Simulation and Implementation of a Curve Run of a Magnetic Levitated Transportation Vehicle

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Abstract—**This paper deals with the simulation and implementation of a curve run for an autonomous, linear motor driven transportation vehicle. The vehicle is equipped with a magnetic levitation system and optionally supplied by a contactless energy and information transmission.**

In a first step measurements at a rectilineal test bench of the system have been made. After that a simulation model has been built and the simulation results were compared to the measurements. In a second step a control strategy has been developed to drive the vehicle through horizontal curves. After the implementation at the test bench the capability of this strategy was proved.

The transportation system, the motor and the simulation model of the drive are explained. Simulation results and finally the results of the implementation of the curve run are given.

***Key words*—curve run, linear homopolar motor, magnetic levitated transportation vehicle, simulation.**

1. INTRODUCTION

Magnetic levitation combined with linear drives offers many advantages, such as high velocity, no wear and therefore no maintenance. Because of the contactless movement such a system provides a high reliabilty. Furthermore no noise appears because of the missing mechanical contact. Possible applications are conveyor systems for clean rooms, for the food industry or luggage transportation systems at airports. Due to the high velocity of the drive e.g. the time between an arriving flight at an airport and the connecting flight can be decreased significantly. In the same manner personnel costs for maintenance can be reduced. In a larger industrial application many vehicles can be used on a long, ramified track to create a flexible and powerful transportation system. The track is passive, so if the system fails, the source of defect can only be in the vehicle. Thus after removing the faulty vehicle off the track the system is ready for use again.

Since horizontal curves are necessary in each transportation systems this paper describes the development and the implementation of a curve run.

2. THE TRANSPORTATION SYSTEM

The presented transportation system consists of a vehicle, which moves along a passive track. The vehicle comprises a bogie with a propulsion and levitation head on each corner and a luggage shell on top of the vehicle. Two cross bars connected by a main bar form the bogie. In order to permit a curve run an articulated joint for a horizontal rotation of the axle is mounted between each cross bar and the main bar. Optionally the vehicle is supplied with a contactless energy transmission. A wireless data transmission to transfer the control data of the vehicle was developed, improved concerning the quality of the data transmission and implemented on the vehicle successfully.

A short-stator type permanent-field linear homopolar motor has been chosen [1]. The contactless bearing of the vehicle is done in accordance with the principle of electromagnetic levitation. Depending on the load the levitation magnet is U- or E-core shaped and hybrid excited. Permanent magnets compensate the static load of the vehicle, while the current in the coils stabilizes the magnet in its working point. The levitation air gap is set in a way that the current in the coils is minimized. In order to obtain higher reluctance forces for the lateral guidance the reaction rail is slotted. The power converters for levitation and propulsion are mounted on the vehicle. Eddy current sensors detect the air gap of the levitation system. Three light barriers at each propulsion head are used to detect the position of the vehicle at regular intervals of 10 mm.

The track consists of two passive rails, one for levitation and lateral guidance and one for propulsion. The energy- and information transmission lines will be situated below the motor. The motor itself is located below the levitation system. Fig. 1 displays the test bench of the transportation system [2].

Because of the principle of motor, bearing magnets and energy- and data transmission the transportation system has no wear and therefore requires no maintenance. The passive tracks are cheap and easy to build.

