Observer-based measurement of contact forces of the nonlinear rail-wheel contact as a base for advanced traction control

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Abstract: The trend of the development of modern locomotive traction control concepts contains a better use of the friction potential of the rail-wheel contact. This contribution defines the idea of an observer-based traction control concept. Core of the concept is the Proportional-Integral (PI) observer. Task of this linear observer scheme is the estimation of the unknown contact force of the rail-wheel contact. The contact force highly depends on the kinematical contact situation and additionally on external physical effects like rain or temperature.
By observing the contact situation by the PI-Observer the actual adhesion characteristic between rail and wheel can be determined. The komplex inside into the dynamical micromechanic contact gives the base for advanced traction control concepts.
To get online-estimations of the contact force in this problem field, there should not be made any assumptions about the geometry of contact and about other parameters should be made. The proposed observer scheme solves the task due to its design concept. Simulations of the driven wheel contact show the efficiency of this approach. Therefore a special maneuver for the driven torque ist used to simulate the dynamical contact. Using stochastical disturbed friction-slip relations the physical effects are modeled.
As a result it is possible to say that observer-based measurements of the nonlinear rail-wheel contact force are realizable.

1 Motivation

The railway system is one of the most popular public transport systems. The acceptance is mainly determined by the effectivity of this transport system. The effectivity includes the transport time needed for transported people to reach their final destination. This global aspect are connected to the rail-wheel contact in detail.
The adhesion-friction micromechanism is the core of the transport mechanism of locomotion. It is known that the adhesion potential is not completely used without slip. If it is possible to optimize the transport power of the rail-wheel contact, electric locomotives are able to carry higher loads on stronger gradients, or reach even faster higher velocities. Figure 1 gives possible contact situations of a rail-wheel contact. The area of an optimal use of the contact situation is defined due to two assumptions: the maximum position of the friction-slip ratio on the left hand side of the maximum, if a maximum is available. The rail-wheel contact is highly nonlinear due to the complex geometrical contact problem and the unknown environment parameters (temperature et al.). Several papers focus to the modeling of the contact phenomena, trying to understand the effects as well (cf. Kalker, 1997; Stiebler et al., 1996). Furthermore the interaction between the elastic track, the elastic rail, the elastic contact itself and the wheel is of interest, because of several safety, economical and comfort aspects (Ripke, 1995).
As a temporary result it should be noted, that the traction or adhesion control is a highly sophisticated and experimental oriented task. Due to the mainly unknown effects of the contact it is necessary to prove the developed approaches by experiments (cf. Hahn et

al., 1993; Lang, 1993 ; Schreiber, 1996; Buscher, 1993).
On the other side the structure of the developed control approaches should be parameter and problem-structure independent, or so-called robust to structural and parametrical changes.

