Submission to the 9 th IFAC Symposium on Control in Transportation Systems 2000, June.13-15, 2000, Braunschweig, Germany

DESIGN OF A RAILWAY CARRIAGE, DRIVEN BY A LINEAR MOTOR WITH ACTIVE SUSPENSION/TILT MODULE

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Abstract : This paper presents the design of a railway carriage whose drive is realized by a linear motor. An integrated suspension/tilt module makes possible increased ride comfort and cornering speed in comparison to existing systems. *Copyright © 2000 IFAC*

Keywords: Linear motors, Active vehicle suspension, Modelling, Simulation, Control-design, Railways

1. INTRODUCTION

In the past years, technological progress in railway technology has brought about a large network of railways that does not need extension. It is suitable both for the fast transport of passengers and for that of heavy freight. The principle of the force-closed drive via contact of wheel and rail has not changed much, yet there are still some drawbacks to it: on the one hand, together with velocity, friction will increase, and so will energy consumption and the wear of the components; on the other hand, the force closure will decrease in the case of wet or icy rails and during cornering. The suspension in conventional trains, realized by means of relatively hard springs and dampers, is very uncomfortable for the passenger.

In contrast, a system driven by a linear motor will offer the advantage of a frictionless drive of the respective vehicle. Many of these systems require a new line of their own, especially if the linear drive is combined with magnetic levitation, as is the case with the German high-velocity system Transrapid (Henning, 1995) or the Japan-based HSST (Jayawant, 1981). The environment will be extensively affected; financial and political problems will seriously endanger future realization.

2. APPROACH TO A SOLUTION

The research team *New Railway System Paderborn* has designed a railborne, linear-motor-driven railway carriage that combines the advantages of the two systems. The drive is effected by means of a travelling magnetic field, contact-free via the linear drive and not via the contact between wheel and rail. The motor can be integrated into the existing railway system and the infrastructure of the latter can thus be used.

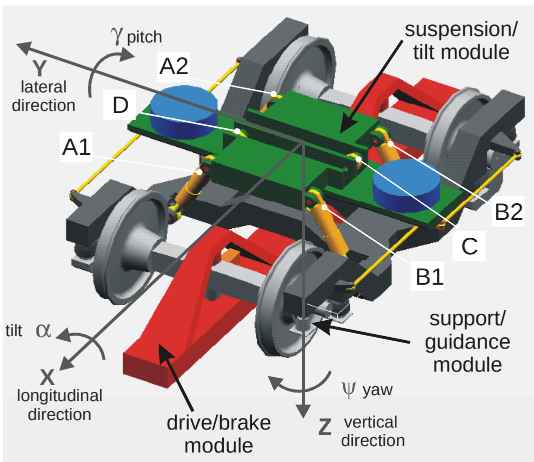

Fig. 1 – The fully automated modular railway system

Decoupling the drive from the wheels allows an optimal design of an active suspension/tilt module, because the bogie can be mounted easily and unsprung masses will be reduced. Thus ride comfort can be improved; the active tilting device allows higher cornering velocities. When the existing railway wheel-rail-system is used, the functions "supporting" and "guiding" can be realized without further energy expenditure.
The railway carriage consists of three modules (Lückel *et al*. 1999):
Drive and brake module: With a linear drive, it is possible to start up and brake a carriage wear-free. Thus existing railway lines can be used for the concurrent operation of conventional and novel systems.
Active suspension and tilt module: Active suspension brings about comfortable suspension of the coach body, reduces sensitivity to unevennesses in the track bed, and the same actuator system allows to realize the tilting module in order to increase cornering speed.
Support- and guidance module: Use of the existing railway wheel-rail-technology.
These three modules, coupled with the passive primary suspension, make up a fully automated undercarriage that allows the shuttle to operate flexibly, without a driver, and for the transport both of passengers and of freights.
The modular structure of the undercarriage allows for an independent design and testing of the drive and the suspension/tilt modules.

3. THE DRIVE SYSTEM

3.1. Systematics

The linear motor in the main consists of the following electro-mechanical components:

- the primary (stator), installed between the rails,
- the secondary, mounted on the undercarriage.

