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SCIENCE AND TECHNOLOGY

(FOUO 1/82)

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WEST EUROPE REPORT

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CONTENTS

TRANSPORTATION

TRANSPORTATION

CURRENT RESEARCH EFFORTS IN MAGNETIC LEVITATION TECHNOLOGY

West Berlin ZEITSCHRIFT FUER EISENBAHNWESEN UND VERKEHRSTECHNIK in German Oct 81 pp 311-319

[Article by Prof Dr-Eng Herbert Weh, Technical University of Braunschweig: "Research Efforts in the Areas of Magnetic Suspension Technology and Linear Drives"]

[Text] 1. Introduction

Contactless transport technology is still today at the beginning of its development. In the FRG the direction taken by magnetic suspension technology is characterized by a developmental trend in which components are employed for combined propulsive and support functions.

The area of application of various designs always enlarges whenever it is possible to improve the characteristics of the functional elements. This continues to be true when it is a matter of applying contactless transport technology to small vehicles and to goods transport. Both of these latter call for a substantial simplification and cheapening of the primary structural components.

The research studies described in the following paper relate in each case to subdomains of contactless support and propulsion technology. They are segments of the research projects carried out at the Institute for Electrical Machines, Propulsion Systems and Roadways of the Technical University of Braunschweig for the German Federal Ministry of Research and Technology (BMFT). These projects aimed at developing further improvements for the future application of magnetic suspension technology.

2. The Design of an Energy Supply for Long-Stator Drives

The long-stator drive presents us with the task of outlining and developing while maintaining the desired high efficiency a cost favorable procedure for processing energy and conducting it to the winding. Here one must take into account the need for keeping thrust variations low. There are also a number of technological prerequisites which must be taken into account here. For reasons of economy preference is given to the use of conventional switches to serve as switching elements connecting the winding sections with the power lines. The transmission voltage must be set at about 5 kilovolts in order to limit losses at the given conductor cross section.

The power feed design and winding arrangement for the Emsland Transrapid Test Facility (TVE) are shown schematically and in single phase in Figures 1a to 1c [1]. The winding sections are fed alternately by the inverted converters (WR) I and II. This synchronous procedure [2] permits a shockless motion of the vehicle from one winding section to another but on the other hand gives rise to only about 50-percent utilization of the inverted converters. The latter involve a pulse rectifier with automatic commutation which accounts for a substantial fraction of the cost of the substructure equipment. The engineering design which is still satisfactory for the test series of the Emsland project appears to be too expensive for the commercial use of magnetic suspension technology.

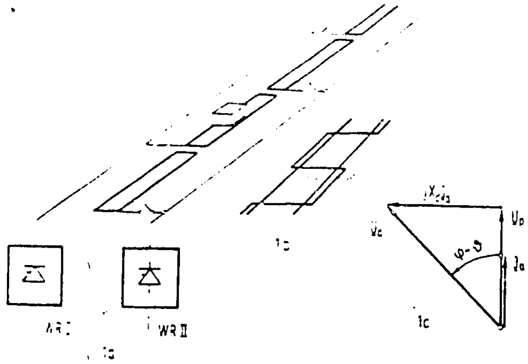

Figure 1. Single-strand winding, synchronous circuit (one slot per pole and phase).

The basic idea of a new design which is being investigated with the support of the BMFT is:

i. full utilization of the inverted converters and

ii. reduction of the apparent power of the winding sections.

By subdividing the winding strands of the three-phase winding into two parallel substrands and by feeding them separately through the inverted converters 1 and 2 it is possible to sharply reduce the inverted converter power by using the power feed scheme sketched in Figure 2a and 2b.

The circuiting is so selected that in providing vehicle power both winding strands carry current. Thus normally both inverted converters are in use. It is not necessary to hold an additional inverted converter in reserve. In addition there is the fact that as a result of the displaced longitudinal arrangement of the winding sections their total idling power demand is reduced in comparison with the single-strand arrangement. This situation is also shown in the voltage diagram 2c and there in particular corresponds to the length of the inductive voltage X_d/a'. For the same total length of the winding sections, the full magnitude of the surface magnetic energy is generated only by the section within whose two strands current is being carried. However, in comparison with the single-strand winding it has only half the length. On the remaining half of the corresponding section the magnetic energy is lower. Here the current in the winding is reduced by at least half so that the surface energy amounts to at the most one-quarter.

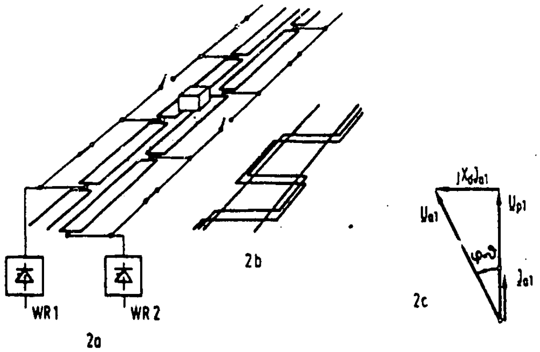

Figure 2. Double-strand arrangement, one inside the other.