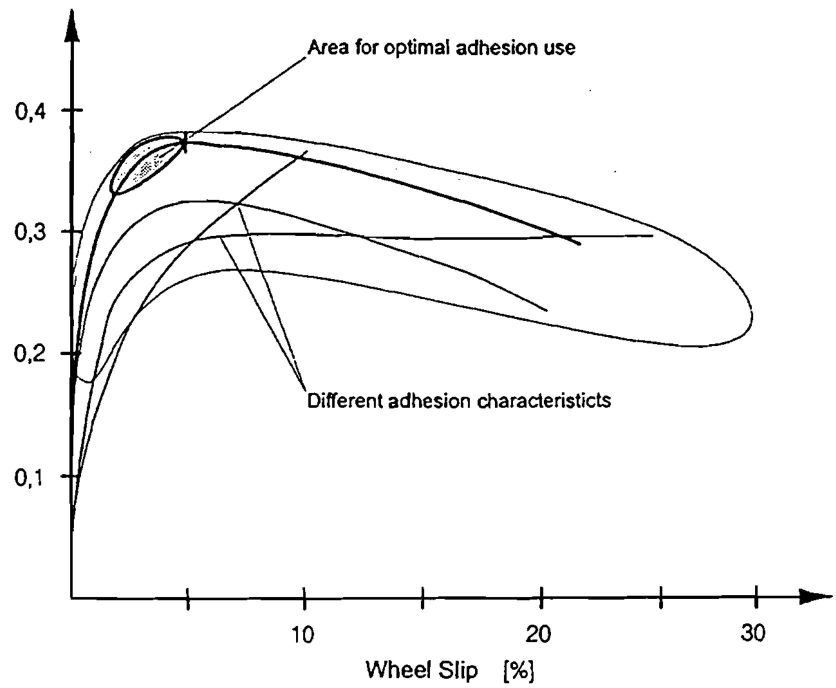

Fig. 1: Area of the optimal adhesion of the rail-wheel contact

In (Söffker, 1993) a robust nonlinearity-observer is applied to estimate unknown (and fictitious) forces of a cracked turbo-rotor. This technique is practically proved by several similiar applications (cf. Neumann, Moritz, 1990). Theoretical hints for understanding the estimation behavior of this linear technique applied to nonlinear problems can be found in (Söffker et al., 1995a).
This gives the direction of the proposed work: to demonstrate the possibilities of observer-based identification of nonlinear contact forces it is not necessary to work with detailed models of the mechanical system itself rather than with arbitrary disturbed models to examine the robustness of the observer technique itself to its own model assumptions.
The paper is organized as follows: chapter 2 briefly shows the basics of the rail-wheel contact, chapter 3 introduces to the used PI-Observer. Modeling and simulation of a dynamical interacting rail-wheelset is the core of chapter 4. Here the equations of motion of the mechanical system are given, and the observer application is demonstrated. The results of estimating nonlinear contact forces and of determining the actual adhesion situation concludes this chapter. Chapter 5 resumes the work and gives hints for future work.

2 The rail-wheel contact

Modeling of the contact between two elastic bodies is a classical problem. The solution to the normal-contact problem - the determination of the contact area and the planar pressure functions - was given by (Hertz, 1882). In this contribution the contact area is assumed as an ellipse, described by the radi a, b. This includes that the contact partners are shifted together with the distance

$$\delta = \left(\frac{N}{\sqrt[2]{R_a}} 2 \frac{(1-\nu)}{G} \right)^{\frac{2}{3}} \alpha_a , \quad (1)$$

with N as acting normal force, R_a as wheel radius, ν as the contraction number ($= 0.3$ (steal)), the shear modulus G and the coefficient α_a. The ellipse radi are connected by

$$b = a\sqrt{1-e^2} \quad \text{(cf. Knothe, 1992)} , \quad (2)$$

where e defines the eccentricity of the contact ellipse. Relations between the radi R_a, R_b of the contact partners and the eccentricity are given by

$$\frac{R_b}{R_a} = \frac{(1-e^2)D(e)}{B(e)} \quad \text{(cf. Knothe, 1992)} , \quad (3)$$

with the coefficients $D(e)$, $B(e)$ as solutions from elliptic integrals. Tabular solutions are given in (Lurje, 1963).

The practical rail-wheel contact problem is a dynamical problem, so for numerical simulations the contact model relations and the related elliptical integrals have to be solved in every time-step. In this contribution a dynamical contact is assumed, where the coefficients R_a, R_b, α_a are fixed. The coefficient α_a is choosen with $\alpha_a = 0.549$.

The contact force can be modeled assuming the theory of Kalker (Kalker, 1990). Here the tangential contact force is modeled using the model of Shen-Hedrick-Elkins (Shen et al., 1983). In contrast to advanced considerations (Zhang, Knothe 1995) only the tangential slip η is considered. The tangential contact force T_ξ is modeled by

$$T_\xi = \alpha T_\xi^{lin.} = -\alpha a b G C_{11} \eta , \quad (4)$$

with

$$\alpha = 1 - \frac{1}{3}\left(\frac{T_\xi^{lin.}}{\mu N}\right) + \frac{1}{27}\left(\frac{T_\xi^{lin.}}{\mu N}\right)^2 \quad \text{for} \quad T_\xi^{lin.} \geq 3\mu N \quad (5)$$

$$\alpha = \frac{\mu N}{T_\xi^{lin}} \quad \text{for} \quad T_\xi^{lin.} < 3\mu N , \quad (6)$$

with C_{11} as a Kalker coefficient depending on (a, b) and the friction coefficient μ. The equations (1-6) define a piecewise constant contact force / slip relation for the elastic contact. It should be noted that more complex models exist. Core of the proposed approach is a model- independent observer-approach. This implies the fact that a precise model (for a operating and environmental parameters) for the considered relation is not necessary to show the efficiency of the approach.

