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XLEV : A NOVEL MAGNETIC LEVITATION SYSTEM FOR A CONVEYOR VEHICLE

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***Abstract*—In this paper a novel magnetic levitation system XLEV is presented. The XLEV system may be used for any material handling system where high conveyor speeds and high operational availability are key issues. After presentation of the eXtended LEVitaton system some aspects of the design are discussed. The mode of operation for a conveyor vehicle on a rectilinear track and during a curve run are described in detail. Also described is the passing of a passive switch without loosing the levitation state. Some words are said about the levitation controller. A small trick in the way the electromagnets are activated short-circuit the disadvantages accompanied in the control of the statically indeterminate magnetically levitated XLEV vehicle. Finally, as an appropriate application, a first vehicle prototype is presented for the use as part of a luggage transportation system at airports.**

***Key words*—conveyor vehicle, electromagnetic suspension, material handling system, passive switch.**

1. INTRODUCTION

Businesses that ship, receive, store, handle, manufacture or distribute as a core part of their mission know that a conveyor systems can become nothing less than their operation's physical nervous system; the one thing that must operate for everything else to function. That's why a high operational availability is a key issue of every modern conveyor system. Decreasing shorter time to market requires faster material handling. Here, conventional conveyor systems reach their limits. Because conventional systems suffer from friction, high conveyor speeds may not be obtained in the first place or come together with a immense increase in maintenance demand. In order to achieve a high flexibility in the design of the conveyor system track, switches are crucial elements. Because active switches may have a unacceptable high response time, passive switches are favourable in any modern conveyor systems.

At the Institute of Electrical Machines research is done about a new conveyor system. The system consists of a track with curves and passive switches and many conveyor vehicles. Each vehicle carries a load from one point in the system to another. Depending on the current status of the track, the vehicle by itself will decide which way is best suitable in order to get the load as fast as possible to its destination.

To avoid problems with friction, a conveyor vehicle equipped with a magnetic suspension system was chosen. Linear motors for propulsion and an inductive energy transmission module round up the completely contactless technology, thereby short-circuiting all problems associated with friction like limited conveyor speed and the cost-intensive demand for maintenance. Different on-board controllers enable the operation of the vehicle as a stand-alone application. With all these components, an autonomous operation of the vehicle is enabled. This autonomous operation together with the contactless technology guarantee the high operational availability of the conveyor system. When a vehicle breaks down on the track, just a small section of the track is blocked and that only for the time it takes to remove the vehicle from the track.

First the new system which is called XLEV is presented. The mode of operation is described in detail. Furthermore, some aspects on the design are discussed and some words about the levitation control are said as well. As an appropriate application, a first vehicle prototype is presented for the use as part of a luggage transportation system at airports. Current research is focussed on this topic.

2. THE XLEV SYSTEM

XLEV stands for eXtended LEVitation. The novel levitation system comprehends both elements of a EMS type suspension system: 1) the electromagnets : conventional EMS type maglev vehicles are equipped with electromagnets mounted underneath the guideway, which pull the vehicle towards the reaction rail. Besides these electromagnets, the XLEV system also contains electromagnets mounted above the guideway which can actively push the vehicle downwards. 2) the reaction rail and track: as being described below, the constraints on the dimensions of the track fix the dimensions of the vehicle and the electromagnets.