If the "short-circuit system" is designed in accordance with Figure 2a then one must also take into account that in the unfed winding as a consequence of the magnetic field in the fed winding a current is induced which further weakens the primary field. The effect of this process becomes all the greater the more closely the two strands lie together (Figure 2b). In the case when the arrangement is in separate equidistant slots the coupling is about 20 percent. The resulting voltage drop then corresponds roughly to that of the diagram in Figure 2c. It may be seen that in comparison with the single-strand winding design one obtains a sharp reduction in the phase angle between current and voltage. The apparent power of the two circuits is clearly less than the apparent power of an unsubdivided winding.

It is evident that the procedure of double-strand displaced winding sections is not exclusively confined to the use of "short-circuit feed lines" but can also be used jointly with the tap line design (in analogy to Figure 1a). The two subconductors can here also without disadvantage be placed in a common slot. Examination of the problems of switching over shows that here, too, there are clear advantages on the side of the double-strand winding. In the case when the switching process compels a current interruption for one winding strand the residual thrust still amounts under the most pessimistic assumptions to 50 percent of the initial value. Through dynamic processes in the current circuit, through the tendency of the winding to keep the magnetic flux constant, the thrust-generating winding will, however, carry a somewhat higher current and will thus partially compensate the interruption of force.

In order to obtain a full smoothing out of the thrust variations the switching on of the new winding section can be carried out already prior to entrance of the vehicle. If one simultaneously employees in the other strand a somewhat increased current then the two common-fed sections can be operated at a reduced current with very slightly increased voltage. Since the startup processes take place very rapidly and can be very rapidly stabilized by means of the regulating system it is possible to avoid oscillations in the thrust if the inverted converters are slightly overdimensioned. The rated output of the inverted converters 1 and 2 taken together is also in this case no higher than that associated with about 50 percent of the power of the inverted converters I and II in the case of a single-strand winding.

3. Inverter Design for Short- and Long-Stator Drives

The magnitude of the drive power requires for the transport of energy transmission voltages in the range of 5 kilovolts. Low-loss linear drives are at the present time fed via automatically commutated inverted converters. This places a restriction on the conditions which must be met in order to obtain limited costs for the substructure equipment in the case of a long stator and to obtain low structural volumes and weights for a short-stator drive attached to the vehicle. In addition there is the fact that while it is possible for additional transformers to be used on the load side of the inverted converters in the case of the long-stator design nevertheless this gives rise to difficulties in achieving simple and cheap switching arrangements. Also in the case of short-stator drives a transformer on the vehicle implies an undesirable increase in weight which in turn must be paid for with greater drive power. Thus there arises a demand for frequency converters of sufficiently high voltage and having a design which is as simple as possible. Converter circuits which get along with natural commutation are most likely to meet this demand. Another argument in favor of such converters is the fact that semiconductor components are available which permit a higher blocking voltage and greater currents. Admittedly, the use of naturally commutating converters should not be insisted upon at the cost of having to operate the linear motor in a state of hyperexcitation. This could result in too great disadvantages for the overall process of energy conversions; with traditional inverted converter circuits it also implies limitation of the inverted converter function to frequencies which are not too low.

A compromise solution may be found if one employees adjustable idle current inputs on the load side, such as switchable condensers. They permit, e.g., natural commutation above 50 percent of the highest frequency while in the lower range they serve as energy reservoirs for the quenching circuits of the automatic commutation.

An inverted converter design operates throughout the entire frequency range without change in circuitry; its intermediate circuit is designed (Figure 3) in the form of a resonance circuit [3]. The connection to the primary power supply as well as to the load is through an inverting rectifier for single-phase connection to the oscillating circuit. This inverter is thus fully controllable with regard to frequency and power--in both directions, so far as the power is concerned. It requires for the primary power supply no idle current in reserve and imposes no requirements on the load resistance. Its control design is simple; its frequency range is large and not tied to the frequency of the primary power supply. A series arrangement of the rectifiers for adaptation to high operating voltages appears here to be far freer of problems than in the case of automatically commuting inverters. The described inverter design obviously eliminates the frequency variations so familiar with direct inverters but involves only two-thirds of the rectifiers required by the latter. Within the framework of the research project funded by the BMFT investigations are being carried out of the properties and dimensioning conditions of this type of inverter.