3 The Proportional-Integral Observer

In this paper a Proportional-Integral Observer (PIO) is introduced, which allows the robust estimation of modeled system states, additionally the estimation of unknown

inputs in desired / interesting input channels. If the nominal system behaviour can be described by a nominal linear system description, changes in the system structure or of system parameters can be understood as additional external inputs acting to the nominal system and representing the fault. In contrast to the Extended Kalman Filter, this procedure considers the dynamical changes both of structure and parameter. In contrast to actual works about the Unknown Input Observer (UIO) (Hou et al., 1992), this approach works in an approximated wise, but with weak conditions.
In the sequel it can be shown that the PIO allows the robust estimation of such unknown inputs interpreted as disturbances to the nominal system. The main idea of this paper is the application of this observer type to nominal known systems for fault diagnosis, in the way that the operator of a dynamical system gets a new tool looking for inner, unmeasurable states of a system. Combining the estimations of the PIO a new quality of inner informations of the faulty structure is available. The main details of PIO is already given and proved in (Söffker et al., 1995a). In this paper the PIO is extended for applications as Unknown-Input Observer (UIO), applied for estimation of unknown additive inputs, like the contact forces of the rail-wheel contact.

3.1 History of Disturbance Estimation

Based on a linear and deterministic description of the plant, which describes the nominal unfaulty dynamical behaviour of the plant, the Luenberger observer can reconstruct unmeasurable states using measurements of outputs. This permits the employment of the Luenberger-observer scheme to dynamic systems of the form

$$\dot{x} = Ax + Bu, \quad y = Cx, \tag{7}$$

with the state vector x of order n, the vector of measurements y of order r_1, and the known input vector u of order m. The system matrix A, the input matrix B and the output matrix C are of appropriate dimensions. However, it is not directly applicable to nonlinear systems or systems with unknown inputs. Since the proposed type of observer beside the proportional feedback like the Luenberger-observer, also uses integral information of the estimation error, it is called PI-observer (PIO). It is known from literature, that the PI-observer design is useful for linear systems with constant disturbances (Anderson, 1989).
Here the PI-observer is developed from another viewpoint. Continuing the ideas of (Johnson, 1976), who introduced linear models for disturbances acting upon linear systems, and Müller (Müller and Lückel, 1977; Müller, 1989), who gave the conditions and proofs for modeling disturbances as linear models also acting upon linear systems, this paper deals with the idea of constructing a 'disturbance model' for more general use, especially to the practical case, in which no information about the disturbance, the structure of the fault resp., is available. Here the term 'disturbance model' describes the use of disturbance models describing the signal behaviour of external inputs regretted as disturbances, representing the disturbance rejection philosophy given in (Johnson, 1976; Müller and Lückel, 1977; Müller, 1989). Here this term is used only to relate the proposed development of the PI-observer to the known disturbance rejection strategy, which can be considered as a special case.

The following aspects are the points of consideration: usual Luenberger observer fails, if the system (7) is only roughly known or/and there exist additional unknown inputs caused by nonlinearities. Using known PI-observer techniques this disadvantage can be compensated, but only for piecewise constant disturbances (Anderson, 1989). If the unknown input is caused by modeling errors or unmodeled nonlinearities (unmodeled dynamics), this assumption is not fulfilled.
In the general case of a fault, which can not be described by a linear model extension (disturbance rejection theory), the system description (7) fails. Therefore, a more general description of such systems is given

