Review of Electrodynamic Bearings

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Abstract—**When Earnshaw stated his theorem in 1839, it did not seem possible to levitate objects in static magnetic fields. 100 years later Braunbeck 1939 was able to show mathematically that levitation is actually possible in unvarying magnetic fields for diamagnetic materials. Today levitating toys based on weakly diamagnetic graphite and permanent magnets are available on the market. Some other materials like superconductors or moving conductors have properties that to a much higher extent resemble those of diamagnets, and these may also levitate in a static magnetic field. Levitating experimental full scale trains based on both of these effects exist today. In this paper the most important technical achievements regarding electrodynamic levitation will be reviewed, dating from 1922 and on, with particular focus on rotating bearings and demonstrated levitating prototypes.**

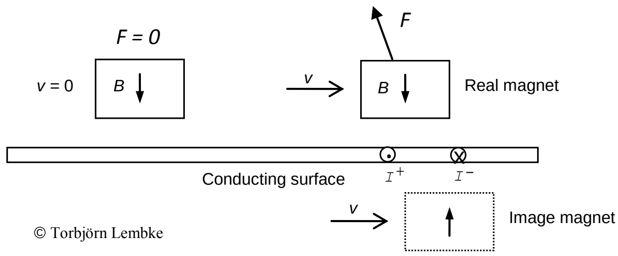

Figure 1. The electrodynamic repulsion principle. A magnet moves over a conducting surface, and forces act as if there is a mirror image below and slightly in front of the real magnet.

I. Early work

A. Introduction

When Earnshaw [1] studied the "Luminiferous Ether" he found that electrically charged particles could not be stably levitated in a static electric field. The same equation is, at least mathematically, valid for magnetic "monopoles" in a static magnetic field. This theorem has later been extended to dipoles and magnets of arbitrary shapes.

1922 Anschütz-Kaempfe [2] patented an apparatus for stable levitation based on the electrodynamic effect from an alternating field, which not contradicts the Earnshaw theorem. However, in 1939 Braunbeck [3] was able to show that levitation is actually possible in unvarying magnetic fields for diamagnetic materials like graphite.

Superconductors with Meissner effect are often described as perfect diamagnets and are the best example of Braunbecks findings. Today diamagnetic bearings with either graphite or superconducting elements are available on the market.

Actually, the Meissner effect itself is not necessary for levitation. The zero resistance of superconductors is enough, and this is a special case of the electrodynamic effect, in which the induced currents do not decay. Thus permanent levitation is possible. Should the resistance increase, the currents have to be constantly renewed by an alternating field created by AC-coils or moving magnets.

B. The "Magnetic Mirror"

The electrodynamic levitation principle above is based on Lenz´ law. According to this law a change of magnetic flux through a conductor will induce a voltage in the conductor in such a way that a current is produced that tries to maintain the magnetic flux at the original level. In reality this means that any changing electromagnetic flux will be reflected on a conducting surface, thus giving rise to repulsive forces. The maximum force is generated at infinitely high speed. This force can be calculated as if there is a mirror image of the real magnet on the opposite side of the surface. This is very much like the superconducting effect described earlier, and the bearings are equally strong, at least for high frequencies. At low frequency an electromagnetic bearing has very low lift force. Thus at low speed electrodynamicly levitated vehicles will have to touch down on for instance retractable wheels, while rotating electrodynamic bearings will require auxiliary or integrated touch down bearings.

The "magnetic mirror" analogy brakes down at low speed. However, the author has found it quite useful from a pedagogic point of view to illustrate the image magnet as a weaker magnet slightly in front of the real one trying to push it upwards and backwards as in fig. 1. The explanation would be that the image magnet is induced, not by the field itself, but by the field gradients, and they of course come in front of the real magnet.

C. First Patents

In 1922 Anschütz and Kaempfe [3] patented an apparatus for stabilization based on the electrodynamic effect. They levitated a stationary conducting spherical gyro platform in a varying magnetic field. The electrodynamic effect was used to stabilize the gyro, but since the field was too weak to levitate the mass of the body, gravity was compensated for by letting it barely float in a liquid.

This product does not seem to have come to much use, but it is historically important from one point of view. It demonstrates that eddy currents alone are not enough to levitate an object over a long period, since the heat generation both in the coils and in the conductor is too high. One way of gravity compensation is necessary so that the eddy currents only need to be responsible for the stabilizing centering effect.

However, for some applications heat generation is advantageous, like the one patented by Okress and Wroughton et al in 1952 [4]. It combines the effects of levitating, melting and mixing pure metallurgic specimens, a method that is still in use.