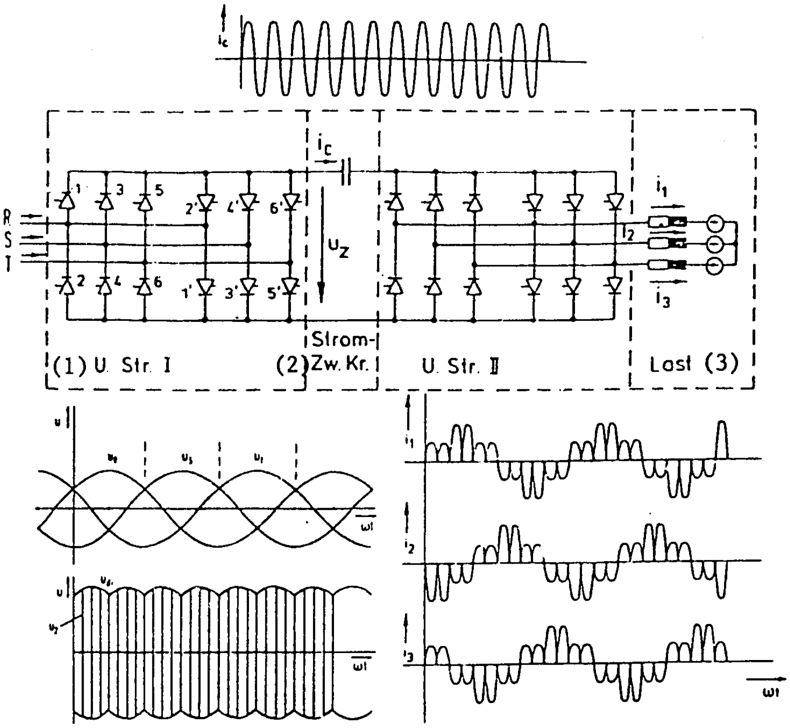

Figure 3. Circuit and current profiles of a new inverter design.

Key:
1. Inverting rectifier ...
2. Current intermediate circuit
3. Load

The obviously favorable structural volume makes this inverter appear to be very well suited to application to vehicles. Figure 4 shows a circuit in which two inverters of this type, each of which feeds a linear motor, are electrically connected in series. Here the power is fed from the DC power supply, or in other words, via DC current carrying electric rails having a voltage of, e.g., 4 kilovolts. The voltage division is symmetrized by a current control which operates on the two motor current circuits. In the design of the motors the series circuitry has the advantage that the windings need be insulated only for the half-voltage and this is important for heat dissipation and in the construction of lightweight motors. Through the saving in transformers and the favorable design of the motors it is possible to obtain a clear improvement in the vehicle design.

4. The Use of New Magnetic Materials

The technologies of magnetic suspension and electrical linear drives are of particular interest to the engineer specializing in magnetic technology because it is apparent that often very slight improvements in individual parts (magnets) can lead to considerable savings in other vehicle or roadway components. Thus, e.g., merely an increased flux density in the magnets--even when this involves a certain added expense--can lead to a quite significant cheapening of other vehicle or roadway components. Simultaneously it is possible with new and more efficient magnets to achieve an improvement in the levitation characteristics. More favorable dynamic properties in the levitation magnets yield a more rapid return to a new position of equilibrium after a perturbation. In turn one can also derive from this savings in the control elements of the magnets. In the chain of elements, mutually interdependent in their dimensioning, the supporting and propulsion magnets assume a "strategically" important place; improvements in these specially critical locations have a particularly marked effect upon the characteristics of the entire system.

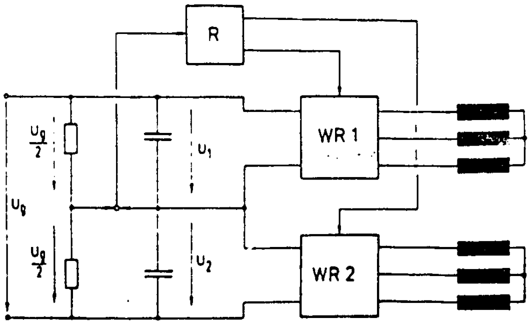

Figure 4. Series circuitry of the inverted converters for feeding power to linear motors.

The use of new magnetic materials makes possible, as has recently been learned, a new design of linear motors which are in fact of a type previously written off because of their too unfavorable operating characteristics for use in the transport sector. It now seems to be becoming possible to achieve high efficiencies and power factors simultaneously with acceptable weights for the drive. In consequence the installation of power-carrying motor parts into the vehicle (short-stator technology) is again becoming more attractive. Specially favorable design solutions evidently arise whenever the motor can also take over the function of the supporting element.

As a further example of the use of high-energy permanent magnets (REC magnets) some statements should be made regarding possible improvements in the repulsive support process on the basis of permanent magnets. This support technology had already been suggested more than 10 years ago; however, its characteristics for use in transport technology had not yet become sufficiently favorable. Then the course was adopted of using superconductive coils as vehicle magnets and of introducing current-carrying rails or coils in place of magnets (normally conducting) along the side of the roadway. This procedure which has been still further developed by the JNR in Japan requires a relatively high energy consumption for the support technology and leads to a rather complex overall system.

5. High-Energy Permanent Magnets in Long-Stator Technology

Synchronous long-stator drive is either designed with superconducting exciter coils in the vehicle--in which case it then uses an ironless stator--or else the iron-containing stator variant is employed so that electromagnets and/or permanent magnets can be used for the exciter field. In the case of iron-containing technology it is also possible to use the normal forces of the motor to compensate the weight of the vehicle. When a controlled magnetic field is used one can dispense with further supporting elements such as wheels [4].

For high velocities the dynamic effects produced by perturbing forces and inaccuracies in the roadway acquire increasing significance. In the case of mechanical guidance they give rise to increased wear of the (mechanical) guiding elements. For this reason contact-free suspension is an attractive transport variant; not least of all it also has the advantage of reduced maintenance cost. But in addition it is also possible to allow greater tolerances in the accuracy of the roadway and this in turn can yield a cheapening of the roadway construction.