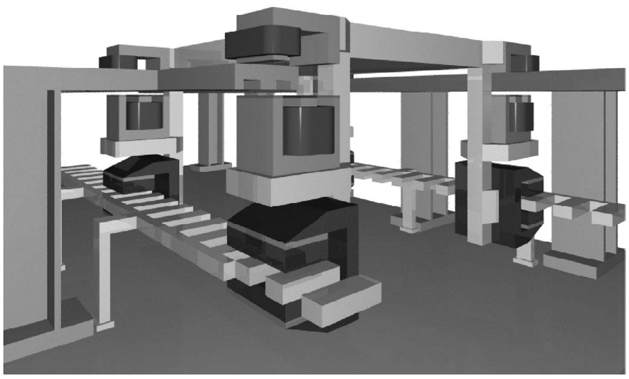

Figure1. The XLEV vehicle

Fig. 1 shows a XLEV conveyor vehicle. On each corner of the vehicle one recognizes the lower (E-shaped yoke) and the upper (U-shaped yoke) electromagnets. Further on, the vehicle has four short-type homopolar linear motors. This suspension/ propulsion combination is chosen in order to have a completely passive track, which is easy to manufacture and does not require any maintenance. The passive track consists of the reaction rail and the flux guiding pieces, forming the secondary part of the homopolar motor. The vehicle's frame is stiff, its structure is comparable with the structure of a common table. This 'elevated' structure is required in order to pass a passive switch as presented in Fig. 2. The inductive energy transmission modules are not depicted in Fig. 1.

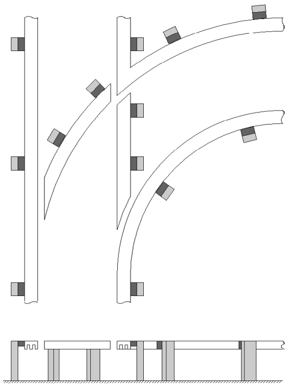

Figure 2. The XLEV passive switch

3. XLEV SYSTEM DESIGN ASPECTS

Starting point for the XLEV design are the constraints of the track geometry, in particular the passive switch geometry. Radius of curve/switch and track width form the boundary conditions upon which the further design is based. Fig. 3 shows

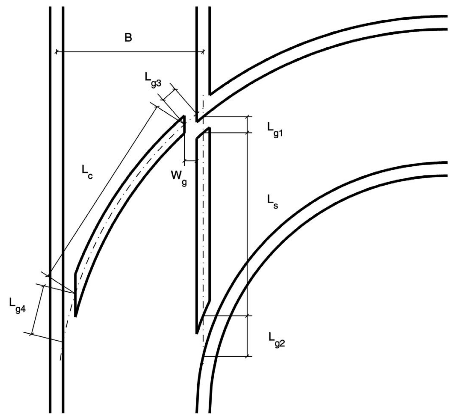

Figure 3. Outlines of the XLEV passive switch

a bird's eye view on the passive switch. The magnetically levitated vehicle moving straight ahead, passes gaps 1 and 2, the vehicle taking the right hand turn passes the gaps 3 and 4. High conveyor speed implies that it is not possible to interrupt the levitation status in order to pass the gaps. The dimensions of the vehicle's frame, the electromagnets and the track are matched in such a way that three pairs of electromagnets are guided at any time. The stiff frame prevents the fourth corner, positioned in a gap, loosing the levitation state. This condition can be translated into in a mathematical boundary condition for the axle-base of the vehicle which is defined as the longitudinal distance between two centres of electromagnets :

$$L_{axle-base} \le \min(L_c, L_s) - L_{EM}$$
$$L_{axle-base} > \max(L_{g1}, L_{g2}, L_{g3}, L_{g4}) + L_{EM} \quad (1)$$

L_{EM} is the length of an electromagnet. The other symbols are defined in Fig. 3. Example: for a track width B=0.925m, a gap width W_g=0.075m and a reaction rail width W_{rr}=0.075m the linear dimensions are given in Fig. 4 as a function of the inner radius. It can be seen that according to (1) a vehicle that should pass a passive switch with an inner radius of 1.5m may have an axle-base length of 0.6m. If L_{EM}=0.09m this vehicle is able to pass switches with inner radii varying from 0.75m until 3m. This flexibility is a great advantage of the XLEV system.

