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## THE USE OF ELECTROMAGNETS AND PERMANENT MAGNETS IN MAGNETIC LEVITATION TECHNOLOGY

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Résumé - Dans le domaine des moyens de transport magnétique à grande vitesse, les électroaimants sont caractérisés par le fait que la tension qui génère le champ magnétique est créée par une bobine de courant, alors que dans le cas des aimants permanents on utilise un matériau magnétique. Afin de trancher entre les deux méthodes, les deux types d'aimants ont été mis à l'épreuve sur la plateforme d'essai des établissements Thyssen Henschel à Kassel.

Abstract - In the field of high-speed magnetic transport systems, electromagnets are characterized by the fact that the voltage which generates the magnetic field is created by an electrical ampere turn while in the case of permanent magnets, the magnetic field is generated by using permanent magnet material. In order to decide on the further concentration of development activities, the two magnets were measured on a magnetic test bench of the Thyssen Henschel company in Kassel.

## 1. INTRODUCTION

In the early seventies, the Federal Republic of Germany undertook research and development activities in the field of a high-speed electromagnetic transport systems in an attempt to improve the traffic situation between northern and southern Germany in regard to profitability, travel time, greater choice of means of transport, passenger comfort and environmental stress.

At that time, the electromagnetic support and guidance technology was considered as a principle that offered, at high speeds, potential advantages compared with the alternative wheel-on-rail system.

These facts led to an ambitious start of the research and development activities for this technology which may be of great importance in the future.

In the meantime, the electromagnetic rapid transit system has reached an advanced state of development.

On the Emsland Transrapid test facility with a projected 31 km long test track in the final construction stage, a 54 m long electromagnetic levitation vehicle will be tested in semi-operational conditions. Priority is given here to the verification as a means of passenger transport in Europe (figure 1).

Although this new technology has reached a semi-operational state in the meantime, the development of some components is still not considered to have reached maturity.

A technological program pursued in parallel to the high-speed electromagnetic transport system project incorporates the latest technical achievements in the development of magnetic levitation. In theoretical studies and practical tests this technological program investigates the feasibility of individual components.

Important goals of this technology program are e.g. the improvement of the long-stator propulsion technology with regard to efficiency and of the electromagnetics levitation and guidance technology. The system consists of the following main components:

- magnet
- chopper
- air gap sensor
- controller.

The mode of operation of these components is shown in figure 2.

Attracting ferromagnetic forces between magnet and reaction rail provide the supporting force. In the example given here the magnetic field is generated by a current-conducting magnetic coil. In order to stabilize the inherently unstable relationship between force and distance, the magnetic coil current is controlled as a function of the magnetic air gap. For this purpose, an air gap signal is measured and transmitted to a controller whose output signal in turn is sent to a current chopper. By changing the magnetic winding current, the magnetic force can be altered in such a way that a constant air gap of a few millimeters is obtained.

2. SUPPORTING MAGNET CONFIGURATION

The principle of the synchronous, long-stator motor requires a supporting magnet design allowing an alternative magnetic flux in the magnetic poles. In this case the supporting force is proportional to the square of the magnetic flux density in the magnetic air gap while the propulsion force results from the product of the magnetic flux density and the current induced in the reaction rail.

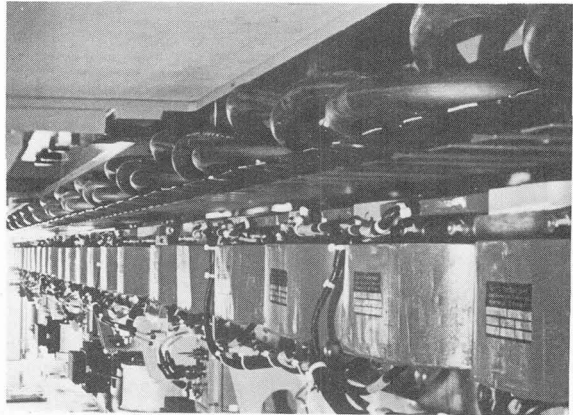


Figure 1: Supporting Magnets on Test Carrier TRO6 (Emsland Transrapid Test Facility)

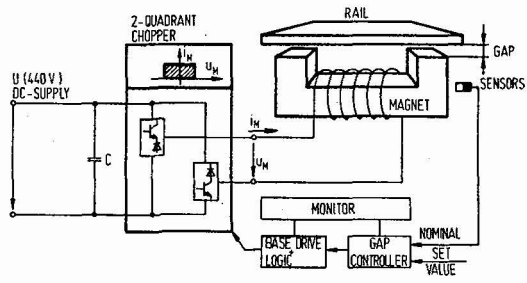


Figure 2: Magnet Control Circuit

The current induction is provided by a three-phase winding system which is inserted in slots of the reaction rail.