In the stator, a magnetic travelling field is generated that exerts a force on the electrically excited secondary in the carriage (Fig. 2). Primary and secondary are interlinked only magnetically by the air gap, with the latter, which is indispensable for the proper functioning, being ensured by the tracking of the carriage. A comfortable control of the longitudinal dynamics can be easily obtained because the power is directly transmitted to the secondary without power losses due to the transmission.

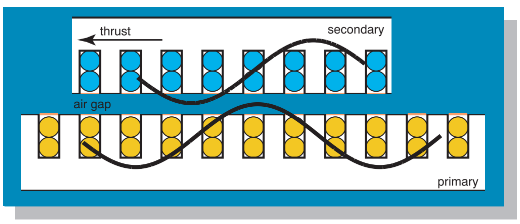

Fig 2 - Thrust build-up in the linear motor

In many an application of the linear-motor technology, the excitation field is generated in the secondary and the thrust is controlled by means of the stator current according to reference values set by superordinated control loops concerning velocity and longitudinal dynamics. Only one secondary per stator segment can then be operated because the stator current as control variable would affect all coaches. In order to make the carriage motion more flexible, a relative motion between different coaches on the same stator has to be made possible. This puts high demands on the actuators as well as on the control and information-processing units (Fig. 3).
A synchronous long-stator linear motor is not able to produce the desired relative motion; therefore the secondary in the coach will be equipped with a three-phase winding. Thus the excitation flux can be varied relative to the position of the coach and an asynchronous operation comes within reach.

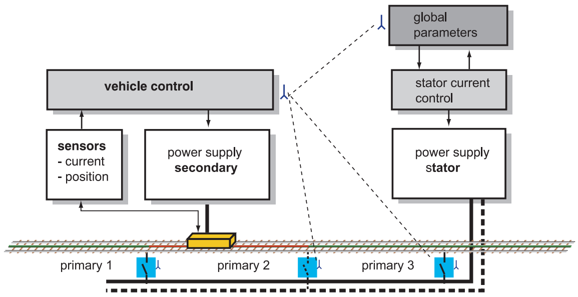

Fig 3 - Overall structure of the drive system

The actual thrust control is effected on board and the motor is double-fed, i.e., primary and secondary can align their magnetic fluxes at any time (Kiel, 1999; Henke, 1999).
In order to avoid constant power supply to the entire track, the latter is divided into segments that are supplied with voltage by different power-supply units (substations). They index the power supply to the next position in dependence of that of the coach. As a result, the energy consumption of the drive is optimized because the track is supplied with power only in the respective segment where there is a coach on the stator.

3.2. Modelling of the Drive System

To analyze the behaviour of the linear motor its mathematical model is drawn up and the overall behaviour of the drive is analyzed in the simulation.

Coordinate System
The currents in the secondaries are going to be controlled according to a uniform coordinate system common to all coaches; thus the interactions between the shuttles can be traced clearly. The primary and the secondaries share the same electrical position of the stator current as the statorflux linkage depends also on the respective current of the secondary.

The coordinate system employed is thus oriented according to the stator current. The model of the secondary in the coach is built up oriented to the stator current and the stator-current orientation makes up the d-axis of the coordinate system (Fig. 4) with $i_{Sq} = 0$.

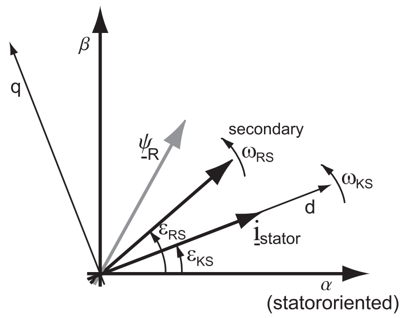

Fig. 4 - Stator-current-oriented coordinate system

Electrical Subsystem

The equations of the electrical subsystem of the double-fed linear motor rely on those of the asynchronous linear motor.

