Design and Simulation of a Magnetic Levitation Conveyor Vehicle

J. Van Goethem, L. Schober, G. Henneberger

***Abstract*—Design of a new transportation system presupposes a thorough understanding of the dynamics of the system. This paper presents a simulation environment to analyse the dynamic behavior of a magnetic levitation vehicle designed to convey luggage at airports. The simulation environment is built in a modular way so that it can easily be extended. The conveyor vehicle is modeled as a rigid body with 6 degrees of freedom. The Newton/Euler equations of motion provide the basis of the mechanical model. Two models of the support magnets are presented: a simple analytic model and an accurate model based on finite element calculations. The levitation controllers, based on a state control algorithm, complete the simulation environment. Simulations with different air gaps and/or loads as well as rides through curves are possible. Extensive simulation results prove the usefulness of the simulation environment in designing a new transportation system.**

***Keywords*—linear drive, luggage-transportation system, maglev, magnetic levitation vehicle, rigid body dynamics, simulation model**

I. INTRODUCTION

Maglev is the generic label for a family of technologies, including magnetic suspension, guidance and propulsion with linear motor drives for guided transportation applications. The idea of magnetically levitating, driving and guiding vehicles was invented to overcome the problems associated with conventional trains using wheel-on-rail technology. Common maglev vehicles, such as the german Transrapid, are designed for high speed urban mass transportation. The advantages of the non-contacting system can also be used for low speed conveyor applications.

In this paper a conveyor vehicle is presented which hovers above the guideway, supported, aligned and driven by magnetic forces, with no physical contact. This non-contact feature eliminates contact friction. The component wear is virtually eliminated, resulting in an efficient system with significantly reduced maintenance costs as compared to conventional conveyor vehicles.

The conveyor vehicle will be used as part of a new luggage dispatching system at airports. Latency between landing and take-off of two connecting flights will be reduced because the maglev technology allows higher speeds and is less susceptible to disturbances as compared to conventional luggage dispatching systems.

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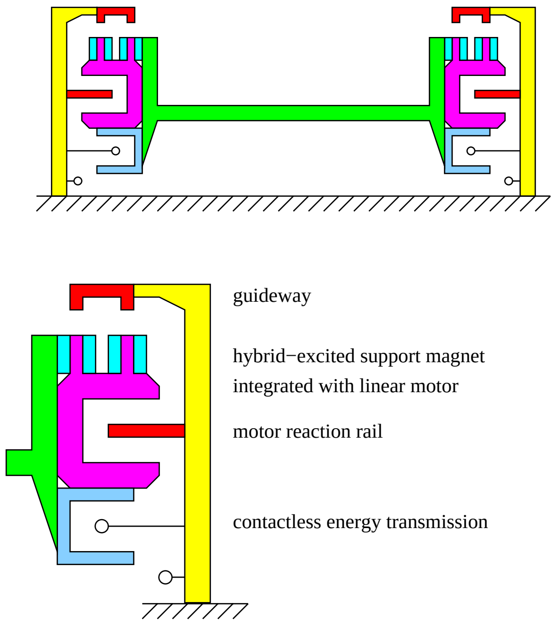

Fig.1 Design layout of the vehicle

Design of a new conveyor vehicle requires analysis of the dynamics of the system to insure the competency of the design. For the levitation system hybrid-excited electromagnets are used. This attractive suspension is inherently unstable and requires precise levitation control to maintain the gap between the magnets and guide rail. The levitation control system relies on an accurate dynamic model of the system. The first step in developing the conveyor vehicle is creating a simulation environment which includes the principal subsystems: vehicle and guideway, support magnets, linear drive and levitation control system. Modelling a system is an evolutionary process. Therefore the simulation environment is built in a modular way. This modularity allows making extensions in a straightforward way. The use of complex nonlinear levitation controllers instead of simple state controllers or the requirement for precise simulation results of a ride through a curve may be reasons to extend the model.