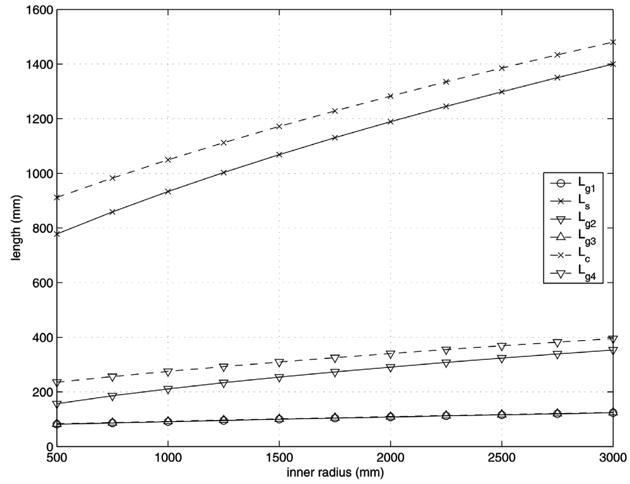

Figure 4. Example evaluation of (1)

4. MODE OF OPERATION

4.1. *Riding on a rectilinear track*

The nominal operation mode is the ride of the XLEV vehicle on a rectilinear track where the four pairs of magnets are guided at any time. In this mode only the lower electromagnets are active and enable the levitation state. If the lower electromagnets are hybrid excited magnets (permanent magnet + coil) energy consumption may be minimised in adjusting the air gap. Design of such a magnetic circuit is based on the mass of the vehicle and the nominal air gap. The quantity of permanent magnet material is such that the support forces caused by the ampere turns of the permanent magnet compensate the weight of the vehicle at the nominal air gap. Because the support force of an electromagnet is inversely proportional to the square of the air gap, a loaded vehicle can be levitated nearly without energy consumption if an appropriate smaller air gap is appointed. On a rectilinear track the vehicle is guided by the reluctance forces of the lower electromagnets. U-shaped yoke electromagnets and a slotted reaction rail result in a lateral stiffness which is sufficient for most cases. A higher lateral stiffness can be achieved if E-shaped yokes are used.

4.2. *Riding through a curve*

A bottle neck of any conveyor system is the limited speed if the vehicle is riding through a curve. In order to achieve high curve speeds a magnetically levitated vehicle may be equipped with additional electromagnets for guiding the vehicle. For person transportation systems this is definitely the right way because of the high mass and high speed involved. For a conveyor vehicle with relative small mass, these additional electromagnets and its periphery may actually be a disadvantage. Its mass makes up a non neglecting part of the vehicle's whole mass and space is limited on a compact conveyor vehicle. The additional reaction rail also complicates the structure of the passive track and more time intensive adjustment work is needed when building the track. The upper electromagnets of the XLEV levitation system, needed for passing a switch, can contribute in obtaining higher curve speeds without additional electromagnets for guidance. Just before the vehicle enters the curve the upper electromagnets are magnetised. This actually means adding a virtual load to the vehicle. In order to continue the levitation state the lower electromagnets must be magnetised stronger, thereby increasing the magnetic induction in the air gap which results in higher reluctance forces. The ampere turns of the upper electromagnets fix the additional amount of reluctance force needed for guiding the vehicle through the curve with the assigned curve speed. For a given vehicle and curve radius the highest possible curve speed is limited by the

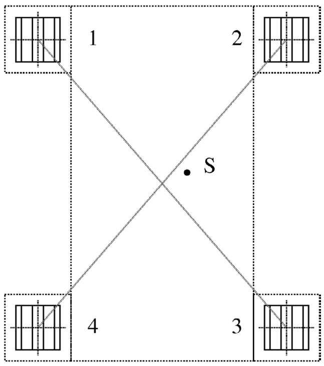

Figure 5. Outlines of conventional maglev vehicle

saturation of the magnetic circuit. This is another parameter that must be considered for the design of the magnetic circuit. If the vehicle has left the curve the magnetisation of the upper magnets is ended. One should notice that separate control loops for the upper electromagnets are not necessary. Because the upper and lower electromagnets are fixedly connected with each other through the stiff frame the ampere turns of the upper electromagnets may be constant, while the control loops of the lower electromagnets do the work for guaranteeing the levitation state. Another advantage compared to the solution with the guidance electromagnets is that additional expensive air gap sensors are not necessary.