In the following, all variables are related to the secondary are indexed *R*, all stator variables, *S*. As regards motor parameters, there are:

L_h, L_σ : mutual and leakage inductances

R_R, R_S : resistance of secondary and primary

ψ_R, ψ_S : flux linkages

ω_{KS}: angular velocity of the stator field

ω_{RS}: angular velocity of the secondary

σ, ρ : leakage and resistance coefficients

The complex equations relating to the voltage of the primary and secondary are displayed in (1) and (2):

$$\sigma L_S \frac{d\underline{i}_S}{dt} = \underline{u}_S - R_S \underline{i}_S - \frac{L_h}{L_R}\underline{u}_R + \frac{L_h R_R}{L_R}\underline{i}_R + j\omega_{RS} L_h \underline{i}_R + j\omega_{KR}\frac{L_h^2}{L_R}\underline{i}_S - j\omega_{KS} L_S \underline{i}_S \qquad (1)$$

$$\sigma L_R \frac{d\underline{i}_R}{dt} = \underline{u}_R - R_R \underline{i}_R - \frac{L_h}{L_R}\underline{u}_S + \frac{L_h R_S}{L_R}\underline{i}_S + j\omega_{RS} L_h \underline{i}_S + j\omega_{RS}\frac{L_h^2}{L_R}\underline{i}_R - j\omega_{KR} L_R \underline{i}_R \qquad (2)$$

The equations are transformed into the statorcurrent-oriented coordinate system. Transformation yields the real part of the equation (1) as follows:

$$\sigma L_S \frac{di_{Sd}}{dt} = u_{Sd} - R_S i_{Sd} - \frac{L_h}{L_R} u_{Rd} + \frac{L_h R_R}{L_R} i_{Rd} - \omega_{RS} L_h i_{Rq} \qquad (3)$$

The imaginary part is

$$\sigma L_S \frac{di_{Sq}}{dt} = u_{Sq} - R_S i_{Sq} - \frac{L_h}{L_R} u_{Rq} + \frac{L_h R_R}{L_R} i_{Rq} - \omega_{RS} L_h i_{Rd} + \omega_{KR}\frac{L_h^2}{L_R} i_{Sd} - \omega_{KS} L_S i_{Sd} = 0 \qquad (4)$$

Thus the angular frequency of the stator current results in

$$\omega_{KS} = \frac{1}{L_S i_{Sd}}\left(u_{Sq} - \frac{L_h}{L_R} u_{Rq} + \frac{L_h R_R}{L_R} i_{Rq} - \omega_{RS} L_h i_{Rd} + \omega_{KR}\frac{L_h^2}{L_R} i_{Sd}\right). \qquad (5)$$

Equations (3) and (4) represent the dynamics of the statorcurrent. To determine the electrical states in the secondary, we now have to derive the equations of the secondary voltage; they yield the secondary currents:

$$\sigma L_R \frac{di_{Rd}}{dt} = u_{Rd} - R_R i_{Rd} - \frac{L_h}{L_S} u_{Sd} + \frac{L_h R_S}{L_S} i_{Sd} - \omega_{KS}\frac{L_h^2}{L_R} i_{Rq} + \omega_{KR} L_R i_{Rq} \qquad (6)$$

$$\sigma L_R \frac{di_{Rq}}{dt} = u_{Rq} - R_R i_{Rq} - \frac{L_h}{L_S} u_{Sq} + \omega_{RS} L_h i_{Sd} + \omega_{KS}\frac{L_h^2}{L_R} i_{Rd} - \omega_{KR} L_R i_{Rd} \qquad (7)$$

The force equation of the motor is the following:

$$F_m = -\frac{3\pi}{2\tau_p} L_h \cdot i_{Sd} \cdot i_{Rq} \qquad (8)$$

The power is thus proportional to the stator current i_{Sd} and to the secondary component i_{Rq}. Fig. 5 displays the block diagram of the motor. Here, five variables have to be controlled: The velocity of the coach, the components of the rotor current, the stator-current frequency, and the amplitude of the stator current (i_{Sd}).

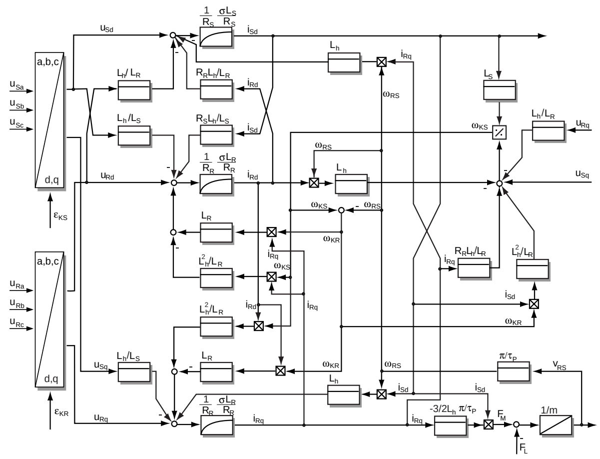

Fig. 5 - Model of the double-fed linear motor

The electrical actuator of the linear motor is a converter generating the voltage values that the control requires. On board, a converter supplies power to the on-board batteries and the excitation windings.