Nowadays complexity of the model is not anymore delimited by computational restrictions. A state-of-the-art desktop computer with standard simulation software e.g. Matlab/Simulink masters a complex dynamic simulation within seconds.

First the conveyor vehicle is presented, hereafter the equations of motion are set up. These differential equations provide the basis for the mechanical model of the system. Two models of the support magnets are presented. A levitation controller based on a state control algorithm completes the main simulation environment. As an example of an extension a position sensor signal of the linear drive is implemented to allow precise simulations of rides through curves. Extensive simulation results prove the usefulness of the simulation environment in understanding the dynamics of the conveyor vehicle.

II. The Conveyor Vehicle

Main components of the conveyor vehicle are the stiff light weight framework with loading space and four levitation/propulsion heads, one on each corner of the vehicle. Sensors, switching amplifiers, a power system and a controller board complete the vehicle's equipment.

A levitation/propulsion head consists of a short-stator type linear homopolar motor [1],[2] integrated with a U-core shaped hybrid-excited support magnet and a contactless energy transmission module. Because the energy needed for the whole vehicle is provided by contactless energy transmission, low energy consumption is important. A conventional electromagnet with integrated permanent magnets is chosen as a low-loss magnetic bearing. Permanent magnets compensate the static load of the vehicle, the coil current stabilizes the magnet in its operating point. The levitation air gap is set according to the load of the vehicle in a way that the coil current is minimized. The support magnets interact with a slotted guideway which results in higher reluctance forces for the passive guidance of the vehicle. The vertical position of the vehicle is measured by eddy current sensors, the horizontal position with a set of light barriers on each corner of the vehicle.

The reaction rail of the linear motor and the guideway are made of steel. The track has low manufacturing and material costs. The principal layout of the vehicle can be seen in Fig. 1. Fig. 2 shows a bird's view of the vehicle situated in a curve. Only the outlines of the guideway and the vehicle's framework are shown.

III. The Simulation Environment

A. Equations of Motion

There are several ways how to derive the equations of motion of a mechanical system. The two main formulations of rigid body dynamics are Newton-Euler equations of motion and Lagrange equations of motion. For this application the authors have chosen a formalism presented in [3] which is basically a combination of both formulation. The equations of motion are analytically derived with help from the symbolic computation software Maple.

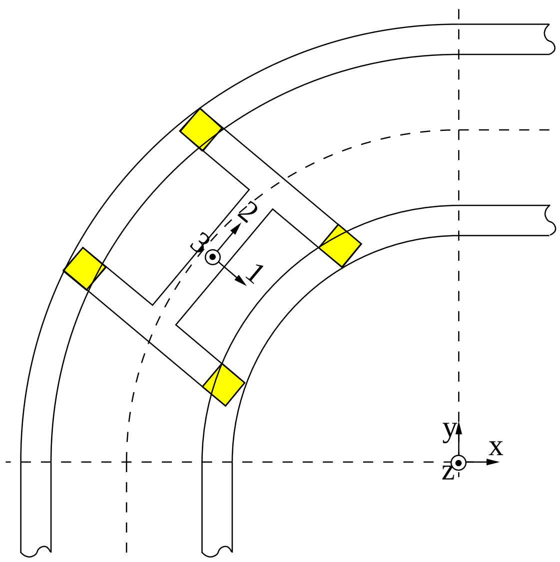

Fig. 2 The conveyor vehicle in a curve

The guideway implemented in the simulation environment is a right hand bend (Fig. 2). The length of the linear pieces is adjustable. For linear motion of the vehicle, a large linear piece is chosen. Two coordinate systems are used:

- an inertial coordinate system and
- a local coordinate system

The inertial coordinate system (x,y,z in Fig 2.) is located in the centre point of the curve, which is a normal circular element. The local coordinate system (1,2,3 in Fig. 2) is located in the mass centre of the unloaded vehicle. Its position is fixed to the vehicle. The conveyor vehicle modeled as a rigid body has 6 degrees of freedom combined in the vector of generalised coordinates

$$Y = [x, y, z, \alpha, \beta, \gamma]^T \tag{1}$$

The coordinates x, y and z locate the local coordinate system in the inertial coordinate system. The angles α, β and γ (Euler angles) describe the rotation of the local coordinate system about the inertial coordinate system. The equations of motion are set up in the inertial coordinate system. The conveyor vehicle belongs to the class of the ordinary ideal mechanical systems. These are characterised by holonomic constraints and external forces which are only dependent on position and velocity parameters. The corresponding equations of motion can always be written as a system of ordinary differential equations of second order [3]. The vehicle's equations of motion summarised in a matrix equation are:

$$M(Y,t)\cdot \ddot{Y}(t) + k(Y,\dot{Y},t) = g(Y,\dot{Y},t) \tag{2}$$

with:

- $M(Y,t)$ the symmetric [6x6] mass matrix
- $k(Y,\dot{Y},t)$ the [6x1] vector of generalised gyroscopic forces
- $g(Y,\dot{Y},t)$ the [6x1] vector of generalised forces

The support magnet exerts a levitating force and a guidance force. The linear motor exerts a propelling force and a normal force. These external forces and the vehicle's weight are all taken into account. It is assumed that the external forces act on the center of gravity of bearing magnet and motor and are aligned with the local coordinate system. Due to mechanical stops the pitch (α) and roll (β) angles are restricted to low values. The simplifications sin(i) = i and cos(i) = 1 for i = α, β are legitimate. To guarantee an accurate dynamic model of the vehicle further simplifications on the equations of motion are not made. Any vehicle's geometry can be simulated. A geometry input file with the location of the working points in which the external forces are acting and the vehicle's inertia properties is loaded during the initialisation process. This universal approach enables a study of the influence of the vehicle's geometry on its dynamic behavior. In the block diagram of the simulation environment (Fig. 9) the mechanical model is displayed as a black box with the external forces as input parameters and the generalised coordinates as the output parameters.

B. The Support Magnets

1) Hybrid-excited Support Magnet:

To obtain good simulation results the nonlinear behavior of the support magnets must be taken into account. The job of the levitation control system is to keep a particular air gap value between support magnets and guideway. Successful operation means that a support magnet can be modeled as a one degree of freedom mechanical system with a mass m equal to a quarter of the total vehicle's mass. The voltage-controlled hybrid-excited support magnet is described by a system of two nonlinear equations of third order:

- Voltage equation of the coil:

$$u = R \cdot \frac{\theta}{N} + \frac{\partial \psi(\theta,\delta)}{\partial \theta} \cdot \frac{d\theta}{dt} + \frac{\partial \psi(\theta,\delta)}{\partial \delta} \cdot \frac{d\delta}{dt} \tag{3}$$

- Equation of motion:

$$m \frac{d^2 \delta}{dt^2} = -F(\theta,\delta) - f_h(\delta_A - \delta) + mg \tag{4}$$

The levitating force F and the flux linkage Ψ both function of air gap δ and current linkage θ are calculated based on a 3D finite element model of the controlled hybrid-excited support magnet. The splines are shown in Fig. 3 and Fig. 4. The partial derivatives are shown in Fig. 5 and Fig. 6. The normal force of the homopolar motor changes proportionally with the air gap (f_h=130N/mm, δ_A= 2.5mm). With the aid of lookup tables an accurate simulation model of the nonlinear system can be built.