$$\dot{x} = Ax + Bu + Nf(x, u, t) \quad y = Cx \quad . \tag{8}$$

In Eq. (8) the vector function $f(x, u, t)$ of dimension r_2 describes in general the nonlinearities caused by the fault e.f., unknown inputs and unmodeled dynamics of the plant and may be a nonlinear function of states, control inputs and time. The matrix N is the corresponding distribution matrix locating the unknown inputs to the system. Without loss of generality it is assumed that the matrices N, C have full rank. Based on the well known method of Disturbance Rejection Control (DRC), several successful practical and theoretical applications concerning machine diagnosis (Söffker et al., 1993) and also observer-based control (Ackermann, 1989; Neumann and Moritz, 1990) are known. In all of these cases an approximation

$$f \approx Hv \tag{9}$$

of the vector of nonlinearities f(friction torques, forces caused by the crack) was used. In the theory of DRC (Johnson, 1976; Müller and Lückel, 1977; Müller, 1989), the linear time-invariant system with the unknown inputs Nf caused by nonlinearities, unknown inputs or unmodeled dynamics is described by the linear exo-system

$$\dot{v} = Fv \quad . \tag{10}$$

The resulting extended linear dynamical model includes these inputs and appears as

$$\begin{bmatrix} \dot{x} \\ \dot{v} \end{bmatrix} = \begin{bmatrix} A & NH \\ 0 & F \end{bmatrix} \begin{bmatrix} x \\ v \end{bmatrix} + \begin{bmatrix} B \\ 0 \end{bmatrix} u, \tag{11}$$

$$y = \begin{bmatrix} C & 0 \end{bmatrix} \begin{bmatrix} x \\ v \end{bmatrix}, \tag{12}$$

and can be used as an (extended) base building up a linear observer. Here the matrix N relates the fictitious approximations Hv of the unknown inputs f to the states where they appear. The signal characteristics of these inputs will be approximated by a linear dynamical system with the system matrix F. Using the extended system description (11,12) an extended observer can be designed, so the estimate $\hat{v}$ of v represents the approximation of the disturbances, whereby $\hat{x}$ is the estimation of x.
In the applications (Söffker, 1993; Ackermann, 1989; Neumann and Moritz, 1990) it is noticed that using

$$F = 0\,, \quad F \to 0\,, \text{[resp.,]} \tag{13}$$

leads to a very good reconstruction of the diagnosted nonlinearity. This means that without exact knowledge about the dynamical behaviour of the unknown inputs f ($F = 0$ represents a constant disturbance (Anderson, 1989), a very general approach is possible by assuming the disturbance as piecewise constant (related to the 'disturbance model' - philosophy), but applying the observer scheme to applications where this assumption is not fulfilled. Although this approach has been successfully used in many theoretical and also practical problems; the estimation of friction torques of the ROTEX-robot of the german D2-space mission e.f.; the interpretation of the interaction among the fictitious model F of the exo-system of (10), the designed extended system as a base for constructing observers (11), and the observer itself is not yet exactly clear.

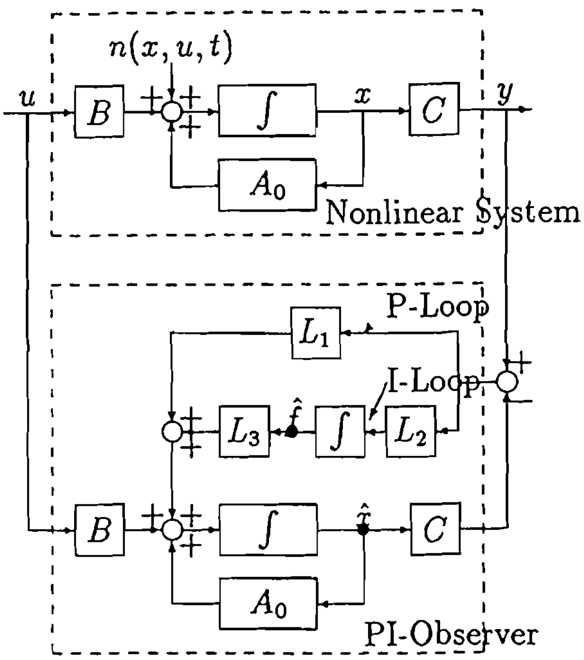

Fig. 2: Structure of PI-observer

By the given procedure using '$F = 0$' in the sense of disturbance model philosophy, the successfully applied scheme appears as the PI-observer and will be seen as a natural comprehensible extension of the well known Luenberger observer (Söffker et al., 1995a). To prove and to extend this hypothesis will be applied core of this contribuation.