Mechanical Subsystem

The coach is modelled as a one-mass system. This yields the simple mechanical equation for the coach motion:

$$m\ddot{x} = F_m - F_L \qquad (9)$$

The load F_L affecting the secondary of the motor is a combination of:

- wind resistancies, gradients, friction
- load forces resulting from the energy transmission to the coach
- longitudinal vibrations of the coach

3.3. Drive Control

We have already stated that the system behaviour forces to decouple the stator-field control from the control of the coach.

Control of the Stator Field

Contrary to conventional linear drive systems, the stator here builds a unit whose current has to be controlled as to constant frequency and amplitude during operation. Disturbances here are the voltages induced by the moving secondaries.

Control of the Longitudinal Dynamics of the Vehicle

Every coach controls its own longitudinal dynamics via the electrical position of the excitation flux and uses the stator flux common to all coaches. Here, the control takes into account the switching between the stator segments. As the stator current is fixed at a constant value, the only remaining actuating variable of the thrust control is the q-component i_{Rq} of the secondary current, cf. equ. (8).

Control of the Energy

The current component i_{Rd} and the slip s (the latter can be regulated only to a certain degree) do not affect the build-up of thrust, yet they have influence on the energy flux in the air gap. The actuating variable u_{Rd} serves to regulate the current i_{Rd} so as to bring about the desired energetical behaviour. The reference value of i_{Rd} can be set so as to minimize the secondary losses. Furthermore, to feed the secondary, energy has to be provided on board by batteries whose charge influences the reference values for the energy control.

3.4. Global Control Structure

For the control of the carriage, there are thus three remaining variables to be controlled: the complex components of the secondary current and, superordinated, the velocity v_{RS} of the carriage.

The actual values of i_{Rd} and i_{Rq} are directly determined from the measured primary and secondary currents in a flux model.

Precise knowledge of the position of the coach is vital to its control. The position has to be detected with very high precision and high dynamics. For this purpose, magnetic-field sensors on board the coach are used to determine the position in relation to the stator field. The use of high-performance signal processing allows to estimate the position on the basis of measured current and voltage values for thrust control. Fig. 6 displays in detail the overall structure of the coach control:

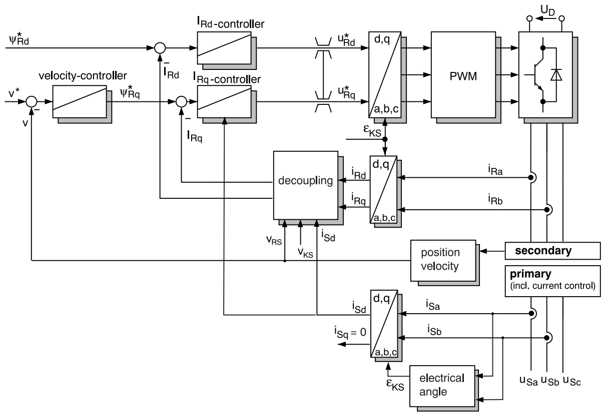

Fig. 6 - Statorcurrent-oriented control structure

he air gap between the primary and the secondary has to be assessed because a change would immediately affect thrust and braking forces (Gieras, 1995). Alterations in the air gap affect the build-up of force and voltage as alterations in the gain, so the thrust controller will have to be adapted accordingly.

3.5. Simulation

For the control shown above, a simulation model has been made up (Henke, 1999). The simulation is based on parameters of a linear drive, which is used to propell a 1:5 scaled prototype of the railway vehicle.

Fig. 7 displays the simulation results.