2) Electromagnet:

In the model of the hybrid-excited support magnet the guidance force is assumed to be proportional to the lateral position of the magnet. This assumption is not appropriate for simulation of a ride through a curve. In order to become the required splines for an accurate model many finite element calculations must be done which takes a lot of time. At the early stage of the design process these accurate results are not necessary. Quantitative results of the vehicle's dynamic behavior in the curve are more than satisfying. Therefore, an analytic model of a conventional electromagnet with an equal nominal levitating force as the hybrid-excited support magnet is used. Such a model is presented in [4]. The levitating and guidance forces are given by:

$$f_z(\varepsilon,\delta,\theta) = \frac{1}{4}\theta^2 \mu_0 \; l \left(-\frac{a-\varepsilon}{\delta^2} - \frac{4\varepsilon}{4\delta^2 + \pi \; \delta \; \varepsilon} \right) \tag{5}$$

$$f_y(\varepsilon,\delta,\theta) = \frac{1}{4}\theta^2 \mu_0 \; l \left(-\frac{1}{\delta} + \frac{4}{4\delta + \pi \; \varepsilon} \right) \tag{6}$$

with ε: the lateral position of the electromagnet
a: the yoke's width
l: the yoke's length

Equations (5) and (6) together with an equation of the flux linkage are used to model the electromagnet in a similar way as the hybrid-excited support magnet. Future modeling work will be focused on extending the hybrid-excited magnet model with a guidance force.

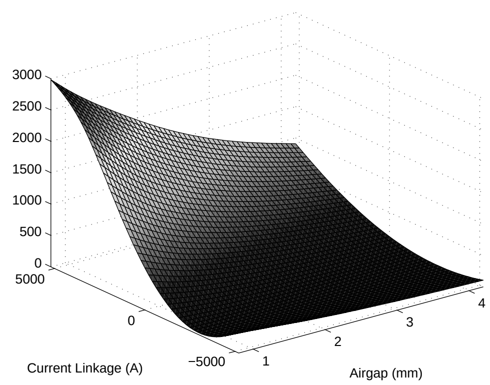

Fig. 3: Levitating force F(θ,δ)of a hybrid-excited support magnet [N]

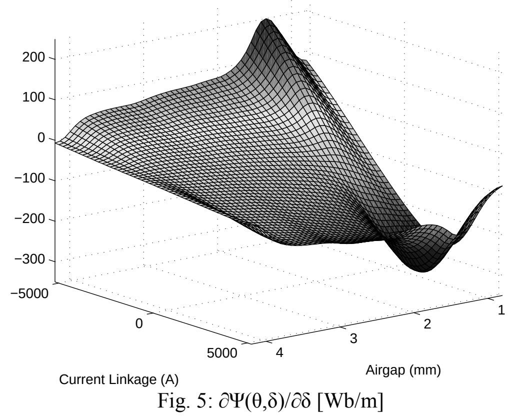

Fig. 5: ∂Ψ(θ,δ)/∂δ [Wb/m]

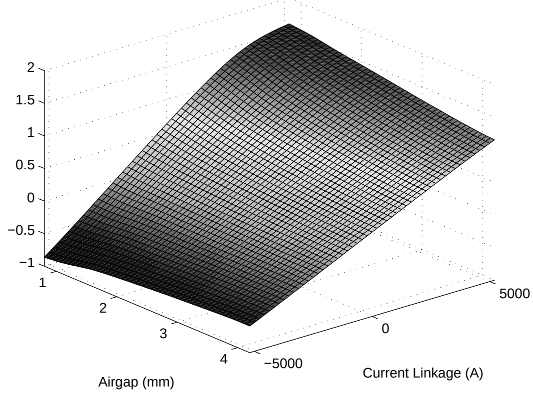

Fig. 4: Flux linkage ψ(θ,δ)of the windings [Wb]

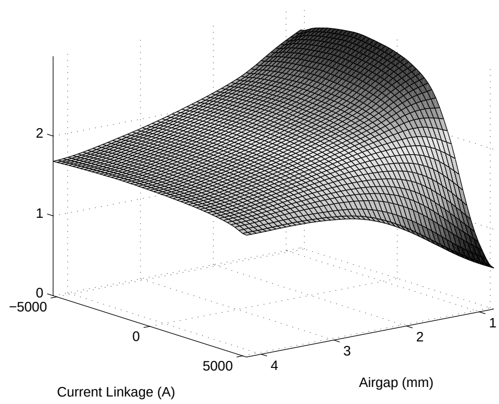

Fig. 6: ∂Ψ(θ,δ)/∂θ [10e-4 Wb/A]

