Coupled Pitch and Velocity Control of a Doubly-Fed Linear Motor

Bo Yang, Michael Meyer, Horst Grotstollen
EIM-E/LEA, Institute of Power Electronics and Electrical Drives
University of Paderborn
Warburger Str. 100, D-33098 Paderborn, Germany

ABSTRACT

This paper proposes a new coupled pitch and velocity control of a doubly-fed linear motor, which is applied for a novel mechatronic railway system based on the operation of shuttles. Compared with conventional trains, a single axle undercarriage is developed for the shuttle. The primary of the linear motor is installed between the rails and the secondary is fixed on the axle only via the middle. In order to prevent the secondary from pitching and maintain a constant air gap between the primary and the secondary, the secondary windings are divided into two parts to be supplied separately. A decoupled pitch and velocity control is introduced in [1] in detail. Because the currents for pitch control don't contribute to velocity control, they cause higher power losses of the system. Therefore, a coupled pitch and velocity control is developed and presented in this paper.
Keywords: NBP, Modelling, Pitch Control, Velocity Control, Kalman Filter, Doubly-Fed Linear Motor

1. INTRODUCTION

Since 1997, a novel mechatronic railway system within the research project 'Neue Bahntechnik Paderborn' (NBP, New Rail Technology of Paderborn) has been developed at the University of Paderborn, which integrates advanced linear drive technology into the conventional railway system and is based on the autonomous operation of small trains, so-called shuttles. The shuttles are designed by using mechatronic design methodology and are embedded in an overall logistic structure to realize the autonomous, effective and flexible drive on desire, namely, direct to the destination without shuttle transferring. Nowadays, a 530-m NBP test track at a scale 1:2,5 is built in Paderborn and an official test drive of the shuttle will take place in June, 2003.
Both parts of the linear motor, primary and secondary, are fitted with three phase windings, so that magnetic fields of both the primary and the secondary, can be orientated arbitrarily. On the other hand, the doubly-fed linear motor is capable of transmitting energy contactless to the on-board power system. One component of the linear motor - the primary (stator) is installed between the rails, and the other - the secondary (rotor) is fixed under the carriage.
Because of the small size of the shuttles, a single axle undercarriage instead of traditional bogie variant, is developed for the shuttles to reduce the weight compared with conventional trains. The secondary is fixed on the axle only via the middle. It puts forward new control demand except for the required velocity control: The thrust force between primary and secondary drives the shuttle and its point of application is in the center of gravity of the secondary, i.e., under the axle (Fig.1). A torque is generated during the operation, in other words, a pitch motion of the secondary can't be avoided and the air gap between primary and secondary will vary accordingly. In order to prevent the secondary from hitting the primary and keep the air gap constant, the secondary windings are divided into two parts, which are supplied separately.
A pitch controller is designed by utilizing the normal forces of the two secondaries to compensate the pitch torque[1]. More precisely, the pitch control is independent of velocity control. One component of the secondary current (d-axis current) is used only for pitch control and is irrelevant for velocity control. In order to minimize the power losses, a coupled pitch and velocity controller is designed and implemented by using a dSpace digital multi-processor system.

2. MODELLING OF SYSTEM

2. 1 Reference Frame

From the drive control point of view, a primary current oriented reference frame is chosen for modelling and control of the system, which offers the advantage, that the reference frame is common to all secondaries, namely to all shuttles. To simplify the reference frame, the q-axis primary current is set to zero, i.e., the electrical orientation of the primary current has been chosen as the d-axis primary current I_{Sd} [1]. Therefore the secondary current in the orthogonal q-axis results in building up of thrust force because of the interaction of primary flux linkage and the orthogonal secondary current(Fig.2).