The disadvantage of the electromagnets lies in the fact that particularly in the case of low-loss design they possess a large time constant. In order to achieve adequately rapid interventions in stabilizing the supporting function there are therefore required high values of maximum voltage and high power amplifications. The result is an increase in the quantity of power-electronics devices in the vehicle. If one dispenses with a high response speed in the magnets then this implies greater deviations between the roadway contour and the magnet pathway. This requires a greater average distance from the rail and a higher magnet power. The simultaneously increased magnet mass has an additional negative effect upon the levitation behavior and the attainable riding comfort.

Especially from the dynamic point of view a relatively narrow range of options is available in the design of supporting magnets and propulsion magnets.

Low magnet weight, low losses and high force gradients are the desired goals. An average gap of about 1 cm is sought. The maximum gap deviations resulting from flexure of the carriers should not exceed 3 mm. In this way it is possible to meet conventional comfort criteria, which essentially restrict the vertical accelerations of the passenger cabin, up to velocities of more than 400 km/hr. Here it is assumed that over carrier spans of about 25 meters the maximum flexure amounts to about 0.8 cm.

The use of high-energy permanent magnets (REC magnets) for carrying and propulsion substantially increases the range of design options in achieving a high riding comfort for given roadway tolerances. A placement of the permanent magnets directly at the air gap permits, with remanence inductions of about 0.9 T, flux densities from 0.4 to 0.5 T and is characterized by small leakage flux. However, the use of additional control coils turns out with this form of magnet to be very unsuitable.

The additional electrical excitation of the magnet required for gap control requires, it is true, a modified magnet design. The average magnetic flux, which corresponds to the stationary state, generated by the permanent magnet has superimposed upon it an adjustable flux generated by a coil. With relatively small additional flux components it is possible because of the quadratic relation between flux and force to produce proportionately great control forces. It is certainly important for the magnetic circuit to be so configured that the additionally required flux components can be generated with limited circulation of magnetic potential through the coils [5]. The latter should also continue to be small for the maximum value of force as compared with the value required for electromagnets. In this connection experimental investigations have been carried out with the support of the Federal Ministry of Research and Technology in the Institute for Electrical Machines, Drives and Roadways (see Figure 5) which confirm the superiority of controlled permanent magnets in comparison with electromagnets. As the force current characteristic curves show when compared as in Figure 5 it is possible to carry out the control of the permanent magnets with relatively small circulations. Figure 6 shows an arrangement of magnets in which the flux-conducting magnet surface is greater than the pole surface (flux focusing) and in which soft iron poles serve to deflect the flux in the region of the air gap. In this way the magnetic resistance of the permanent magnet segment is diminished. As a consequence of the relatively small circulation of magnetic potential the winding cross sections can be reduced in comparison with the electromagnets. The magnetic time constant which is proportional to the winding cross section is also reduced. In this way the dynamic behavior of the magnet is made more favorable; the force gradient rises with constant voltage elevation. With the aim of obtaining the same dynamic behavior it is possible to diminish the power amplification (size of the current regulators) [5-7].

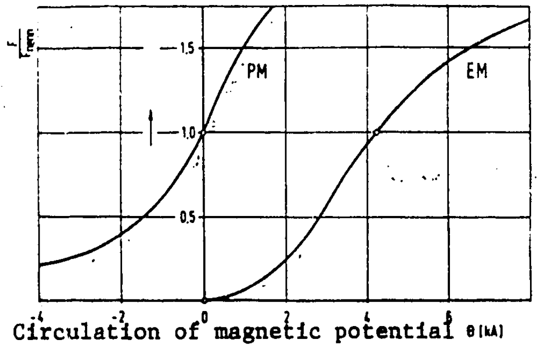

Figure 5. Supporting force comparison between permanent magnet and electromagnet.

A consideration important for applications in the case of long-stator drive is the reduction in levitation power. This power, apart from some other smaller elements, decisively determines the on-board energy requirement and is thus of essential importance for the provision of energy on board the vehicle. If it is desired to accomplish the latter without resorting to turbine power supplies or to a special power transmission system then one can make use of an induction effect. Through the slot openings of the stator there arises in opposition to the fundamental wave of the exciter field a harmonic wave which varies relative to the exciter poles as a function of travel velocity. Its energy can be decoupled by means of an alternating current winding in the poles of the vehicle. The use of the permanent magnets contributes significantly to limiting the power of this linear generator.

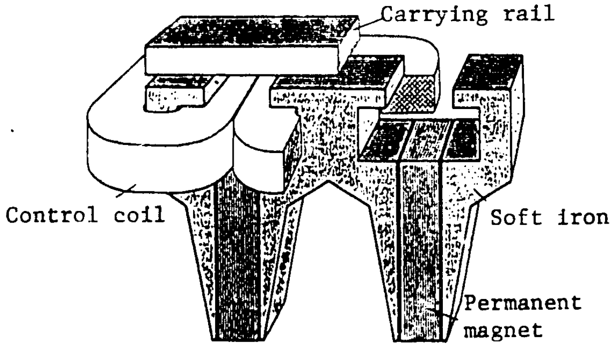

Figure 6. Permanent magnet arrangement.