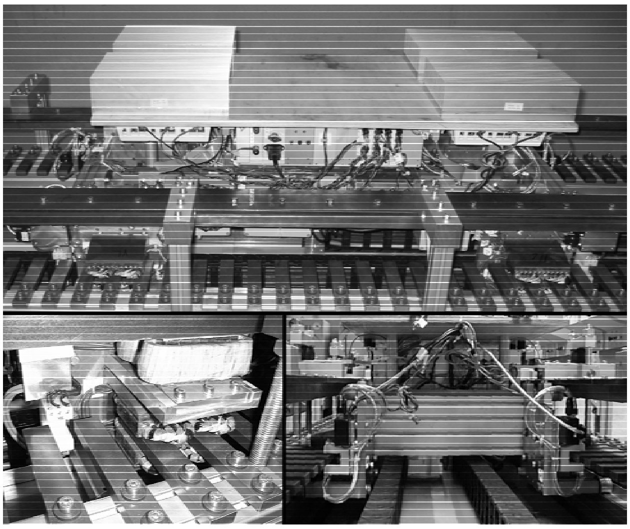

Fig 1. Test bench of the transportation system

3. THE HOMOPOLAR MOTOR

The design of the motor and the force calculations were carried out in advance by means of the finite-element method [3], [4]. The principle of the applied double-sided homopolar motor is shown in Fig. 2. Two rare-earth permanent magnets generate the excitation flux. The flux is guided by the flux concentrating pieces in the track and closes through the armatures and the U-shaped yoke. As a result the flux density under pole A is high whereas it is low under pole B. If the armature coils, designed as a conventional 4-pole travelling-field winding, are fed with field-orientated current the propulsion force under pole A is high whereas it is low in the opposite direction under pole B due to the modulation of the flux density. The resulting force acts into the driving direction. The armature coils are fed with square-wave currents: The positive and the negative phase-currents with a length of 120° electrical each are separated by a zero current with a length of 60° electrical. So every 60° electrical the current commutates to the next phase. Though the airgap is large the motor achieves a high efficiency.

In the symmetrical position, i.e. upper air gap is equal to lower air gap, the normal forces are equal to zero because of the double-sided design of the motor. As a result of a vertical displacement of the motor, normal forces approximately linear to the vertical displacement are created whereas the propulsion force remains constant. Compared to other motor principles these normal forces are rather small.

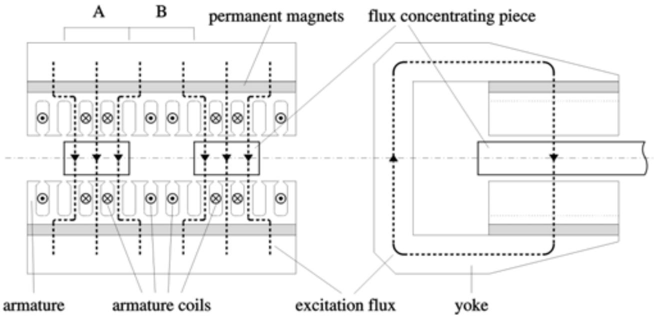

Figure 2. Principle of the homopolar motor

4. SIMULATION MODEL OF THE DRIVE

Fig. 3 shows the structure of the control system of the drive [5]-[7]. It is a three stage cascade controller comprising the inner tolerance band current controller and the outer PI speed and position controller. To control each motor separately the speed and the current controller are quadrupled. In the curve the speed of inner and outer motor has to be different, so the output of the position controller, the setpoint value of the velocity, is adapted for each motor. In order to simulate the behaviour of the driving system and to develop a curve-driving strategy a simulation model of the controlled system consisting of converter, motor and vehicle has to be build. Because of the vehicle's inertia and the high speed of the current control loop the current controller, the converter and the current transformer of the test bench are modelled as ideal devices. So it is assumed, that I_{set}=I_{act}. The model of the controlled system consisting of homopolar motor, vehicle and position encoder is depicted in Fig. 4. The actual current I_{act} (=I_{set}) is the input variable and the actual quantized position $s_{act,q}$ is the ouput variable. Due to the current in the coils and the actual electrical angle the motor generates a propulsion force F_{mot}. The relationship between force, electrical angle and current as a result of the FEM calculations is deposited in a two-dimensional look-up-table. So far the energy supply at the test bench is realized by a trailing cable. The friction force of this cable depending on the actual speed and the actual position decreases the motor force. Divided by the mass the actual acceleration is obtained. A double integration leads to actual position, s_{act}. The actual position is rounded to full centimeters, $s_{act,q}$, to model the quantization of the light barrier position encoder.