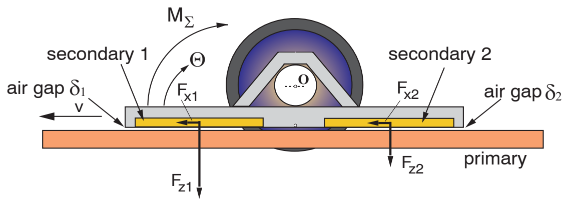

Figure 1: Structure of linear drive module

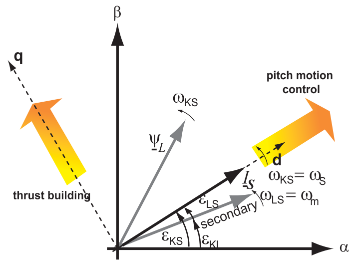

Figure 2: Primary current oriented reference frame

Since the d-axis current of the secondaries doesn't influence thrust force, it is used to control the normal forces of the secondaries to compensate the pitch torque. The q-axis current of secondaries is used as control variable for velocity control. By this means, linear drive control and pitch control are decoupled completely (Fig.2). [1]

2. 2 Differential Equations of the System

Using the Langrange method, a non-linear differential equation can be derived to describe the system. [1] Due to an overall length of the carriage of 1.2m and an air gap between primary and secondary of only 10 mm, the maximum pitch angle Θ_{max} is smaller than 1 degree. Moreover, as the objective of pitch control is, to keep the pitch angle as close to zero as possible, the actual pitch angle during operation of the vehicle will be considerably smaller than Θ_{max}, i.e., the system will work close the point: $\Theta = 0$. Therefore, the non-linear system can be linearized at the stable point: $\dot{\Theta} = 0$.
There are three schemes to control the pitch motion. The pitch angle Θ and pitch velocity $\dot{\Theta}$ are set as state variables for all cases.
• Decoupled pitch and velocity control
Pitch angle and velocity of the linear drive module are controlled separately. The d-axis currents of the two secondaries are defined as control variables for pitch controller. For this control scheme the differential equation of the pitch angle is expressed by using the state variables and d-axis secondary currents.

$$\Delta\ddot{\Theta} - a_d\Delta\Theta = b_{d1}\Delta i_{L1d} + b_{d2}\Delta i_{L2d} + b_{d3}\Delta F_x + b_{d4}\Delta\delta_1 + b_{d5}\Delta\delta_2 \tag{1}$$

'Δ' means the relative value to the point at which the system is linearized.
• Coupled pitch and velocity control
In this case, the pitch angle and pitch velocity are controlled by using q-axis secondary currents only, which are applied to velocity control at the same time. This coupled controller utilizes normal forces and thrust forces of the secondary to balance the pitch torque on the axle. In order to avoid an interference with velocity control, the sum of the q-axis secondary currents should be kept unchanged to achieve a constant thrust force for the linear drive module.
In fact, a q-axis deviation current Δi_{Lq} is generated by the pitch controller. Pitch control and velocity control are coupled by using the q-axis secondary currents. If $i^*_{L1q\_Ref}$ and $i^*_{L2q\_Ref}$ are the reference values of secondary currents obtained from the velocity controller, then the new current reference values will be given by $i_{L1q\_Ref} = i^*_{L1q\_Ref} + \Delta i_{Lq}$ and $i_{L1q\_Ref} = i^*_{L1q\_Ref} - \Delta i_{Lq}$ respectively.

$$\Delta\ddot{\Theta} - a_c\Delta\Theta = b_{c1}\Delta i_{L1q} + b_{c2}\Delta i_{L2q} + b_{c3}\Delta F_x + b_{c4}\Delta\delta_1 + b_{c5}\Delta\delta_2 \tag{2}$$

• Combination of decoupled and coupled control
The normal force of this doubly-fed linear motor is higher than the thrust force and the force arm of the normal force is also much longer than that of thrust force. Consequently, there may be a problem for coupled pitch and velocity control at a uniform motion, because the pitch torque of the thrust force may be too small to compensate the pitch torque generated by the normal force.
In order to solve this problem, i.e., to ensure that pitch motion can be controlled in all situations of operation, and to minimize power losses simultaneously, a combination of decoupled and coupled control is developed as a result.
Depending on the acceleration of the linear drive module, the controller for the combination is switched from coupled

1. All variables with subscripts'S' are used for primary, with subscript'L' for secondary.'S' and'L' are abbreviations for Stator (in English, Stator) and Laeufer (in English, Rotor).

pitch control to decoupled pitch control. As long as the drive module is accelerated or braked, the coupled pitch control will be implemented to save energy.