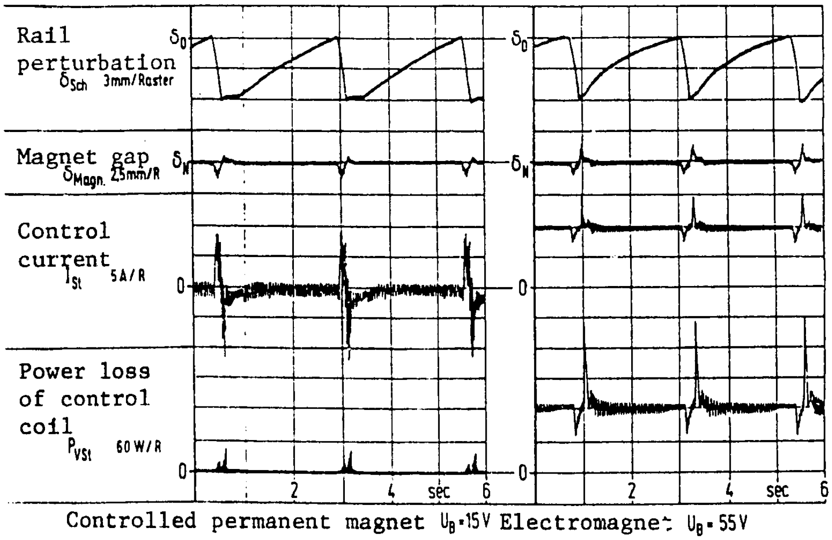

Figure 7. Oscillograms of controlled permanent magnets.

Figure 7 shows oscillograms which display the favorable behavior of controlled permanent magnets. The measurements show that in the case of electromagnets of the same weight perturbations of the same size are responded to with about the same gap deviations as in the case of the permanent magnet only if the battery voltage is approximately tripled. A perturbation was produced by exciting the carrying rail with a pulse generator. It is also apparent that for the controlled permanent magnet the power peaks are very much lower than for the electromagnet.

If one attempts to simulate the effects of carrier flexure at high velocity (400 km/hr) on power requirement one can make a computational estimate of the requisite carrying power. To this end the selected simple two-mass model supplies a comparatively conservative estimate (with a proportionately high value). Converted to a vehicle which is about 50 meters long the simulation shown in Figure 8 yields a power peak of about 20 kilowatts; the average power is very much lower. These power values are to be compared with a carrier power of more than 300 kilowatts in the case of a vehicle using electromagnets.

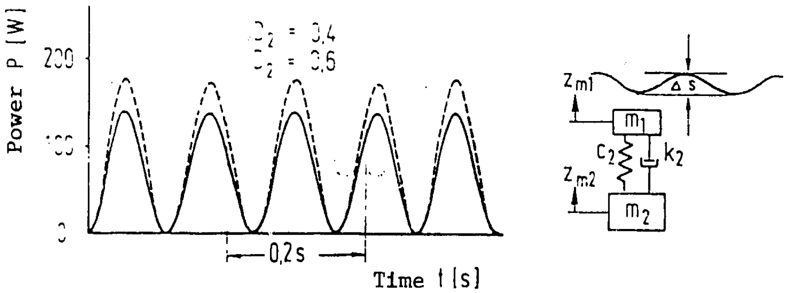

Figure 8. Power requirement in the case of sinusoidal perturbation (Δs = 8 mm); nominal force of the magnets: $F_0 = 15,000$ N.

The qualitatively favorable levitation behavior can be made useful for high-velocity vehicles in various ways. Besides the positive effects upon the design and size of the control elements as well as upon the necessary on-board power the greater force gradients also permit more favorable conditions for allowing greater roadbed tolerances [7].

In order to test the adequacy of this magnet design on the scale of actual application there was developed in cooperation with Thyssen Henschel and Thyssen Stainless Steel Works a combined carrying and propulsion magnet having the dimensions appropriate to the IVA vehicle TR 05. Figure 9 shows the magnet on the test stand in the institute. Lifting devices were used in constructing the large-volume magnet units; also used were special assembling devices for installing the magnets.

With an 8-mm gap to the stator the carrying force in the currentless state amounts to 16,000 N; this is about 30 times the weight of the $SmCo_5$ material and about 6 times the magnet weight.

6. A New Short-Stator Linear Motor With High Efficiency

The linear motor designs known up until recently could be adapted to a number of conditions of use; but without exception they all displayed a low efficiency which did not correspond to their power level--this efficiency being clearly less than 90 percent. In the case of a linear induction motor because of the so-called end effects one is limited to efficiencies below 80 percent. In consequence of the large gap and of a relatively high leakage the power factor is generally far lower so that it was hardly possible to exceed products $\eta \cdot \cos \phi = 0.4$. This in turn implies very great design power for the frequency inverter required on the vehicle, thus giving rise to a considerable additional space and weight requirement. If it is to be possible to solve the problem of energy supply at high velocities then there exists moreover the problem of designing a linear motor having an apparent power which is not substantially greater than the yielded mechanical power.