With regard to the application of this system, the so-called "magnetic wheel", in the magnetic levitation technique, the following aspects must be taken into account at the design stage:

- stationary force
- dynamic force variation
- light weight
- reduced consumption of energy
- low power requirement.

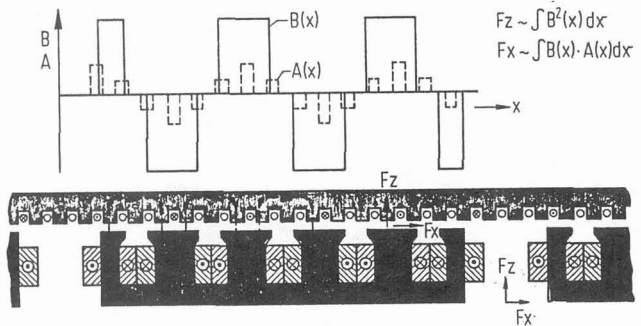


Figure 3: Principle of the Synchronous, Long-stator Motor with Iron Core

The electromagnets which have already been investigated and whose magnetic fields are generated only by means of electric winding currents are characterised by winding losses which cannot be neglected. Of particular importance are the losses resulting from the generation of the nominal supporting force.

Electromagnets working on this principle and whose magnetic forces are generated exclusively by winding currents have been tested many times; the calculation and construction methods are considered reliable.

The use of permanently excited magnets is based on the idea firstly to generate a magnetic field which corresponds to the nominal magnetic force by permanent magnets without loss and secondly to superimpose the variable magnetic field required for stabilisation by currents flowing through control windings. Permanent magnets with a high energy density (rare earth, cobalt) have lower power losses with regard to supporting force and magnet weight and are therefore comparable with electromagnets.

Permanent magnet have also been investigated and their suitability has been experimentally proved.

A permanent supporting magnet with the design features described above was designed and built at the TU-Braunschweig Institute for Machinery, Transmissions Railway Systems. In respect of nominal force and major dimensions this magnet is similar to the electromagnets which were used in the test carrier on the occasion of the International Transport Exhibition 1979 in Hamburg (IVA 79).

The representation of both configurations (electromagnet and permanent magnet) in fig. 4 shows that in the case of permanent magnets, the magnetic material is fitted in a collective arrangement in order to increase the flux density in the air gap.

### 2.1 Magnetic Force Characteristics

In order to define the magnetic force characteristics statial and dynamical measurements

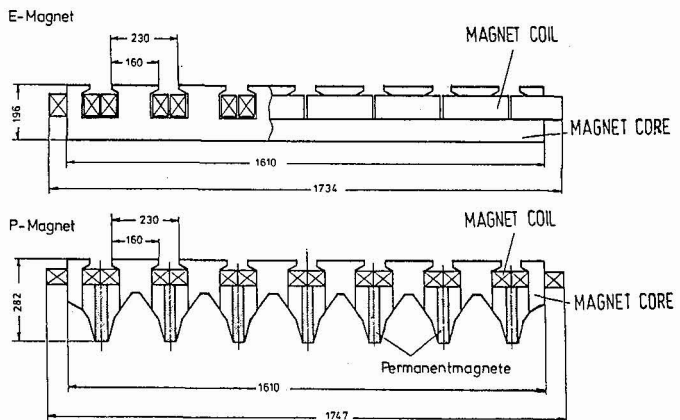


Figure 4: Electromagnet and Permanentmagnet

of both magnets were performed by THYSSEN HENSCHTEL in Kassel on a magnetic wheel test stand.

The characteristic curves (fig. 5) show the stationary relationship between supporting force and windings current as a function of the mechanical air gap between the surfaces of the magnetic coil and the reaction rail. The square slope function between force and current is given for both magnets only in the range of small magnetic currents and/or large air gap values. In the case of large magnetic currents and small air gaps, the degree of saturation of the iron leads to a flat characteristic curve.

