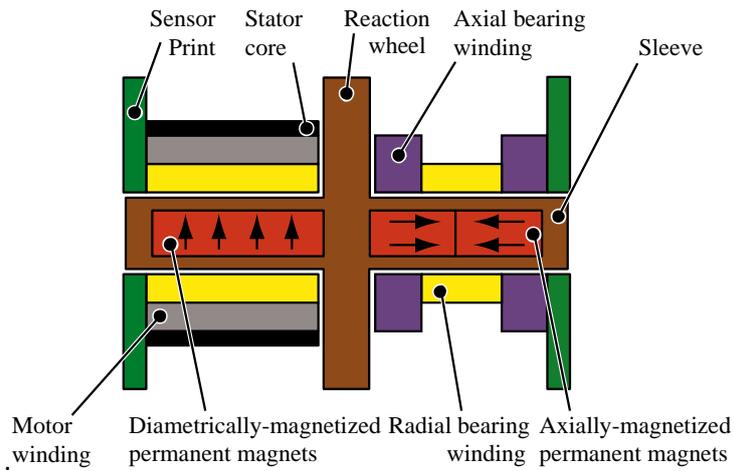


Figure 4. Cross section view of a magnetically levitated reaction wheel demonstrator.

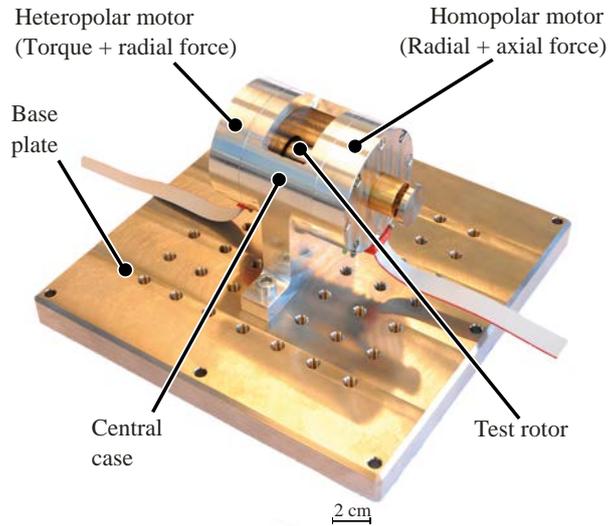


Figure 5. Magnetically levitated reaction wheel demonstrator with a rotational speed of over 200,000 rpm.

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