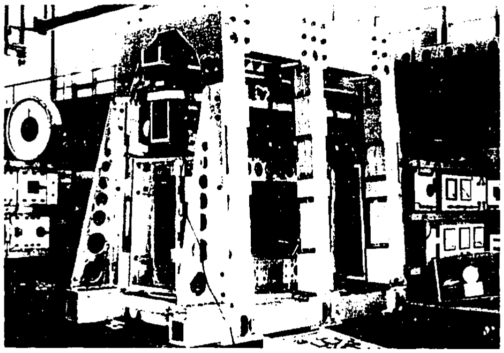

Figure 9. Test stand for investigating controlled permanent magnets

Figure 10. DELSYM model motor.

Within the framework of a research program for developing vehicles having short-stator drives investigations are being carried out at the Technical University of Braunschweig of a new synchronous motor with permanent magnet excitation. In contrast to previously known types this motor has no electrical excitation but an excitation through REC magnets, thus reducing in this way the losses and the motor weight. By doubling the exciter arrangement it is possible to achieve an additional amplification of the interaction between the magnetic field and the armature currents. The effects of a homopolar and of a heteropolar interaction are superposed and lead to an increase in the induced voltage. The armature winding is designed with toroidal coils [9].

Figure 10 shows the model motor as used for the first tests for force measurement. The rail employed here is of massive design. Measured force values are plotted in Figure 11 as a function of the surface current of the armature winding; the magnet height amounts to 2 cm. It is apparent that the force densities required for propulsion can be generated with relatively small surface currents. This in turn implies that the motor can be operated with low winding losses so that an efficiency of about 95 percent appears to be obtainable. Of special interest with regard to achievement of a light vehicle is a motor configuration which provides not only the propulsive forces but also the carrying force and when necessary the lateral force. The cross section of such an arrangement is sketched in Figure 12. In addition to the REC magnets there is an arrangement of guide coils which via a control element excite the additional flux components required for dynamic stabilization. A control coil inserted in the toothed region outside the winding produces by means of inward or outward field displacements controllable lateral forces for guiding the vehicle. These flux components generated by the control coils can also generate lateral forces when the vehicle is in the middle position.

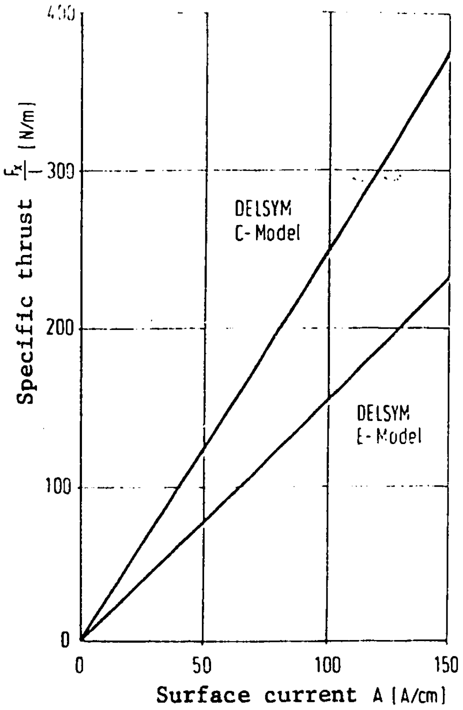

Figure 11. DELSYM: thrust as a function of the surface current (h_{PM} = 2.0 cm and 1.0 cm).

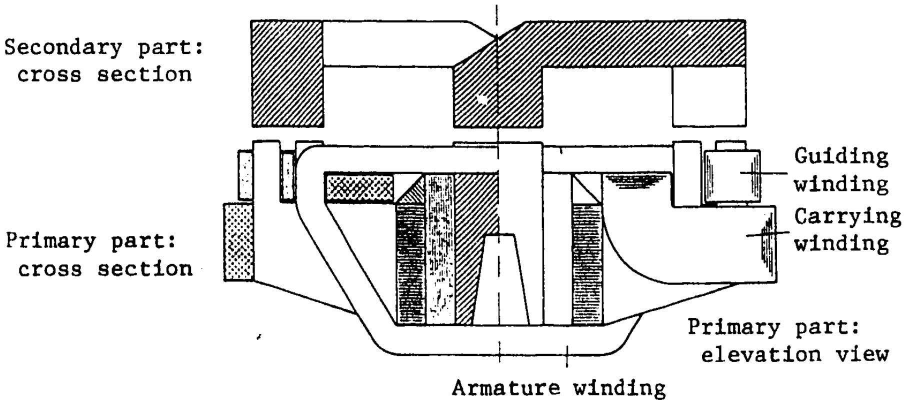

Figure 12. Integrated DELSYM carrying and guiding motor.

Computations show that, when thus designed, combined carrying, guidance and propulsion elements in approximately uniform distribution over the length of the vehicle lead to interesting characteristics of a magnetic suspension system. In such a case the weight of the motor elements is probably not more than 20 percent of the vehicle weight. In consequence of the very high magnitude of the product of efficiency and power factor there is a considerable reduction in the design power of the inverted converter as compared with previously known design solutions.