D. The Null Flux Scheme

The first successful method of reducing eddy current losses is known to have been presented by Powell & Danby [5], [6] who patented their solution in 1969 for use in a ground transportation vehicle. Later, several authors have proposed means of reducing eddy current losses in linear electrodynamic bearings for magnetically levitated trains, maglevs, based on their results. Powell & Danby introduced what they called the "Null Flux Scheme" for maglev applications, where a track of conducting coils are placed between oppositely directed superconducting magnets.

Later, in 1974, Powell & Danby also introduced an unloading device of superconducting coils and an iron plate [8], which they integrated into the design. The unloader allows the stabilizing coils to operate in the null-flux region.

A variant of this principle, used for rotating bearings, was patented by Sacerdoti et al, [7] in 1971. They used a rotating conducting plate between permanent magnets. The concept is described by the author in fig. 2 left. The benefit with the null flux scheme is that the conducting plate operates in a null or at least reduced flux region. Thus the magnets are arranged in such a way that they do not induce currents until they are needed, that is when the conductor position is of center.

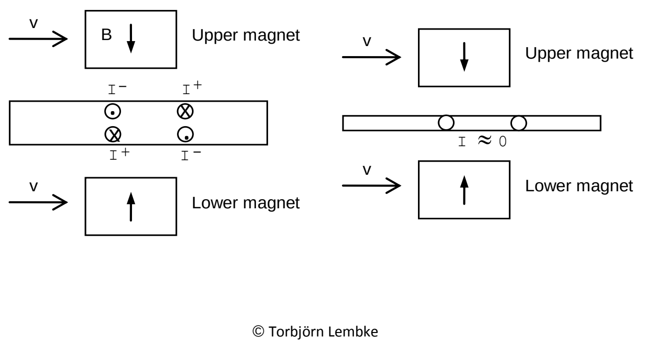

Figure 2. The null flux scheme. Magnets are placed over and under the plate oppositely. If the plate is thinner than one skin depth, most of the eddy currents cancel out.

For best utilization of the null-flux effect, the author [11] found that it is important to adjust the plate thickness to the skin depth. The plate to the left is more than two skin depths thick and there are surface currents counteracting each other but still producing losses. If the plate thickness is thinner than two skin depths the currents begin to cancel each other out, and when the thickness equals one skin depth or is slightly thinner, then the surface currents will almost cancel each other out, which is illustrated in fig. 2 right. This solution was analyzed by the author in 1989-1990 [11] and later patented for linear as well as rotating bearings in 1992 [12]. Figure 3 shows an axial and a radial bearing based on this concept.

To avoid confusion the author will refer to this concept as to the thin plate null flux scheme.

Most linear levitation principles above can easily be adopted to rotating bearings by simply "bending the track". Here there is the option to either rotate the magnets or to rotate the conductor. Since magnetic bearings are usually used for high speed applications, the solution with rotating magnets is not so attractive due to the need for proper bandages. Nevertheless, the majority of successfully demonstrated prototypes have rotating magnets, since this approach leads to less rotating losses and thus better stability.

The arrangement by Sacerdoti et al. was used as an axial bearing in a "Self-Centering Rotary Magnetic Suspension Device" which they patented [7]. It combined the electrodynamic axial bearing with rotating conductor with two permanent magnet radial bearings of reluctance type. These bearings were adjusted to compensate for the weight, so that the conductor could operate in the centered null flux region. It is not known to the author if this system ever levitated, but as described in the patent no damper was present, and thus stable levitation would not have been possible. On the other hand such details are often excluded in patent applications, so the author believes that the concept actually might have worked.