C. *The Levitation Control System*

The state controller is an often used control structure for maglev applications. If connected with an integral element static offset is reduced to zero for all valuable operating points. The state controller with an integral element achieves a good performance with a relatively simple control structure. The control algorithm requires little calculating time which enables a high control frequency. The standard levitation control system consists of four state controllers. Each support magnet is controlled by its own controller independent of the others. Modularity however enables the simulation of any levitation control system, e.g. a nonlinear linked control algorithm.

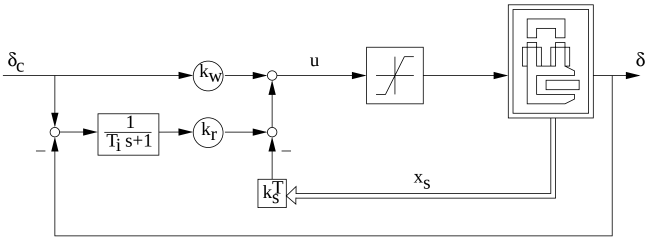

Fig. 7: Block diagram of the state controller

The block diagram of the levitation controller connected with a P-T1-element is shown in Fig. 7. Air gap, air gap velocity and current linkage are the elements of the state vector (x_S). Estimated values of the control parameters k_w, k_r, T_i and k_S ([3x1] vector) are calculated based on a linearised model of the system through eigenvalue assignment [5]. Fine tuning is iterated based on simulations done with the nonlinear model.

D. *The Linear Drive*

The propulsion force of a homopolar motor depends on electrical angle and motor current. Accurate implementation requests a position encoder and the use of look-up tables. Because most simulations are done with a vehicle moving with a constant velocity, in a first approach the acceleration process was implemented with constant propulsion forces. The vehicle is accelerated until a velocity setpoint value is reached, from that moment the propulsion forces become zero and the vehicle moves with the wanted constant velocity. Aerodynamic braking forces and braking forces due to eddy current losses are neglected.

To obtain more precise results of the acceleration / deceleration process a position encoder system and an extended linear drive controller system must be added. As an example of a possible extension of the simulation environment, the next section presents an accurate implementation of the position encoder system.

E. *Position Encoder System*

The motor reaction rail is a slotted rail built up of many flux concentrating pieces (Fig. 8). The position of the vehicle can easily be measured by a set of light barriers placed on each corner of the vehicle. Simulation results will show that a vehicle moving through a curve starts yawing. To examine the effect this yawing has on the correct steering of the vehicle, an accurate position encoder system is needed. In the inertial coordinate system the location of the flux concentrating pieces is known. The position of one light barrier presented as a black dot in Fig. 8 in the inertial coordinate system is the sum of vector r̲ and vector p̲, both depicted in the inertial coordinate system. Vector p̲, a constant vector depicted in the local coordinate system, must be transformed with the Euler angles. Comparison of the position information results in a high (low) level signal when the light barrier is (not) between two flux concentrating pieces. Calculation of the lateral deflection is done in a similar way.