Typical the permanent magnet is the fact that no additional excitation by means of a magnetic coil is necessary for a nominal supporting force of  $F = 20 \text{ kN}$  if the air gap amounts to  $7.5 \text{ mm}$ . An electromagnet, however, requires a winding current of  $I = 16 \text{ A}$ .

These data, valid for the conditions given, are only conditionally applicable since approaching an operational configuration the magnet is subjected to continuous dynamic and quasi-static extreme loads.

To assess the dynamic magnetic properties a parameter is usually indicated for a chosen working point with regard to the potential temporary change in force (force gradient).

This value is a function of both the instantaneous values of magnetic force and air gap as well as the maximum current chopper voltage. In the following, it is given for the nominal value of the investigated magnet and of a maximum current chopper output voltage of  $U_B = 580 \text{ V}$  (valid for each magnet (cf. table 1)).

Properties	IVA-P-magnet	IVA-E-magnet
force gradient for the nominal point ( $F = 20 \text{ kN}$ , $s = 7.5 \text{ mm}$ )	$dF/dt = 1.5 \text{ kN/ms}$	$dF/dt = 1.0 \text{ kN/ms}$
current dependence of the magnetic force for the nominal point	$dF/di = 1 \text{ kN/A}$	$dF/di = 2 \text{ kN/A}$
increase of the current as a function of time for the nominal point	$di/dt = 1.5 \text{ A/ms}$	$di/dt = 0.5 \text{ A/ms}$

Table 1: Dynamic Force

The current rise velocity is dependent on the number of magnetic coil windings while the force (dependent on the current) is conditioned by the magnetic flux.

The advantages of a high current rise velocity resulting from a small number of permanent magnet windings are partially offset by a greater current dependence of the magnetic force due to the high ampere turn values of the electromagnet since also the magnetic force features a square functional relation to the number of windings (ampere turn) given a constant magnetic current.

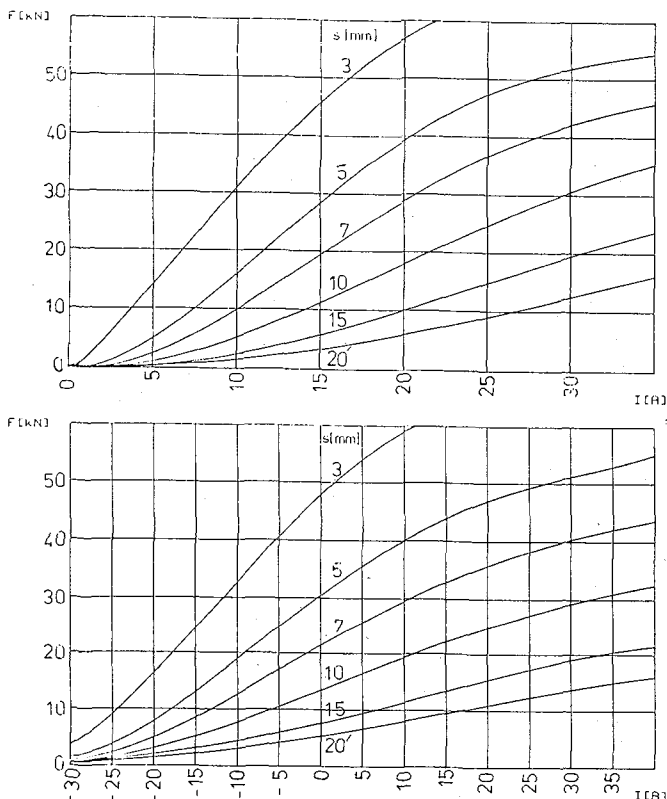


Figure 5: Stationary Characteristic Curves  
 a) E-Magnet  
 b) P-Magnet

2.2 Efficiency

Investigations which have been carried out so far show that supporting magnet used in the long-stator technology has to be designed for a maximum supporting force of  $F_{zmax} = 1.64 F_{znom}$  and a minimum supporting force of  $F_{zmin} = 0.5 F_{znom}$ .