In contrast to the synthetic procedure of modeling disturbances no assumptions about disturbances as unknown inputs have to be made. Fig. 2 gives the structure of an observer using the information proportional and integral to the estimation error. Here in contrast to the conventional Luenberger approach a second loop with two gain matrices L_2, L_3 and integrator is used additionally.

Now, the question is how to determine the matrices L_1, L_2 and L_3 such that the corresponding PIO works well. Therefore the estimation performance is analyzed for different cases of the dynamical behaviour of the fault, or the unknown input related to the nominal system.

3.2 Estimation Behavior

From the structure of the PI-observer depicted in Fig. 2 it follows, that the dynamics of PI-observer is described by

$$\dot{\hat{x}} = A\hat{x} + L_3\hat{f} + Bu + L_1(y - \hat{y}) \quad \dot{\hat{f}} = L_2(y - \hat{y}) \tag{14}$$

where $\hat{y} = C\hat{x}$. Writing (8) in a matrix form gives

$$\begin{bmatrix} \dot{\hat{x}} \\ \dot{\hat{f}} \end{bmatrix} = \begin{bmatrix} A & L_3 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \hat{x} \\ \hat{f} \end{bmatrix} + \begin{bmatrix} B \\ 0 \end{bmatrix} u + \begin{bmatrix} L_1 \\ L_2 \end{bmatrix} (y - \hat{y}) \tag{15}$$

or

$$\begin{bmatrix} \dot{\hat{x}} \\ \dot{\hat{f}} \end{bmatrix} = \underbrace{\begin{bmatrix} A - L_1C & L_3 \\ -L_2C & 0 \end{bmatrix}}_{A_e} \begin{bmatrix} \hat{x} \\ \hat{f} \end{bmatrix} + \begin{bmatrix} B \\ 0 \end{bmatrix} u + \begin{bmatrix} L_1 \\ L_2 \end{bmatrix} y. \tag{16}$$

Now the problem is how to design the gain matrices L_1, L_2, and L_3, such that the observer can estimate approximately the states x of the plant.
Defining the estimation error as $e(t) = \hat{x}(t) - x(t)$. Then, from Eqs. (7), (8) and (16) we have that

$$\begin{bmatrix} \dot{e} \\ \dot{\hat{f}} \end{bmatrix} = A_e \begin{bmatrix} e \\ \hat{f} \end{bmatrix} \tag{17}$$

in the case of system (7), or

$$\begin{bmatrix} \dot{e} \\ \dot{\hat{f}} \end{bmatrix} = A_e \begin{bmatrix} e \\ \hat{f} \end{bmatrix} - \begin{bmatrix} N \\ 0 \end{bmatrix} f \tag{18}$$

in the case of system (8) with unknown inputs or nonlinearities. From Eq. (16) the following result can be obtained (Söffker et al., 1995a).

3.3 Known System without external inputs

Theorem 1. If the pair (A, C) is observable, then there exists a PI-observer with any dynamics for the system (7), such that $\lim_{t\to\infty}[\hat{x}(t) - x(t)] = 0$ for any initial states $x(0)$, $\hat{x}(0)$ and $\hat{f}(0)$.
Proof. From the dynamics (16) of PI-observer it can be seen that the dynamics or poles of (16) can be arbitrarily assigned if and only if the matrix pair $\left(\begin{bmatrix} A & L_3 \\ 0 & 0 \end{bmatrix}, \begin{bmatrix} C & 0 \end{bmatrix}\right)$ is observable, i.e.