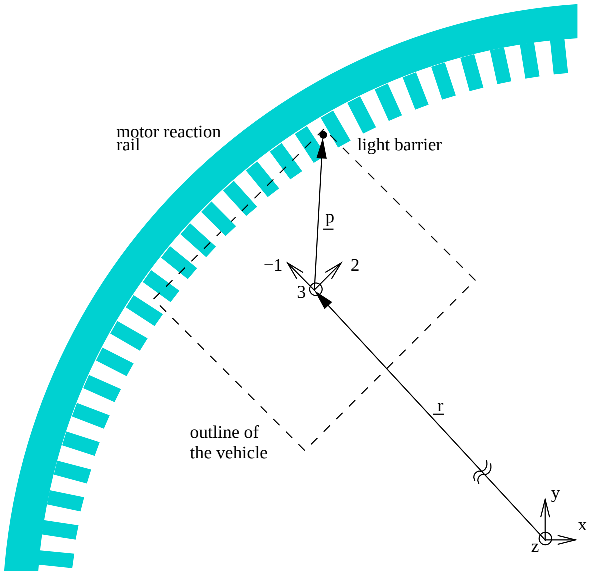

Fig. 8: Position of the vehicle in a curve

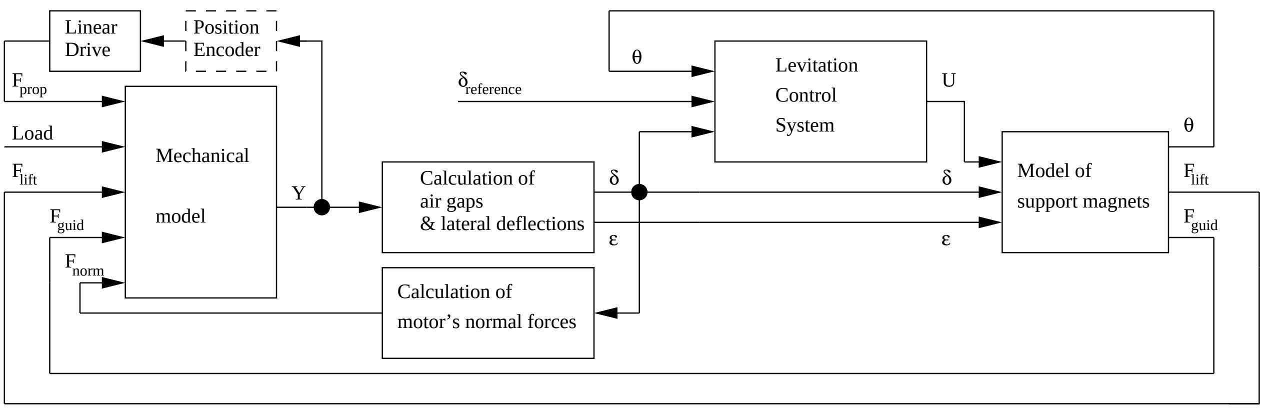

Fig.9 Block diagram of the simulation environment

F. Block Diagram

The block diagram of the simulation environment is shown in Fig. 9. Most arrows represent vector signals with a width of four. The vector Y has a width of six. The “load” arrow represents a data structure which contains the position, the mass and the inertia matrix of the load.

The simulation environment is implemented in *Matlab/Simulink*. Implementation of the equations of motion requires great care. Although it is a cumbersome job, setting up the equations of motion and implementing them helps one in understanding the dynamic behavior of the conveyor vehicle.

IV. Simulation Results

A first simulation (Figs. 10-15) shows the vehicle’s behavior moving on a straight line. This simulation was done with the accurate model of the hybrid-excited support magnets. At t=0.5s the vehicle is in its neutral position, this means it rests on the lower mechanical stop. At t=1s it starts levitating. The set point air gap value (2.5mm) is attained without overshooting. The dynamic response of the controlled system is satisfying. At t=1.5s the vehicle is loaded with a mass of 25 kg. Because the load is applied just above the vehicle’s center of gravity the vehicle is uniformly moved downwards. At t=2s the vehicle is accelerated until a velocity of 1m/s is reached. The vehicle’s center of gravity is located above the plane spanned by the homopolar motors. The driving forces cause moments of force about the center of gravity and the vehicle starts pitching. As the acceleration is growing, the air gaps of the front support magnets diminish, those of the rear support magnets grow. The opposite is true for diminishing acceleration. Meanwhile, the levitation control systems prevents that greater deviations can occur. From t=3s onwards the vehicle decelerates until standstill. Similar curves in reverse order are seen. At t=4.2s the vehicle is unloaded. The air gaps grow for a while because the coil current of the support magnets must be reduced. From t=4.5s onwards the vehicle is levitating at an air gap of 2.5mm.