7. The Use of REC Magnets in Repulsive Magnetic Support Technology

With the emergence of the ferrite magnets with their straight magnetization characteristic B(H) in the second quadrant it was possible to consider investigating the possible applicability of a contactless supporting technology which in addition operates without power [sic] [10]. This was also especially attractive because the repulsive magnet arrangement leads to a magnetic vehicle which is fundamentally very simple in its structure, permits a small vehicle cross section and allows a simple attachment of the magnet to the vehicle. Quantitative investigations of ferrites yielded, however, several problem areas. As Figure 13 indicates the attainable force densities in repulsive carrier technology under the same conditions (surprisingly enough) are of the same size as in the case of the pulling magnet arrangement. If ferrite magnets are used then even in the case of lateral ratios of the magnets h:b = 1 only force densities of less than 2.5 N/cm^2 are attainable and this gives rise to very broad magnet rails or magnet coverings and a large magnet mass in the vehicle. Despite low specific magnet costs the result is very expensive vehicle equipment. The proportionately large share contributed by the magnets to the vehicle weight and the limited stiffness of the support characteristic curve imply natural frequencies of from 1 to 2 Hz when the gap is small. Since this type of magnet support is lossless and accordingly takes place without damping it is easy to prove that the procedure is not suitable for vehicles which are intended to reach speeds greater than 50 km/hr.

Also the bilateral use of REC magnets in the roadway and on the vehicle does not come within the sphere of discussion. While this magnet arrangement does yield the desired reduction in magnet weight nevertheless the still absolutely large magnet weights for the given roadway structure are substantially too expensive.

The basically obvious idea of using ferrite magnets on the roadway and REC magnets in the vehicle is to be sure fascinating, but it is not without its problems. For it must first be made sure that the ferrite magnets are either not at all or very little demagnetized in the curved portion of their B(H) characteristic. This must also be the case when taking into account temperature variations. This is all the more readily achieved the thinner the REC magnets and the higher the ferrite magnets and the more favorable their B(H) characteristic profiles (Figure 14). Such magnet combinations lead to force densities close to 5 N/cm^2 and lie approximately in the middle between the two characteristic curves for magnets of the same type according to Figure 13. To this value of the force density there corresponds a reduction in the magnet weight to less than 40 percent of the usual value for ferrite [11].

For the magnet configuration (Figure 15a) the field lines show that in the ferrite magnet there is practically no reversal of the field direction. In Figure 15b there is plotted the carrying force characteristic for various magnet spacings. In order to avoid stronger demagnetizations, approximations of the magnets in the range below 4 mm are "blocked" by suitable coverings. In this way there is produced at the nominal point of the force a gap of 8 mm. Here the carrying force per side amounts to 10 kN/m. In consequence of the low weight of the REC carrying magnets it is possible, when the latter are coupled opposite to the vehicle in individual suspension, to attain a resonant frequency up to about 13 Hz. This yields with regard to the dynamic properties not only gradual changes but also predictions which are fundamentally different from those in the case of a pure ferrite combination. If the magnets are connected via springs and dampers to the suspension structure and if this latter is then connected via the "secondary" springs and dampers at low frequency with the vehicle body then one obtains an oscillatory system (Figure 16) which is well damped over a large excitation range. Also without damping in the range of magnetic support it is possible at all velocities of interest to limit the accelerations of the passenger cabin to values which meet comfort specifications (Figure 17).

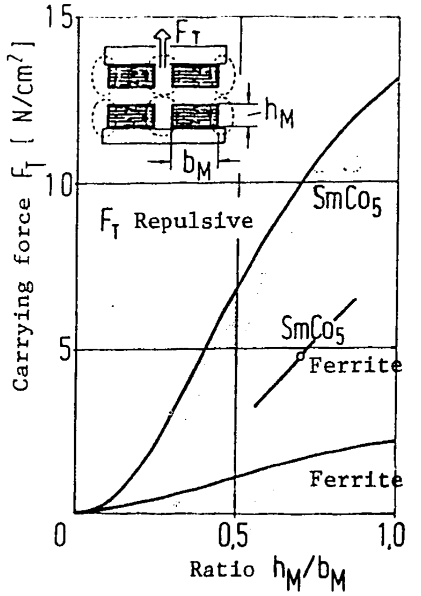

Figure 13. Carrying force as a function of magnet geometry.

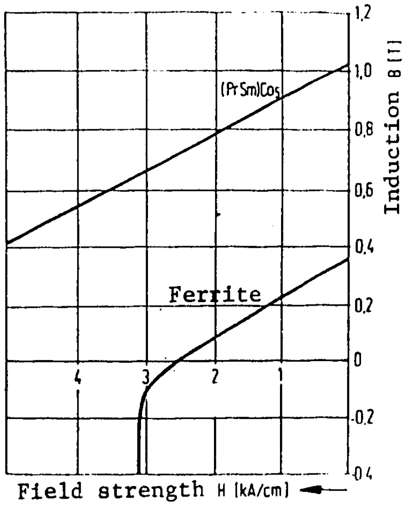

Figure 14. Demagnetization characteristics.