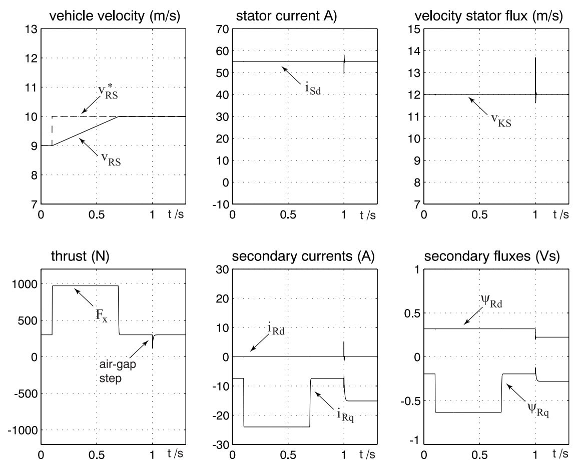

Fig. 7 - Simulation result

At the time t = 0.1 s , a step in the reference value of the velocity is given. At t =1 s an alteration of the air gap affects the coach.

This alteration results in an increase of the secondary current as the required thrust has to be generated with a reduced main inductivity L_h. The force-equation (8) shows, that a decrease in L_h can only be compensated by a higher q-current in the secondary, because i_{Sd} remains constant. The secondary fluxcomponent ψ_{Rd} also decreases, so that ψ_{Rq} has to be increased via i_{Rq} to maintain the desired flux-density in the airgap between primary and secondary. Future work will concentrate on the verification of the results on the drive testbed.

4. THE ACTIVE SUSPENSION/TILT MODULE

4.1. Demands on the Suspension/Tilt Module

The passive system with spring and damper operates in a frequency range (of up to about 200 Hz) that is unpleasant for the passenger because the force proportional to the velocity brings about high damper forces in the upper frequency range. As regards the coach-body suspension, a bandwidth of about 1 Hz is acceptable for the passenger's well-being. It can be reached by means of an active suspension whose aim it is to produce the desired damping resp. spring characteristics in the respective frequency range.
Another demand on the railway carriage is for it to corner track curves at high speed with constant ride comfort and safety. For this an active tilt module is employed.

4.2. Concept of the Suspension/Tilt Module

In contrast to conventional suspension systems, the concept presented is concerned with eliminating all passive dampers in the secondary suspension and on connecting the coach body to the undercarriage only via the airsprings (Lückel, et al., 1999). While the airspring isolates the vibrations in the upper frequency range, the desired damping in the lower frequency range is obtained by an active intervention. Thus transmission of the disturbances stemming from unevennesses in the track alignment to the coach body is nearing zero. The result is a more than satisfactory ride comfort both in the vertical and horizontal directions. The information required to displace the airspring base is measured by appropriate sensors and processed in a hierarchically structured multivariable control (Fig. 8).
The active tilting of the coach body can be realized with the same actuator system through a feedforward of the cornering acceleration.
The core of the actuator system consists of the mechanical components upper and under plate (bogie) resp. the airsprings, the actuators, the sensors, and the information processing (Fig. 8).

While four actuators on the side lift and tilt the coach body, the other two actuators in the middle provide for lateral motion, with pitching being prevented by actuators on the side, and longitudinal and yawing movements being precluded by lemniscate links (Otto, 1999).

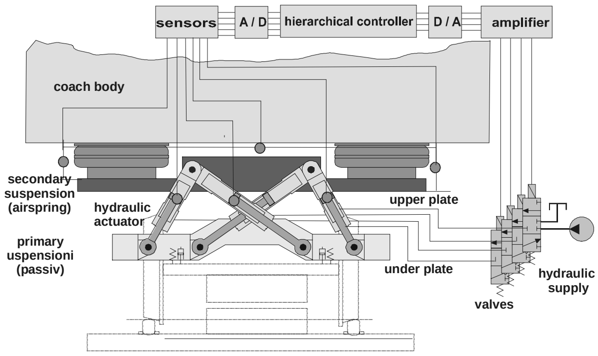

Fig. 8 – Schematic diagram of the suspension/tilt module

Every suspension/tilt module has to ensure three directions of motion: vertical, lateral, and tilting motions. The shuttle (consisting of two modules) allows all controlled rotational and translational motions in lateral and vertical directions. The translational motion in longitudinal direction (thrust) is controlled by means of the linear drive.