$$rank \left\{ \begin{bmatrix} sI - A & -L_3 \\ 0 & sI \\ C & 0 \end{bmatrix} \right\} = \mathrm{n} + dim(\hat{f}) \tag{19}$$

holds for all $s \in$ C. Furthermore, the condition (18) is equivalent to

$$rank\left\{\begin{bmatrix} A & L_3 \\ C & 0 \end{bmatrix}\right\} = \mathrm{n} + dim(\hat{f}) \tag{20}$$

when $s = 0$ and

$$rank\left\{\begin{bmatrix} sI - A \\ C \end{bmatrix}\right\} = \mathrm{n} \tag{21}$$

when $s \neq 0$. The condition (20) implies that the dimension of the integrator must be less than or equal to that of the outputs. Since the matrix L_3 may be arbitrarily selected, the rank condition (21) holds if and only if

$$rank\left\{\begin{bmatrix} A \\ C \end{bmatrix}\right\} = \mathrm{n} \quad . \tag{22}$$

Combining the conditions (21) and (22) leads to

$$rank\left\{\begin{bmatrix} sI - A \\ C \end{bmatrix}\right\} = \mathrm{n} \tag{23}$$

for all $s \in$ C, i.e. (A, C) is observable.
A main motivation to study the PI-observer is to reconstruct the states of the system (8) with nonlinearities. The following two theorems give the results in case of the system (8).

3.4 Known Systems with constant external inputs

Theorem 2. Assume that $\lim_{t\to\infty} f(x, u, \mathrm{t})$ exists. Then, there exists a PI-observer with any dynamics for the system (8), such that $\lim_{t\to\infty}[\hat{x}(\mathrm{t}) - x(\mathrm{t})] = 0$ for any initial states $x(0)$, $\hat{x}(0)$ and $\hat{f}(0)$ if (A, C) is observable and

$$rank\left\{\begin{bmatrix} A & N \\ C & 0 \end{bmatrix}\right\} = \mathrm{n} + \mathrm{r}_1 \tag{24}$$

Proof. Using the construction method, we prove Theorem 2. Let $L_3 = N$. Then, the dynamics (18) of the estimation error of PI-observer (16) becomes

$$\begin{bmatrix} \dot{e} \\ \dot{\hat{f}} \end{bmatrix} = A_e\left\{\begin{bmatrix} e \\ \hat{f} \end{bmatrix} - \begin{bmatrix} 0 \\ I \end{bmatrix} f\right\} \tag{25}$$

where $A_e = \begin{bmatrix} A - L_1C & N \\ -L_2C & 0 \end{bmatrix}$. Similarly with the proof of Theorem 1, the eigenvalues of the matrix A_e can be arbitrarily assigned by the matrices L_1 and L_2 if and only if the matrix pair $\left(\begin{bmatrix} A & N \\ 0 & 0 \end{bmatrix}, \begin{bmatrix} C & 0 \end{bmatrix}\right)$ is observable, i.e.

$$rank\left\{\begin{bmatrix} sI - A & -N \\ 0 & sI \\ C & 0 \end{bmatrix}\right\} = \mathrm{n} + \mathrm{r}_1 \tag{26}$$

holds for all $s \in \mathbb{C}$. This condition is equivalent to

$$rank\left\{\begin{bmatrix} A & N \\ C & 0 \end{bmatrix}\right\} = \mathrm{n} + \mathrm{r}_1 \tag{27}$$

when $s = 0$ and

$$rank\left\{\begin{bmatrix} sI - A \\ C \end{bmatrix}\right\} = \mathrm{n} \tag{28}$$

when $s \neq 0$. This implies that under the conditions in theorem 2 the dynamics of PI-observer (15) for the system (8) can be arbitrarily assigned. Therefore, the eigenvalues of A_e can be arbitrarily placed at any locations in the left-half complex plane when the conditions in theorem 2 are satisfied. This means that the dynamics (25) is stabilizable by means of the matrices L_1 and L_2. When the dynamics (25) is asymptotically stable, its solution will converge to the equilibrium. Then, from (25) it can be easily seen that

$$\lim_{t\to\infty}\begin{bmatrix} e(t) \\ \hat{f}(t) \end{bmatrix} = \begin{bmatrix} 0 \\ \lim_{t\to\infty} f(x,u,t) \end{bmatrix} \quad . \tag{29}$$

3.5 Known Systems with arbitrary external inputs

Theorem 3. Assume that $f(x,u,t)$ is bounded. Then, there exists a high-gain PI-observer for the system (8) such that $\hat{x}(t) - x(t) \to 0 \quad (t > 0)$ for any initial states $x(0)$, $\hat{x}(0)$ and $\hat{f}(0)$ if