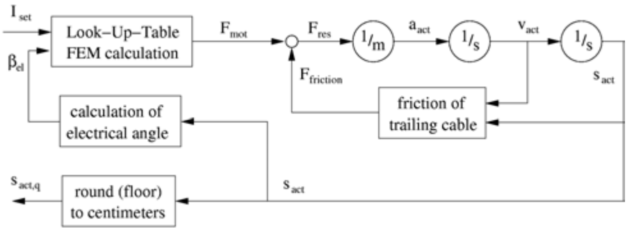

Figure 4. Model of the controlled system

The simplified full model is displayed in Fig. 5. As already mentioned each motor has ist own speed controller. The speed of the inner and the outer motor in the curve is adapted triggered by an inductive proximity sensor at the test bench, which signalizes the beginning of the curve.

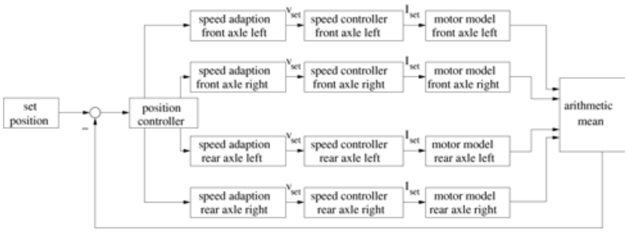

Figure 5. Simplified simulation model

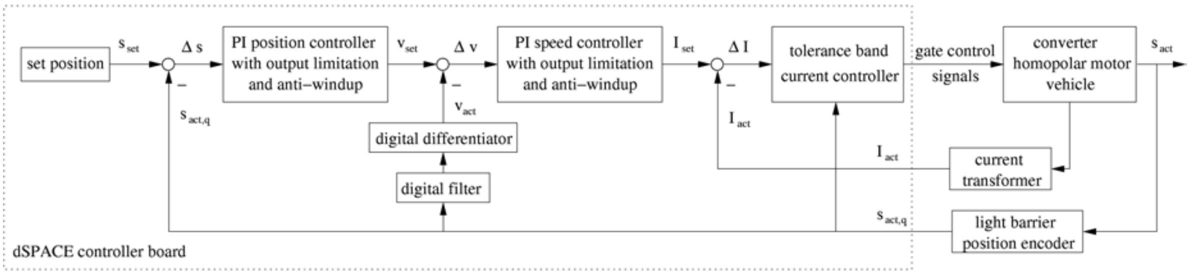

Figure 3. Structure of the control

5. SIMULATION RESULTS

In order to prove the capability of the simulation model, the results of a simulated drive on a straight line were compared to the equivalent measurements. Fig. 6 and Fig. 7 show a comparison between simulated and measured speed and current of a drive on a straight line with 0,5 m/s. There is no difference between measurement and simulation. Not only for this example, but as well for other velocities the simulation corresponds to the measurement very good. So the conclusion of this comparison is, that the model, although it is rather simple, is capable to simulate and describe the behaviour of the real system. It represents the reality in a very good way.

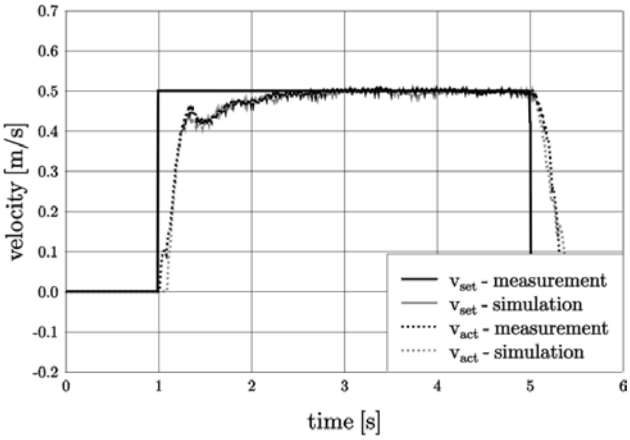

Figure 6. Comparison between simulated and measured speed for the drive on a straight line