3. DESIGN OF CONTROLLER AND STATE OBSERVER

3. 1 Control Structure

Full state feedback with output integration is carried out to control the pitch motion. The resulting state-space equations are described by:

$$\begin{aligned} \Delta\ddot{\Theta} - a\Delta\Theta &= b_1\Delta i_{L1} + b_2\Delta i_{L2} + b_3\Delta F_x + b_4\Delta\delta_1 + b_5\Delta\delta_2 \\ \tilde{Y} &= [1 \qquad 0]\cdot[\Delta\Theta \qquad \Delta\dot{\Theta}]' \end{aligned} \tag{3}$$

namely $\begin{aligned} \dot{X} &= AX + BU + FW \\ Y &= CX + DU + HW \end{aligned}$

where $X = [\Delta\Theta \qquad \Delta\dot{\Theta}]'$, D=0, H=0. $'\Delta'$ means the relative value to the point at which the system is linearized.
In order to let the system state $\Delta\Theta$ track the input R(R=0), integral control is introduced into the controller.
The control input u(t) is given by

$$u(t) = -K_1X - K_2\int(R-Y)dt \tag{4}$$

where K_1 is a 2×2 feedback-gain matrix, and K_2 is a 2×1 feedback-gain matrix, both with constant elements. Naturally, when K_2=0, the system is a state controller with state feedback.
Since the feedback system now has one additional integrator (Fig. 5), the overall system is of (2+1)rd order and also controllable. The closed-loop system state equations matrices are

$$\tilde{A} = \begin{bmatrix} A_{2\times 2} & 0_{2\times 1} \\ \begin{bmatrix}-1 & 0\end{bmatrix} & 0 \end{bmatrix} \qquad \tilde{B} = \begin{bmatrix} B_{2\times 2} \\ 0_{2\times 1} \end{bmatrix} \tag{5}$$

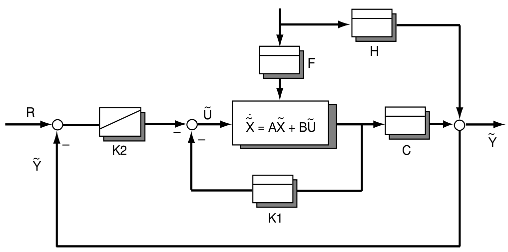

Figure 3: Block diagram of system with state feedback and output integration

With the integral control, the closed-loop system has three poles to be placed. Because the pair $[A, B]$ is completely controllable, a matrix K exists that can give an arbitrary set of eigenvalues of $A-BK$. With the given damping factor and natural frequency, the poles can be assigned.

3. 2 State Observer

The objective of pitch control is to control the air gaps to maintain a constant value, therefore, instead of direct measurement, the pitch angle is calculated by measured air gaps of two secondaries with several eddy current sensors.
The system defined by the pair $[A, C]$ is observable, as a result, it is possible to design an observer to estimate the pitch velocity by using the measured pitch angle and control inputs. The pitch velocity is estimated by a steady-state Kalman-Filter with constant Kalman gain matrix L, which takes measurement noise and process noise into consideration.
The observer can be expressed by the differential equation

$$\frac{d}{dt}\hat{X} = A\hat{X} + BU + L(Y - C\hat{X}) \tag{6}$$

The state feedback K and the observer gain L can be designed separately to yield desired closed-loop system behavior and observer behavior. Certainly, the separation principle is available under controllability and observability assumpitons.

4. EXPERIMENTAL RESULTS

4. 1 DSP Experimental Environment

A 8-m test bed has been built in the laboratory for one linear drive module with 12 primaries and 2 secondaries. The primaries are installed between the rails and two secondaries are mounted on the single axle. The air gap between the primary and the secondary is about 10 mm.