1) (A, C) is observable, which includes

$$rank\left\{\begin{bmatrix} C \\ CA \\ \vdots \\ CA^{k-1} \end{bmatrix}\right\} = \mathrm{n} \quad , \tag{30}$$

where k is the observability index of (A, C),

2) $rank\left\{\begin{bmatrix} A & N \\ C & 0 \end{bmatrix}\right\} = \mathrm{n} + \mathrm{r}_1$; and

3) $CN = 0$

Proof. Let $L_3 = N$. Then, analogously with the proof of theorem 2, it is easily verified that the dynamics of PI-observer (16) for the system (8) can be arbitrarily assigned by means of the matrices L_1 and L_2 if the conditions 1) and 2) in theorem 3 are satisfied. Under the selection of L_3 the dynamics (18) of the estimation error becomes Eq. (25). When A_e is stable, the solution to (25) will be also bounded if $f(x,u,t)$ is bounded. Let $\begin{bmatrix} L_1 \\ L_2 \end{bmatrix} = \rho \begin{bmatrix} \tilde{L}_1 \\ \tilde{L}_2 \end{bmatrix}$. Then, Eq. (25) may be written as

$$\frac{1}{\rho}\begin{bmatrix} \dot{e} \\ \dot{\hat{f}} \end{bmatrix} = \frac{1}{\rho}\begin{bmatrix} A & N \\ 0 & 0 \end{bmatrix}\begin{bmatrix} e \\ \hat{f} \end{bmatrix} - \begin{bmatrix} \tilde{L}_1 \\ \tilde{L}_2 \end{bmatrix} Ce - \frac{1}{\rho}\begin{bmatrix} N \\ 0 \end{bmatrix} f \tag{31}$$

From (31) it follows that

$$Ce = 0 \tag{32}$$

for $\rho \to \infty$. Differentiating (32) and using (18) give

$$C\dot{e} = C(A - L_1C)e + CN(\hat{f} - f) \tag{33}$$

From the condition 3) and Eq. (32) we have

$$CAe = 0 \quad . \tag{34}$$

In the same way under the condition 1) we can obtain

$$CA^{i}e = 0 \quad \mathrm{i} = 0, 1, ..., \mathrm{k} - 1 \tag{35}$$

Then from (32), (34) and (35) it follows that

$$e = 0 \tag{36}$$

due to condition 1. Substituting (36) into (18) gives

$$\hat{f} - f = 0 \tag{37}$$

because of the full-column rank of N. Eqs. (36) and (37) mean that the estimates $\hat{x}$ and $\hat{f}$ of the PI-observer (18) converge to the states x and the unknown inputs f of the system (8) when ρ goes to the infinity. This shows that $\hat{x}$ and $\hat{f}$ may approximate x and f in the case of high gains.
In (Söffker et al., 1995a; Söffker, 1996) furthermore it is shown, that this type of observer also can be applied in general to systems not completely known with unknown additive inputs. In contrast to the mentioned works in the meantime the condition for the application of the PI-Observer to such structures is corrected to the conditions

$$\rho_1 \to \infty \quad \text{and} \tag{38}$$

$$\frac{\rho_2}{\rho_1} \to \infty \quad , \tag{39}$$

which gives theoretical hints to understand the observed success of the observer technique in robotics and machine-dynamics. In this application the PIO is applied to known systems with arbitrary external inputs. The structure of the problem to be considered here is similiar to that of friction estimation of flexible robot joints or ac/dc motors.

4 Modeling and simulation

Figure 3 illustrates the system to be considered: a torsion-stiff wheelset with linear springs c_{wh}, c_{wv} and dampers d_{wh}, d_{wv} for horizontal and vertical degrees of freedom. The electric drive is coupled with an elastic torsion spring-damper combination c_{MW}, d_{MW} to the wheelset. The other constants are the motor inertia Θ_M, the rotational inertia of the wheelset and drive Θ_W, and the related mass of the wheelset m_W. The modeled degrees of freedom are the motor angle φ_M, the wheel angle φ_W, the horizontal displacement of the wheelset u_{wx} and the vertical displacement of the wheelset u_{wz}. Modeled, but not given in the illustration fig. 3 are also the modal displacements of the rail u_{g1}, u_{g2} and the angles for the spatial orientation of the wheelset φ_1, φ_2.