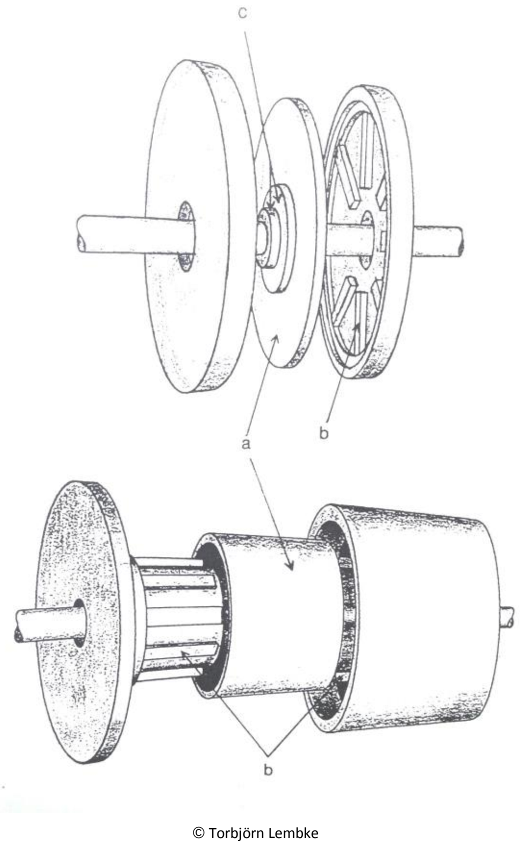

Figure 3. Axial eddy current bearing above, and radial bearing below, based on the thin plate null flux scheme. Both bearings are heteropolar.

One way to increase the lift capacity of these bearings is to use a halbach arrangement instead of the more simple south north arrangements shown. It is very well suited for the null flux scheme. Post et al. did lots of work in this field, both for linear guides and for rotating bearings for flywheels. [13], [16], [18]. Still, Halbach arrangements are seriously examined and investigated for linear transportation also without null flux configurations by for instance Cho et al. [31].

E. Homopolar Bearings

The bearings described above are all "heteropolar" and can be made as either linear or rotating bearings. However, for rotating bearings it is absolutely necessary to have some sort of loss reduction mechanism, otherways the conducting plate or coil will get overheated. A breakthrough for rotating bearings came with the invention of the "homopolar" design, shown in fig. 4 and 5. This concept is only possible with bearings with rotating conductors. The author filed a patent in 1997 [14], but the principle as such was described by Basore [9], [10] already in 1980.

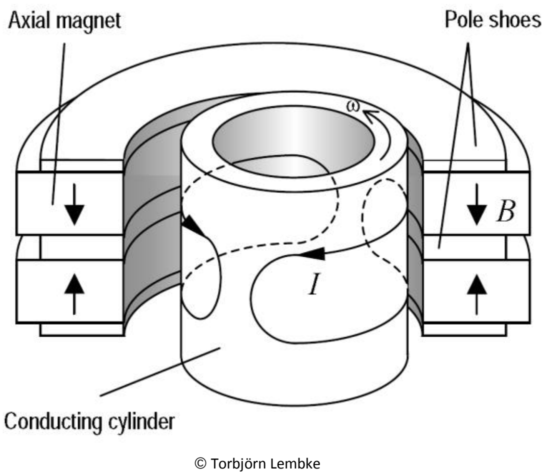

Figure 4. Working principle of homopolar bearing. Restoring eddy currents I are induced when the rotor is displaced.

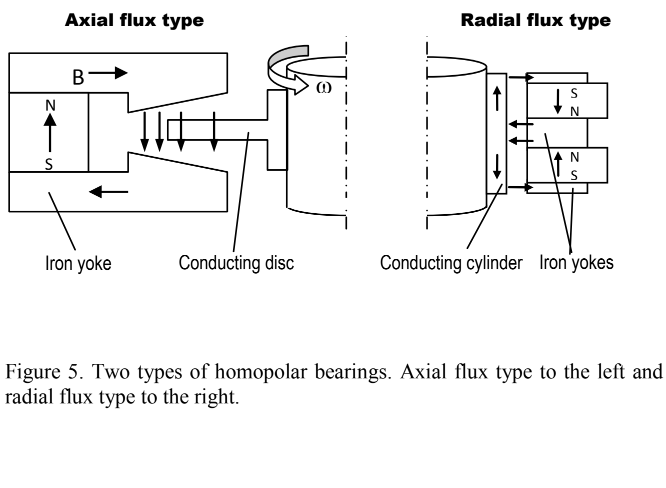

Figure 5. Two types of homopolar bearings. Axial flux type to the left and radial flux type to the right.

Bleuler et al. also did similar work at that time. [17] In 2000 they presented a levitating prototype, fig. 10. In a bearing with a homopolar field there are no induced voltages that need to be eliminated like in the multipole bearings above. Filatov [19] introduced the term "Null-E magnetic bearings" for this bearing concept, to distinguish it from the previously described "Null flux bearings". The circular design avoids the induction of any unnecessary eddy currents, as long as the rotor is centered in the bearing stator. The result is the same, but the homopolar concept is much simpler as no winding is required to avoid all the unnecessary eddy currents. Homopolar bearings can be of either of the axial flux or radial flux type, see figure 5. Filatov and Murakami et al. [15] focused on axial flux bearings and built as well a wire wound rotor and also proposed a solid rotor for a high speed satellite flywheel. The author [25], [26] focused on radial flux solid rotor bearings which have the advantage that they preferably are designed like conventional bearings, fig 11.