4.3. Passing a switch

Active switches may have a too high response time, therefore passive switches are favourable in any modern conveyor system. As already mentioned, high conveyor speed implies that it is not possible to interrupt the levitation status in order to pass the gaps. The upper electromagnets of the XLEV system are essential parts that enable the vehicle as presented in Fig. 1 to ride through a passive switch as presented in Fig. 2 independently of the position of the vehicle's centre of gravity. Fig. 5 shows a bird's eye view on a conventional maglev vehicle with just four E-type yoke lower electromagnets. Depending upon the position of the load the centre of gravity S of the levitated vehicle will be more or less away from the point of intersection of the diagonals, as defined in Fig. 5. Even the centre of gravity of an unloaded vehicle will not always collide with this intersection. If one of the vehicle's corners is positioned in a gap, the position of the vehicle's centre of gravity decides what happens to the corner at the other end of the diagonal. For instance, if the conventional maglev vehicle depicted in Fig. 5 hovers straight through the switch depicted in Fig. 3, the vehicle's corner with number 2 first encounters gap 2. When a corner is positioned in a gap, it cannot any longer contribute to levitate the vehicle. Because this vehicle's centre of gravity is outside the triangle built up of the corners 1,3 and 4, the weight of the vehicle makes that the vehicle twists around the diagonal 1-3, making that the lower electromagnet of corner 4 will glue on the reaction rail, thereby ending the levitation state. On the other hand, a vehicle with S inside the triangle built up of the corners 1,3 and 4 will not twist when it passes gap 2, but will twist when it passes gap 1, after having successfully passed gap 2. What fails is a means to control the vehicle's vertical movement in the direction of the acceleration due to gravity in an active way. For the XLEV vehicle, these are the additional electromagnets mounted above the guide way, as shown in Fig. 1. Hovering of the vehicle depicted in Fig 5, equipped with additional upper electromagnets, straight through the switch of Fig. 3 will look like this: just before the vehicle enters the switch the load of the vehicle is redistributed from the four corners to the corners 1,3 and 4. Corners 1 and 3 will levitate the vehicle, while corner 4 counteracts the moment of force due to the weight. When corner 2 has passed gap 2 the load is redistributed again to the corners 1,2 and 4. Corner 3 is now able to pass gap 2. The same sequence is repeated for passing gap 1 and the vehicle can continue its way. With the additional electromagnets the XLEV system is able to take a passive switch without loosing its levitation state. If the vehicle wants to take the right hand turn, reluctance forces must be high enough in order to steer the vehicle in the right direction. The way this is achieved is already explained in section 4.2. Because the inner curve track has no gaps high reluctance forces can easily be obtained.

5. THE LEVITATION CONTROLLER

The control layout for a magnetically levitated vehicle can be divided into two groups according to its basic structural difference. The first group of controllers is build up of several independent controllers and is called decentral control. Each electromagnet is viewed as a local bearing which means that the air gap at each bearing is controlled individually. On the other hand, control for the levitated vehicle can be implemented in a single central control, this controller is a rather complex MIMO-controller. For the XLEV application the first author has chosen a decentral controller. As the vehicle passes a gap of the switch, there are only three out of four magnet pairs to control. Decentral control layout mirrors this flexibility in changing the number of active independent control loops. A linear PI-state controller scheme is used for the independent control loops of the voltage-controlled electromagnets. Air gap deviation, air gap deviation velocity, coil current deviation and the integrated error signal are the elements of the state vector. Fig. 6 shows the control scheme. The design of the controller is based on a linearised model of a levitated vehicle with only one degree of freedom. The control parameters can be determined by eigenvalue assignment [1].