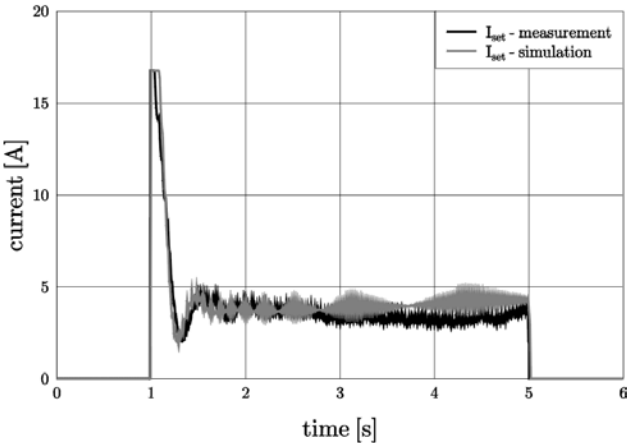

Figure 7. Comparison between simulated and measured current for the drive on a straight line

Because of the dimensions of the vehicle and the curve it is necessary to install articulated joints between the main bar and the cross bars and as a consequence to control each motor separately. If the vehicle is supposed to drive through the curve steadily the outer motors have to cover a longer distance and the inner motors have to cover a shorter distance than the centre of mass of the vehicle. So first of all the speed of the inner and the outer motors for each axle has to be adapted corresponding to the ratio of the radii of inner and outer side, when the vehicle enters the curve. Additionally a curve controller adjusts the deviation from the ideal, radial position of an axle by adding another current to the setpoint value of the current. So now the setpoint value of the current consists of two parts: the output of the speed controller and the output of the curve controller. Inputs to the curve controller, designed as a conventional PI controller, are the actual position of inner and outer side and the average value of inner and outer side to calculate the tipping of the axle. As a third method a short positive current impulse is given to the outer motors, if the vehicle enters the curve. For the inner motors the current impulse is negative to retard this side. Because of the construction of the curve as a part of a circle the current impulse corresponds to the step change of the radius from infinity to a certain value. It helps to make the turn into the curve easier. The model with the additional parts for the curve run are displayed in Fig. 8. Fig. 9 shows the results of a curve run simulation: At first the vehicle runs on a straight line, then enters and leaves a curve axle by axle and after that drives on a straight line again.