II. DEMONSTRATED PROTOTYPES

Many test rigs have been built by different research teams with the purpose to validate force measurements with calculated or FEM-simulated values. However, very few fully levitating prototypes are reported. The author designed one at SKF in 1990, fig. 6. It had one axial bearing, two radial bearings and one unloader of a push-pull magnet arrangement.

The shaft was connected to a gearbox via a flexibly mounted axial ball spline, so that the rotor could move freely both axially and radially, and it could also tilt.

The radial bearings were mounted in tuned rubber dampers, allowing the rotor to levitate stably from 8000 to 12000 RPM. The maximum tested speed was 14000 RPM, when the ball spline broke. A new axially rigid coupling was made, and the prototype still works after 24 years.

The temperature rise during long tests was interesting. The radial bearings got much warmer than the axial one. Obviously, the flat conductor in the axial bearing is more suited for null flux operation than the cylindrical conductor in the radial bearing, due to the geometrical difference between the inner and outer magnets.

Later the homopolar concept has also been demonstrated for full levitation. Bleulers and Sandtners prototype in fig. 10 was reported to levitate safely at 9000 RPM using an air turbine for propulsion. Much research is currently going on and several prototypes are about to be finnished in Europe based on different homopolar designs by Kluyskens et al. [28], [29] and Amati et al. [30], [32],[33].

Instead of solid conductors, it is possible to use wound coils. Filatov & Maslen [19], [20], [21] used rotating coils for the radial bearing and a repulsive PM-bearing for axial levitation and tilt control, fig 5. For improved stability they introduced a series connected inductor, something that was proposed already by Powell and Danby for linear applications. Filatov et al. made a testrig, and the prototype rotor is shown in fig. 7. It was demonstrated and safely levitated in the speed range of 1080 to 3000 RPM.

Figure 6. Prototype with heteropolar bearings designed by the author at SKF in 1990.

The rotor was powered by an external motor via a coupling which was disconnected for spin down tests, which could be performed down to the lower speed stability limit of 1080 RPM.

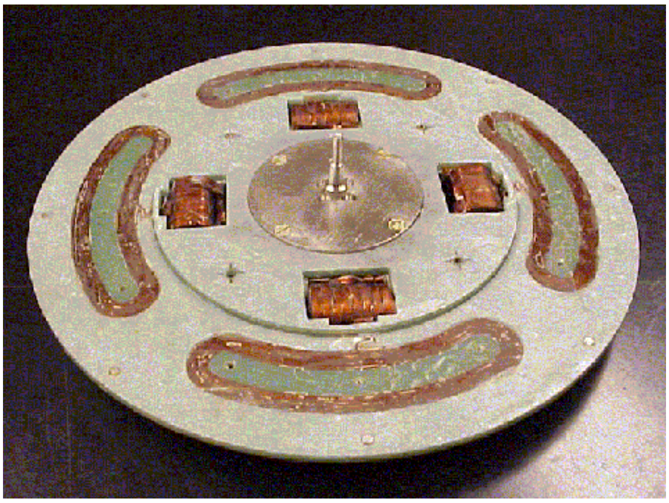

Figure 7. Electrodynamic bearing setup designed by Filatov et al.

Aspers [22] patented a system with rotating magnets between two wound coil systems forming an axial bearing. A null flux scheme is thus not required, since the induced coil voltage can be cancelled out by simply connecting the coils oppositely, fig. 8. This system, in a slightly simplified version, was analyzed by Sandtner & Bleuler [23], [24] and a fully operational prototype was demonstrated in 2004, fig. 9. Like Sacerdoti et al. they used permanent magnet radial bearings. They did mount them in dampers though. They reported a take-off speed of 4800 RPM and stable operation up to the maximum demonstrated speed of 6000 RPM.