A part of the dynamic force, i.e.  $F_{zdyn} = \pm 0.2 F_{znom}$ , is superimposed on these quasi-static loads. The resulting magnetic losses related to the nominal force are indicated in table 2.

A clocked dc-chopper feed the magnets. A unidirectional current flux is typical of the electromagnet supply; the voltage applied to the magnets must be provided in both polarities in order to allow a quick de-excitation of the magnets (2-quadrant chopper).

In order to increase the power rise velocity the maximum chopper output voltage has to be a multiple of the magnetic nominal voltage (sustained over-voltage  $\approx 6...20$ ).

Since permanent magnetic material is used it is necessary to intensify or weaken the permanent magnet flux. Besides the voltage polarity the direction of the current flux has also to be changed. This physical requirement makes it necessary to double the chopper performance (4-quadrant chopper).

The required chopper performance is the product of the maximum chopper output voltage (equal to the battery voltage) multiplied by the maximum magnetic current in positive (and negative) direction.

The maximum magnetic current required depends mainly on one of the following criteria:

- maximum magnetic force for the nominal air gap
- magnetic force for the air gap at lift-off
- magnetic force for the minimum air gap (de-excitation of the P-magnets).

The required chopper performance related to the nominal supporting force is indicated in table 2.

	E-magnet	P-magnet
Magnet losses related to the nominal force $P_V/F_{Znenn}$	36.5 W/kN	4.4 W/kN
DC-chopper performance related to the nominal force $P_S/F_{Znenn}$	0.72 kW/kN	1.5 kW/kN

Table 2: Power Characteristics

### 3. DESIGN AND ECONOMIC ASPECTS

The representation of both magnet configurations in fig. 4 makes clear that the design work and the manufacturing cost for the permanent magnet are comprehensive due to the mechanical arrangement of the permanent magnet material. The increased bending resistance represents an advantage for the application of magnetic units with a length of about 3 m. Furthermore the arrangement of the permanent magnet material in the form of an accumulator offers a favourable mechanical protection.

The permanent magnet is expensive due to the high specific price of the magnetic material and due to the increased manufacturing cost caused by the higher amount of machining work while the electromagnet is characterised by a higher energy consumption.

Since the portion of the overall onboard-power requirement is low as compared to the entire propulsion power this aspect plays a subordinate role. Of particular importance for the support and guidance function of the magnetic vehicle is the consideration of the consequences of the failure of individual components.

With the redundant power supply concept, described unter /4/, the critical failure mechanisms are limited to the magnets as far as the different ampere turns required for the permanentmagnet are provided by two 2-quadrant dc-choppers.

The power supply concept comprises 2-quadrant dc-choppers which, by means of appropriate monitoring devices, exclude the failure case "arc-through" considering the time  $t \leq 50 \mu s$  in the course of which the failure becomes apparent.

It is thus made sure that a malfunction in connection with the supply of an electromagnet can have an effect only towards the safe side (forceless state). In the corresponding supply of a permanent magnet, the currentless state of the exciter coils is also guaranteed in the event of a malfunction; the remanent flux of the permanentmagnet material persists, however. Hence results that failures occurring simultaneously on two magnets, located in the vicinity of a fulcrum, may cause the magnet to start and glide with a high propulsive force.

This failure can probably be mastered only be doubling the chopper number.

## 4. SUMMARY

The investigation results show almost the same force characteristics, related to the magnetic weight, for the electromagnet (6.15) and the permanentmagnet (6.4).

The value of the force gradient displays the advantage of the low permanent magnet inductivity. However, this advantage is significant only for a low battery voltage of the dc-chopper so that, with a battery voltage of  $U_B = 580$  V, taken as a basis for the investigations, also the electromagnet shows good dynamic properties. The necessity of a 4-quadrant operation of the permanentmagnets results in a higher chopper output to be provided for in connection with the required maximum currents, as compared to the electromagnets.

With regard to the magnetic power loss, the permanentmagnet in the accumulator arrangement shows very favourable values as compared to the other investigated magnet configurations.

This advantage, however, is partially reduced by the power required to feed the remaining onboard supply system so that the overall onboard power is diminished by about 18 % as compared to that of the electromagnet.

The disadvantage of the permanentmagnet consists in the double chopper number required to put two magnets, located near a fulcrum, in the forceless state in case these two magnets fail simultaneously.

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