4.3. Modelling and Analysis of the System Behaviour

In order to analyze the behaviour of a dynamical system and then to design a multivariable control, we at first draw up the physical and the mathematical substitute model according to function principles in view of the demands. The model has to represent the kinematic, the statical and the dynamic behaviour of the system in view. Following appropriate simplifications a 3-D model (Kirchner, 1999) is made up for the analysis of the suspension/tilt module (Fig. 9):

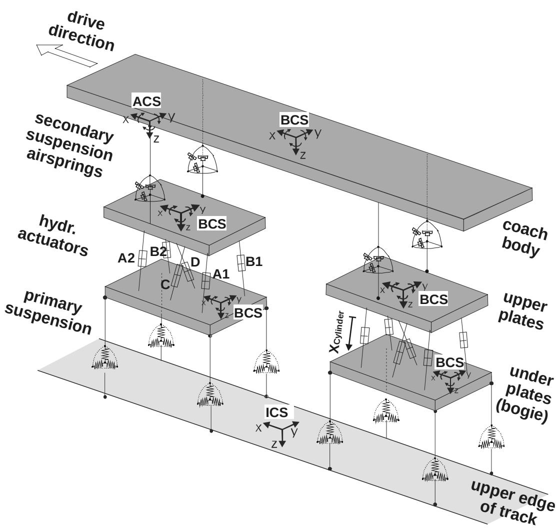

Fig. 9 - 3-D model of the suspension/tilt module

Modelling process is fully supported by the software environment CAMeL (**C**omputer-**A**ided **Me**chatronics **L**aboratory) developed at the MLaP.

CAMeL permits consistent treatment of the mechatronic system in the computer – from the object-oriented, interactive build-up of the modular-hierarchical system in a topological/physical model description, automatic derivation of the corresponding mathematical equations to an automatic generation of C code to a hardware-in-the-loop simulation in real time (Hahn, 1999). This requires systematic analyses of the entire system.

Kinematics of the System

The kinematic behaviour of the system is determined from the degrees of freedom and the geometry of the suspension/tilt module, according to suitable coordinate systems. Fig. 9 displays the ICS (Inertia Coordinate System) on the upper surface of the rails, the BCS (Body Coordinate System) in every rigid body, the ACS (Attachmentpoint Coordinate Systems) in the coupling points between elements and the coordinates of every cylinder piston $x_{Cylinder}$.

By means of coordinate transformations the kinematics and the inverse kinematics of the entire system are computed and later embedded into the global control structure.

Dynamics of the System

The dynamics of the entire system results from the dynamical properties of the mechanical supporting structures, actuators, sensors and digital signal processing.

- *Mechanical Supporting Structure*

The coach body as well as the upper and the under plate of the suspension/tilt module are modelled as rigid bodies with six degrees of freedom each. Corresponding equations of motion are generated symbolically by means of the Lagrange formalisms in CAMeL.

The complex operational mode of the airspring requires much computing (Krettek, et al., 1992). Therefore the simplified substitute model with PDT1 behaviour is employed for each degree of freedom.

- *Actuator Dynamics*

As actuators for the control motions, we use hydraulic differential cylinders which have a series connection to a servo valve (Fig. 10). Here, the electrical voltage of valve is the input value and the cylinder force the output value of the entire transfer behaviour.

Through the displacement of the valve slider, the servo valve converts the electrical signal into an oil flow. This dynamics is modelled by a system of 2nd order (Panther, 1984) and describes the dependence of the position of the valve slider on the input voltage.

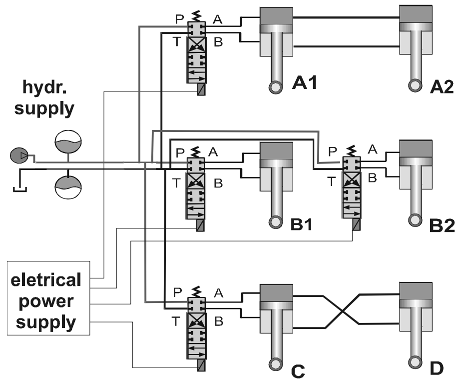

Fig. 10 - Hydraulic interconnections in the actuator

The actuating force of the cylinder is the product of the piston area multiplied by the pressure difference between the two cylinder chambers resulting from the inflowing and outflowing oil. This dynamical process is modelled in a differential equation of 1st order which describes the dependence of the pressure change of the two cylinder chambers on the alteration of volume flows, on the compressibility of the pressure medium, and on losses due to leakage.

- *Dynamics of the Sensor System and of the Digital Signal Processing*

When a digital controller is realized the sample time and the processing time required for computing the control algorithm can be described by means of the dead-time behaviour. This effect is implemented into the model through a Padé approximation.