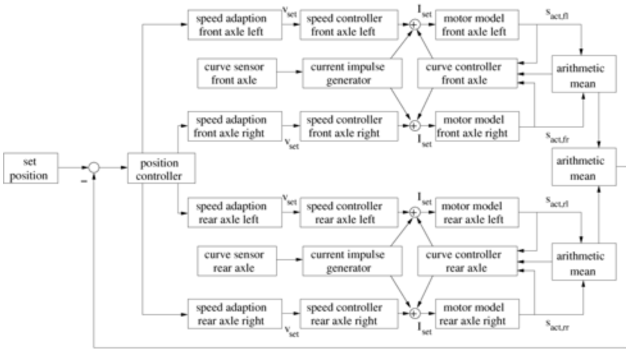

Figure 8. Simulation model for the curve run

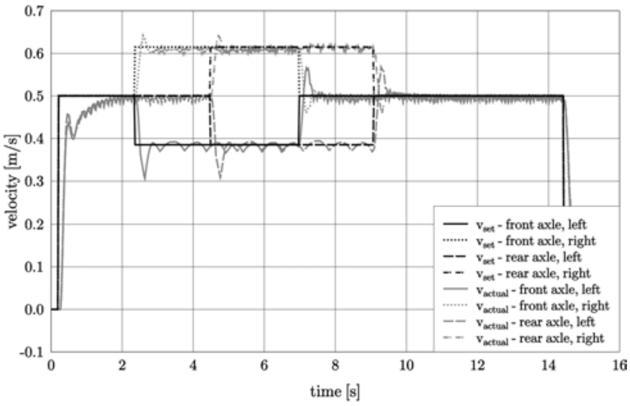

Figure 9: Simulation result of a curve run

6. IMPLEMENTATION

After the successful simulation the curve run strategy was implemented in the test bench control algorithm. The commercial software Matlab/Simulink was used to program this algorithm, executed in real-time on a dSPACE DS1103 controller board. Fig. 10 depicts the results of a curve run at the test bench with optimum controller parameters. The similarity to the simulation results in Fig. 9 is obvious. In this case the vehicle as well drives on a straight line at first and at $t = 6$ s the front axle enters the curve. From $t = 8$ s (rear axle enters the curve) until $t = 11$ s (front axle leaves the curve) the complete vehicle is in the curve and at $t = 13$ s the vehicle leaves the curve and drives on a straight line again. Only at the time, when an axle enters or leaves the curve little speed oscillations occur.

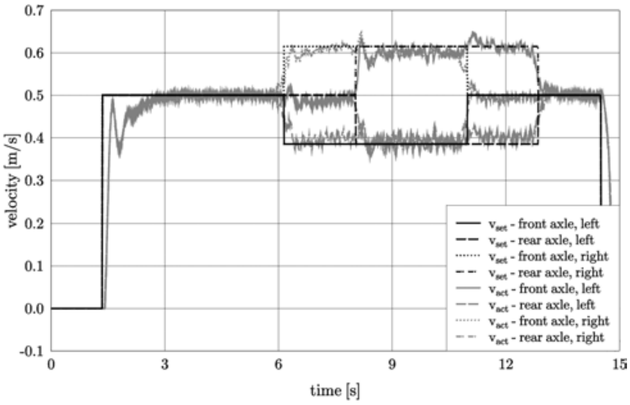

Figure 10. Speed behaviour of the curve run at the test bench

7. CONCLUSION

This paper describes the simulation and the implementation of a curve run of a magnetic levitated transportation vehicle. Therefore a simulation model of the system as simple as possible but as precise as necessary is built to depict the performance of the complex real system. After a comparsion between simulation and measurement on a straight line the control strategy for the curve run has been developed by means of the model. In the next step this control algorithm for the curve run is implemented on the test bench sucessfully, and it is shown that the model predicts the driving behaviour of the vehicle in the curve quite good.

REFERENCES

[1] W. Evers, “Entwicklung von permanenterregten Synchronlinearmotoren mit passivem Sekundärteil für autonome Transportsysteme ”, Dissertation, Fakultät für Elektrotechnik und Informationstechnik der RWTH Aachen, Verlag Shaker, 2000.

[2] D. Brakensiek, G. Henneberger, “Ein Linearantrieb für ein magnetisch gelagertes, autonomes Transportfahrzeug”, 5. VDI-Mechatroniktagung 2003, VDI-Berichte 1753, Fulda, Germany, 2003, pp. 571-586.

[3] W. Evers, G. Henneberger, H. Wunderlich, A. Seelig, “A linear homopolar motor for a transportation system” Proceedings of the 2nd International Symposium on Linear Drives for Industry Applications (LDIA 1998), Tokyo, Japan, 1998, pp. 46-49.

[4] D. Brakensiek, G. Henneberger, “Design of a Linear Homopolar Motor for a Magnetic Levitating Transportation Vehicle ”, Proceedings of the 3rd International Symposium on Linear Drives for Industry Applications (LDIA 2001), Nagano, Japan, 2001, pp. 352-355.

[5] D. Brakensiek, G. Henneberger, “Design of a Controller for a Linear Drive of a Magnetic Levitating Transportation Vehicle” 15th International Conference on Electrical Machines (ICEM 2002), Conference Record, Brugge, Belgium, 2002.

[6] The MathWorks Inc., “Simulink, Dynamic System Simulation for Matlab, Using Simulink ”, Version 4, Natick, MA, USA, 2000.

[7] dSPACE GmbH, “ControlDesk, Experiment Guide, Installation and Configuration Guide ”, Paderborn, 2001.