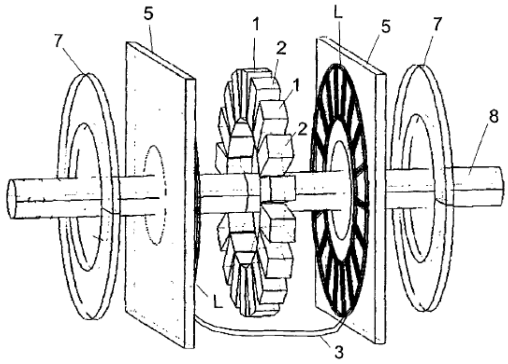

Figure 8. Aspers patented electrodynamic bearing

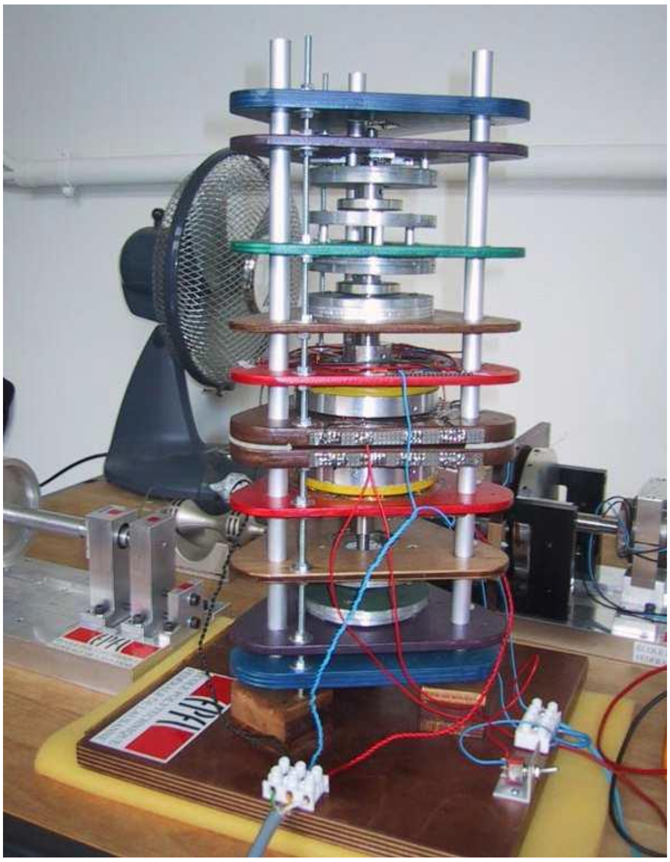

Figure 9. Aspers, Sandtners and Bleulers test rig.

The prototype also used the rotating magnets as motor magnets, by adding additional motor coils behind the stator windings.

As mentioned earlier, Bleulers and Sandtner also did work on homopolar bearings. Their prototype from year 2000 in fig. 10 was reported to levitate safely at 9000 RPM. The author has also tested this bearing, up to 90000 RPM in a vacuum pump [26], but it was not fully levitating since the pump had one ball bearing.

Damping is crucial for electrodynamic bearings [20], and particularly for homopolar designs, since the conductors need to be rotating. To understand the dynamics of electrodynamic bearings it is necessary take speed dependent rotating damping into account, and this has so far only been done by Filatov et al. [20], Kluyskens et al. [28] and Amati et al. [29]. To facilitate implementation of these bearings, some design methodologies have been developed by the author [11] and by Amati et al. [32].

Fig. 10. Bleulers and Sandtners test rig with air turbine and homopolar bearings.

Figure 11. Homopolar bearings allow for simple and idustrially attractive designs.

III. FUTURE PROSPECTS

To prognosticate the future for electrodynamic bearings might be too early. However, by comparing the levitating prototypes presented in this paper, some predictions can be made:

- Heteropolar designs are stable and easy to use and will be used for low and medium high speed, but are not so well suited for high speed operations.
- Conventional permanent magnet radial bearings have been successfully demonstrated together with heteropolar axial bearings, so this combination will likely also find a market niche.
- Homopolar designs are much stiffer and have lower losses and are simpler to manufacture than heteropolar bearings, so they are good candidates for high speed applications.
- The choice of dampers plays an important role, and to understand system dynamics is crucial but not trivial. Thus damper design will be an important research topic.

It is also undisputable that homopolar bearings, particularly in combination with passive axial bearings, exhibits extremely low losses and might provide engineers with means to develop new products or toys inspired by the reachless Perpetum Mobile.

Hybrids between passive, active and electrodynamic bearings might also evolve, each optimized for its specific application. Figure 12 shows such an example with a 1-DOF bearing with electrodynamic/active damper currently being developed by the author, [30], [34].

Figure 12. Reluctance type bearing with electrodynamic damper.

ACKNOWLEDGEMENTS

The author would like to thank, Alexei Filatov, Virginie Kluyskens, J. José Perez Loya, Jan Sandtner and Andrea Tonoli for their contributions and pictures to this paper, a paper which could have been much longer if all who have contributed to this research field through the years should have been mentioned. Hopefully this can be compensated for in a coming review article.

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