A second simulation shows the dynamic behavior of a vehicle equipped with electromagnets riding through a curve. The curve has an inner radius of 2 m and a width of 1 m (Fig. 16). The vehicle is moving with a velocity of 0.25m/s. Close-ups of the rectangles defined in Fig. 16 are displayed in Fig. 17. The limits of the guide way are marked with solid traces. The dash-dotted trace is the center line of the guide way. Depending on the close-up, the solid trace in the middle is the path made by the working point of the front left support magnet or the path made by the vehicle’s center of gravity. When the vehicle runs into the curve it starts yawing. This effect continues after leaving the curve. The vehicle’s center of gravity follows a path with a smaller radius as the middle radius of the curve, this effect could already be seen in Fig. 2.

V. Conclusions

A magnetic levitation vehicle is a complex mechatronical system. The presented simulation environment is a preeminent appliance to analyse the dynamical behavior of the conveyor vehicle. It enables a correct design of the levitation control system and gives valuable indications for the construction of the guideway.

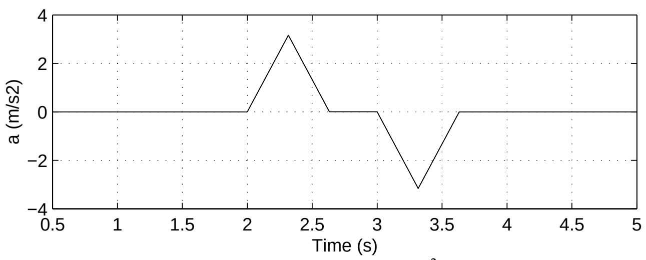

Fig. 10: Acceleration [m/s^2]

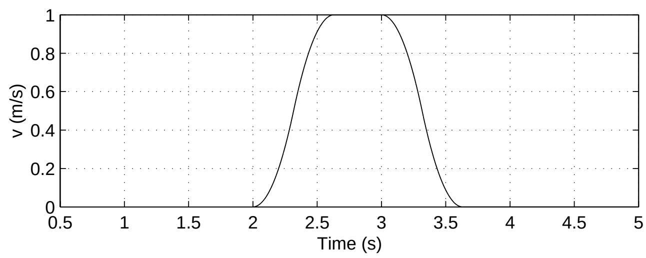

Fig. 13: Velocity (m/s)

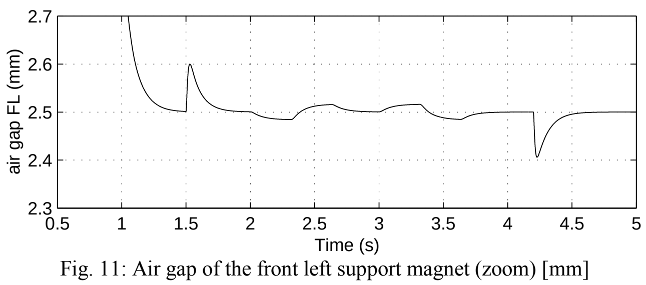

Fig. 11: Air gap of the front left support magnet (zoom) [mm]

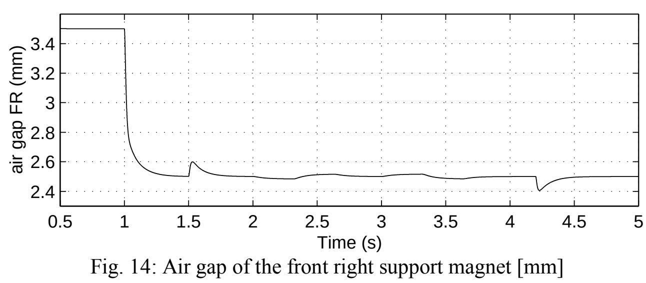

Fig. 14: Air gap of the front right support magnet [mm]