The use of REC magnets with a remanence induction of about 1 T has the effect of causing a highly interesting solution to arise out of a practically unusable design. The computational results shown here were experimentally confirmed with regard to the support characteristic curve (force as a function of magnet spacing) for an appropriate material combination.

Further improvements in the B(H) characteristic curve with REC magnets and ferrites will have an additional favorable effect upon reduction of the magnet volume.

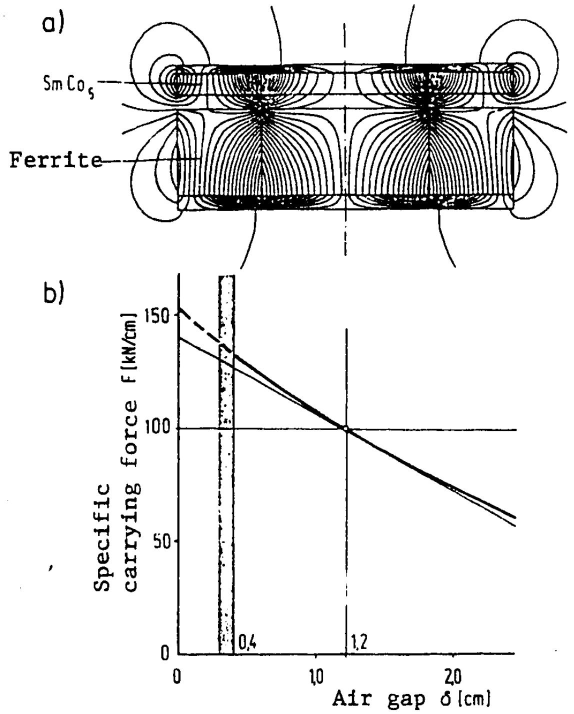

Figure 15. a) Field pattern, b) carrying force as a function of the air gap.

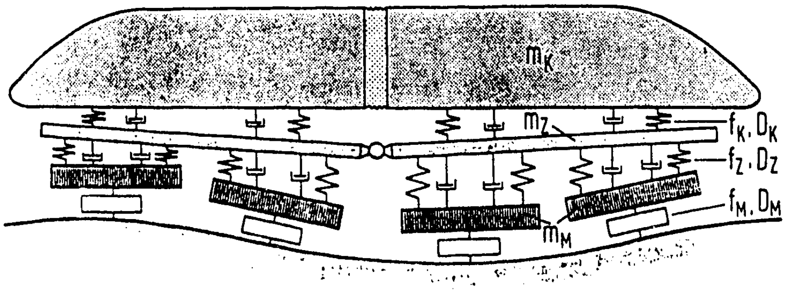

Figure 16. Multimass model for simulating the vehicle dynamics: m = mass, f = resonant frequency, D = damping, index K = cabin, Z = intermediate plane, M = magnet.

For dimensioning the support setup the attainable force densities for a particular gap and also the attainable stiffness represent properties which are of equal importance. A low vehicle magnet weight is of great interest with regard to good dynamic properties. In order to be able to extract the energy of oscillation from the oscillatory magnets when there is excitation coming from the track, the intermediate plane (suspension structure) inserted between magnet and vehicle body must possess a definite minimum mass. This is practically realizable, e.g., by connecting the propulsive motor to the suspension structure.

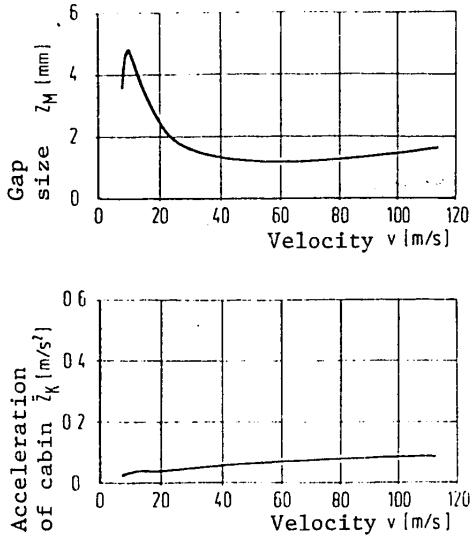

Figure 17. Dynamic operating behavior.

The shock absorptive connection between the magnet and the intermediate plane is in this latter case accomplished with a resonant frequency lying between that of the magnet support and the secondary spring system (see Figure 16). For magnetic suspension technology there would probably be great advantage in being able to secure contactless support without resorting to control-theoretic stabilization. The number of required electronic devices and components can be substantially restricted and in this way a far greater measure of protection against perturbations can be achieved than was the case with the previously considered engineering solutions.

But the fact remains that the lateral guidance of the vehicle, if this is to be contactless, is impossible without resorting to an active control system. The mere use of an uncontrolled permanent magnet guidance system orthogonal to the stably operating carrying forces would produce destabilization for the latter. The multidimensional suspension of bodies in a magnetic field by permanent magnets is known to contradict the Earnshaw theorem. But this is not to say that the described supporting procedure cannot be translated into an entirely favorable system design involving a sharply reduced expense of control electronics.

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