The experiment is implemented by using Real-Time Interface under a dSpace digital processor system, which is a real-time system for in-vehicle control experiments and equipped with processor Motorola 750(480 MHz).

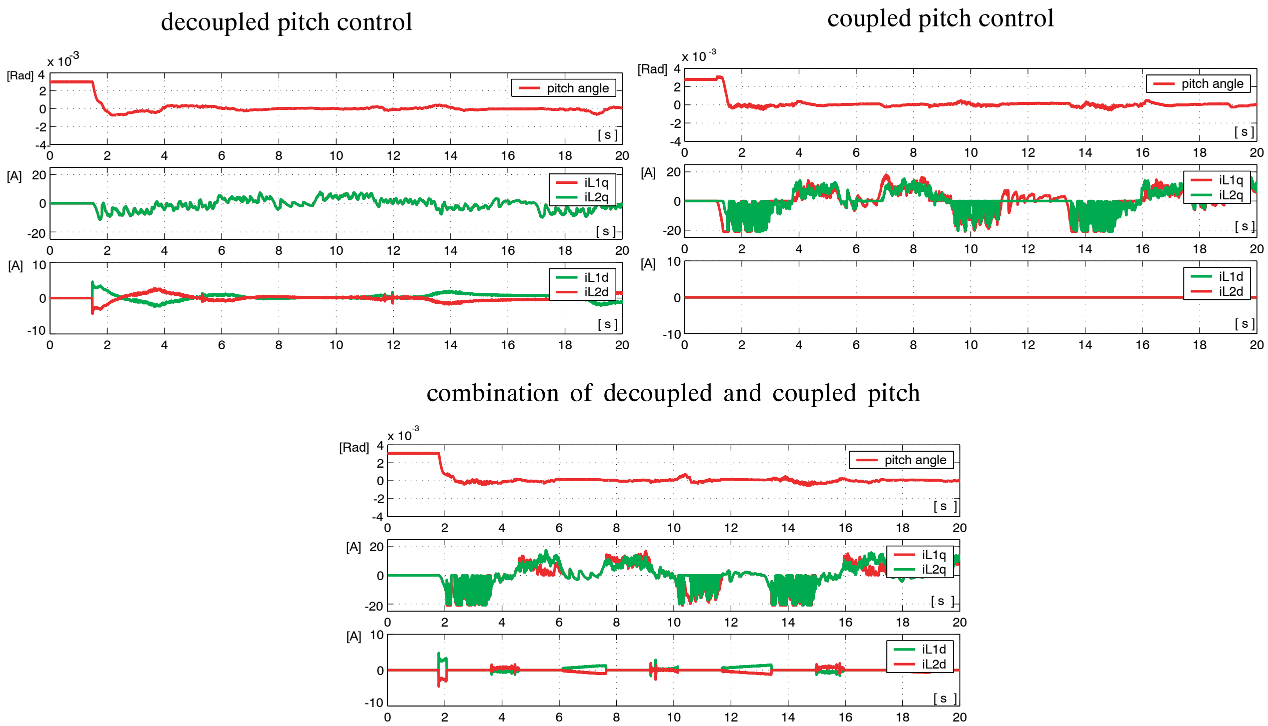

Figure 4: Experimental Results

4. 2 Experimental Results

As illustrated in Fig.4, after the activation of the pitch controller, the pitch angle is controlled from maximal pitch angle to close to zero, i.e., the air gap between the secondary and the primary is kept unchanged. Clearly, the d-axis secondary currents are set to zero for coupled pitch control. In the case of combination control, the d-axis secondary current is much smaller than that of decoupled pitch control. The power loss is then reduced by this means.

5. CONCLUSION

A coupled pitch and velocity control scheme is developed and implemented at the test bed to reduce the power losses of the linear drive system. A combination of coupled and decoupled pitch control is investigated as well.

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