The sensors narrow the bandwidth of the system. In the modelling, a PT2 low-pass filter is used in order to emulate the sensor dynamics.

- *Overall Dynamics*

According to these analysis above the dynamics of the entire module is modelled in the CAMeL environment with the models of every subsystem being topologically linked to suitable interfaces in the computer. With regard to the kinematics the supporting structure is extended by actuators, sensors, and digital effects to build up the overall dynamics of system.

Control Concept and Structure

The multivariable controller is hierarchically structured into two controller groups: global ones operating at the centre and local ones operating decentrally.

Fig.11 displays this hierarchically structured multivariable control of the suspension/tilt module. The superordinated global consists mainly of three blocks. The vertical and lateral displacements as well as the tilt angles of the coach body are derived from the measured cylinder positions and air-spring positions in the block *Decoupling* that is based on the system kinematics. From this the desired spring and damper forces are generated in the block *tuning forces*. With regarding to acceleration the forces bring about the reference values for the subordinated control loops in the *Coupling* block.

As local controls, there are the cascade control structures with three loops that can bring the dynamics of the individual actuator under control quickly enough. The inner control loop is made up of the position control of the gate valve. The velocity of the cylinders is realized via the middle control loop and the outer control loop is made up of the position control of the cylinder.
The parameters of this hierarchically organized control structure is optimized in the CAMeL environment by means of a vector quality criterion.

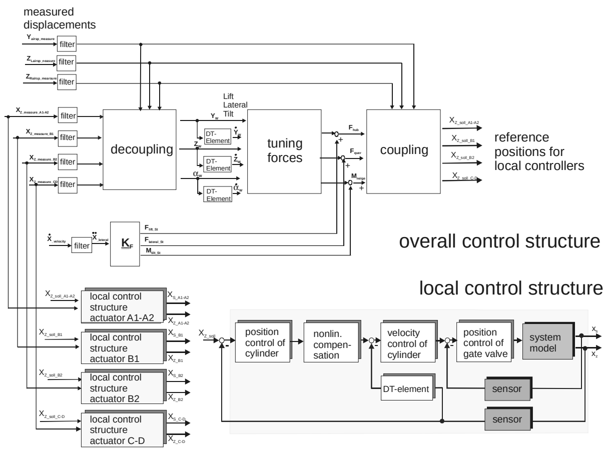

Fig.11 - Hierarchical control structure

Simulation and Display of Results
The controlled entire system was experimented in the computer. In order to show the potential for improving the active control, the passive system was analyzed in the same operating conditions. A step excitation produced by the track is employed.
Fig. 12 displays the coach-body motion of the active and the passive system in vertical direction. The step responses of the nonlinear simulation of lateral and vertical directions show similar curves. The simulation result shows the system behaviour of the active system to boast a considerably higher damping than that of the passive system.

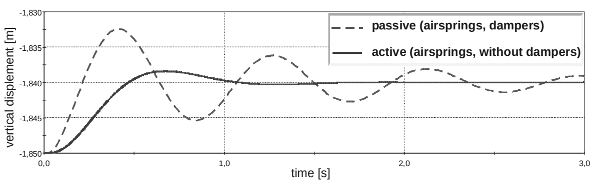

Fig. 12 – Step response of the coach-body motion

As a measure of the accelerations the passenger is subject to, the amplitude spectra of the coach-body acceleration were determined. The area integrated from amplitude spectrum of the active suspension is considerably smaller than that of the passive system (Fig. 13). Thus the active suspension system brings about a ride comfort that is many times better than that of the passive system.