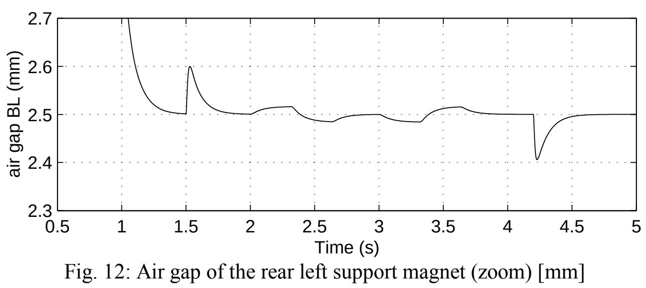

Fig. 12: Air gap of the rear left support magnet (zoom) [mm]

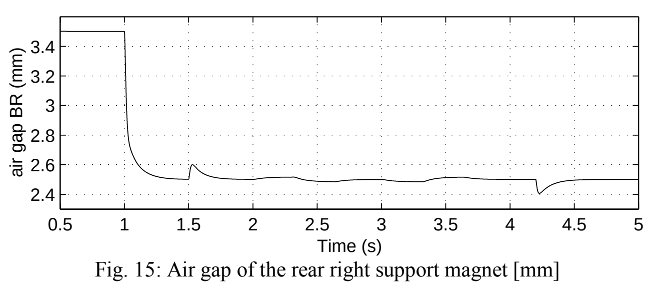

Fig. 15: Air gap of the rear right support magnet [mm]

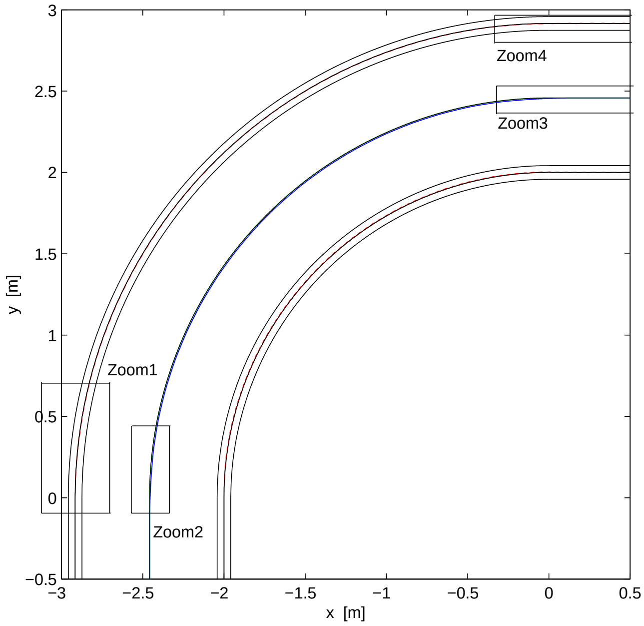

Fig.16: Simulation of the conveyor vehicle in a curve

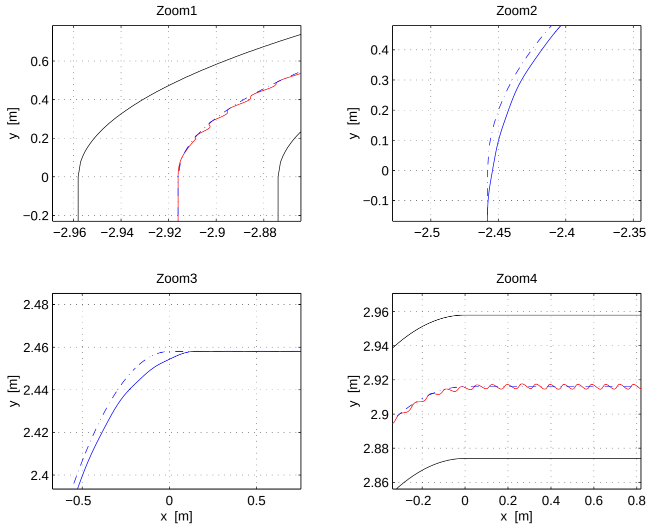

Fig.17: Close-ups of Fig. 16

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