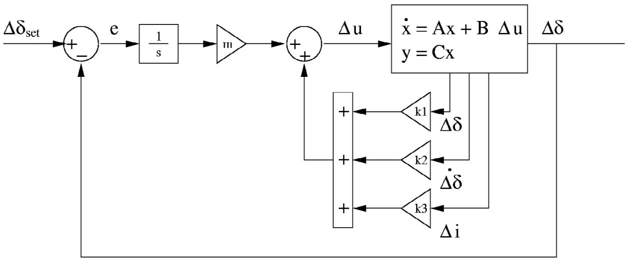

Figure 6. PI-state controller

The integral element was added in order to obtain an infinite static stiffness for each valuable operation point. The vehicle's stiff frame levitated by four electromagnets is a statically indeterminated system. If track and vehicle were ideal components the error signal of the four control loops would be equal in the case of symmetrical load. Torsional stress would not appear in the vehicle's frame. Unfortunately, small deviations in track and frame cannot be eliminated. Due to the integral elements and the specified air gap value these deviations cause torsional stresses in the frame. In the worst case the resulting frame deformation may lead to instability of the system. In any case these stresses mean unnecessary energy consumption. The indetermination of the XLEV vehicle and its related disadvantages can be eliminated if at any time only three out of four control loops are active. For the vehicle depicted in Fig.5, this means that for t=0..Δt: the control loops for electromagnet 1,2 and 3 are active, for t=Δt..2Δt: the control loops for electromagnet 2,3 and 4 are active and so on. This method is called "voltage rotation". Tests have shown that a magnetically levitated vehicle with a stiff frame can operate successfully if the frequency of voltage rotation is of the same order of magnitude as the control frequency of the levitation controller.

6. XLEV APPLICATION

A possible application of the XLEV levitation system is a luggage transportation vehicle for use at international airports. Nowadays the time delay between two connecting flights is fixed by the limited luggage handling speed of conventional conveyor systems between two different gates. The solution is a luggage handling system consisting of many autonomous conveyor vehicles. Each vehicle conveys the luggage of one passenger. According to the current status of the ramified track the vehicle chooses its way in order to bring the luggage as fast as possible to the destination gate. In a first stage of this development project a prototype vehicle was built which is depicted in Fig. 7. The elevated structure of the frame is clearly recognisable. The vehicle has an axle-base of 0.6 m and a track width of 0.925m. It was designed for passing passive switches with a inner radius of 1.5 m. As already seen in Fig. 4, other radii may also be passed. For the moment the vehicle is equipped with four hybrid-excited lower electromagnets. L_{EM} is 0.09m and the yoke has an U-shape. Furthermore the vehicle has four passive short stator type linear homopolar motors. The passive motors do not have a wandering field winding. At the moment propulsion is done by pushing the vehicle manually. The passive motors do produce the periodic normal forces characteristic for any homopolar motor which constitute important disturbances for the levitation controller. With this first prototype vehicle successful levitation experiments were done for different air gap values. The decentral control scheme together with the "voltage rotation" method was used. Voltage rotation frequency and control frequency were both 10 kHz.

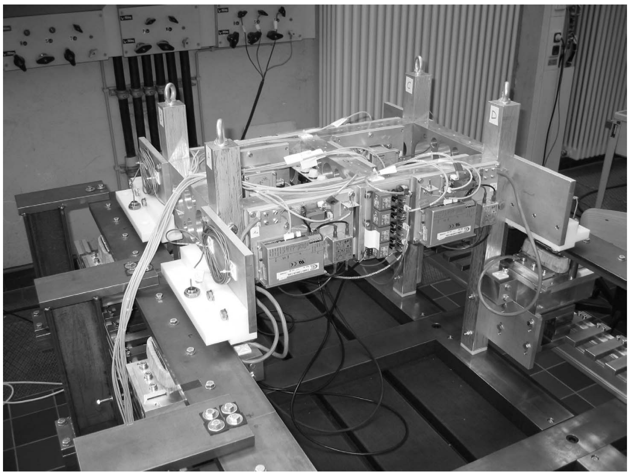

Figure 7. A first prototype

The next step will be the mounting of the upper electromagnets and extension of the rectilinear track with a passive switch.

7. CONCLUSION

In this paper the novel eXtended LEVitaton suspension system is presented. A vehicle equipped with this suspension system can pass passive switches without loosing its levitation state. The XLEV system can also produce higher reluctance forces as conventional maglev systems, leading to higher curve speeds, without the need for separate guidance magnets. As a appropriate application the prototype of a luggage transportation vehicle was demonstrated.

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