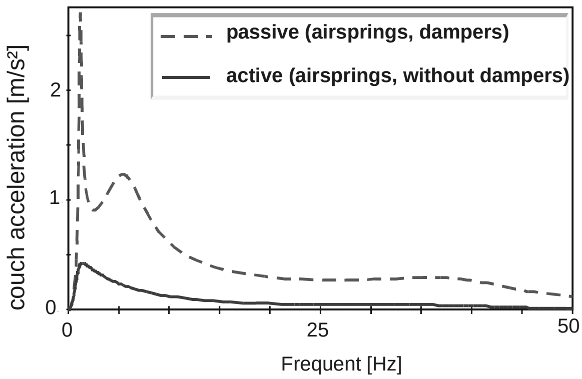

Fig.13 – Spectra of the coach-body accelerations

4.4. Testbed of the Suspension/Tilt Module

Fig. 14 illustrates the whole testbed concept of the suspension/tilt module. It makes up a half-shuttle with a suspension/tilt module on a scale of 1 : 5. The coach body has three degrees of freedem, in vertical and lateral directions as well as tilt, respectively. The excitation cylinders in the test infrastructure emulate the vibrations resulting from the primary part of the undercarriage and from unevennesses in the track bed, as well as from lateral disturbances of the coach body. The testbed rests on six airsprings so as to decouple the system from the vibrations coming from its environment.
On this lab testbed the designed hierarchical control structures and the entire configuration of the system can be measured, analyzed and validated under real-time conditions

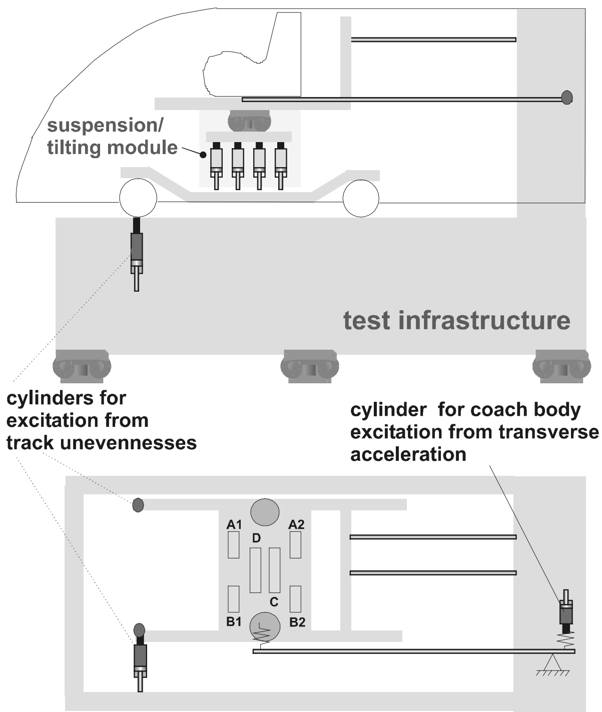

Fig. 14 - Testbed concept

Fig. 15 displays the partial realization of testbed. The positions of cylinder and gate valve as well as the displacements of the air spring are measured; the measured signal are then transmitted by A/D converters to a DSP where the control algorithms are processed and the signals transmitted to the actuating valves via D/A converters.

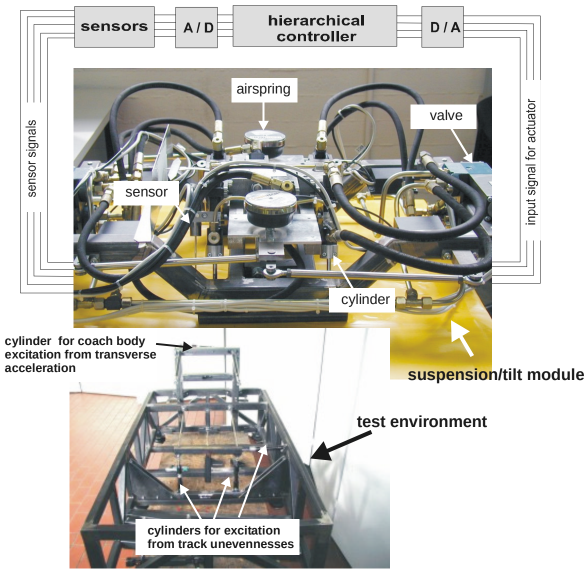

Fig. 15 – Realization of testbed

5. SUMMARY

The paper presented the design of a technically highly complex railway carriage with the drive and the suspension/tilt modules being examined in more detail.

The drive by means of a linear motor allows a very precise control of the longitudinal dynamics because the motor can act on the undercarriage directly without a gear. The active suspension allows to isolate vibrations of the coach body, resulting from unevennesses of the tracks that might impair the passenger's well-being. The result is an increase in ride comfort. The tilt module is realized with the same actuator system.

As regards the drive and the suspension/tilt modules, we presented the design from modelling to simulation till realization. The railway carriage, combining the linear wear-free drive with an active suspension/tilt module, has been designed on several testbeds and is currently being optimized.

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