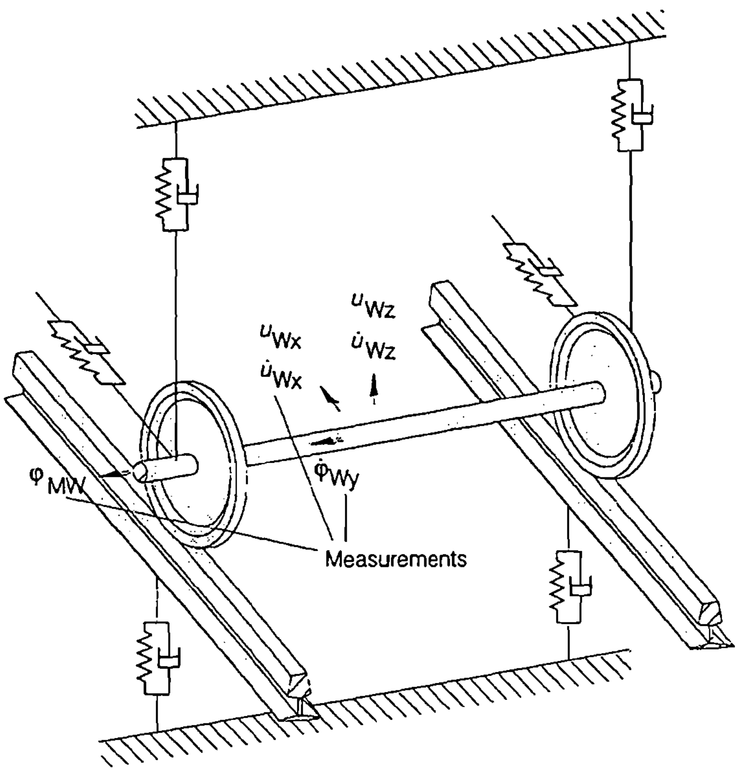

Fig. 3: Illustration of the wheelset to be considered

The equations of motion are given by

$$\ddot{\varphi}_M + \frac{d_{MW}}{\Theta_M}(\dot{\varphi}_M - \dot{\varphi}_W) + \frac{c_{MW}}{\Theta_M}(\varphi_M - \varphi_W) = M(t) \tag{40}$$

$$\ddot{\varphi}_W + \frac{d_{MW}}{\Theta_M}(\dot{\varphi}_W - \dot{\varphi}_M) + \frac{c_{MW}}{\Theta_M}(\varphi_W - \varphi_M) = \frac{2rT_\xi}{\Theta_W} \tag{41}$$

$$\ddot{u}_{wx} + \frac{2d_w}{m_w}\dot{u}_x + \frac{2c_w}{m_w}u_x = \frac{2T_\xi}{m_w} \tag{42}$$

$$\ddot{u}_{wz} + \frac{2d_w}{m_w}\dot{u}_z + \frac{2c_w}{m_w}u_z = \frac{2N}{m_w} - g \tag{43}$$

with the time-dependent normal contact load N, $\dot{N}$. The equations are coupled with the equations for the (modal) rail vibration and mainly due to the kinematic equations for the tangential contact force. The corresponding equation for the slip η is

$$\eta = 1 - \frac{\dot{u}_x}{v} - \frac{r\varphi_w}{v} \tag{44}$$

with the measurable absolute velocity v of the boogie, where the coordinate system is fixed. It should be noted, that there also exists a kinematical coupling between the rail, the elastic contact and the disturbance height Δz

$$d = u_{g1} + u_{g2} - u_{wz} + \Delta z \tag{45}$$

of the rail. For the following simulations Δz (as a stochastic value) works as an exitation. The whole model results as a nonlinear system with 10 elastic degrees of freedom. The main features of this model are taken from (Lange et al., 1995).
For the observer design a classical optimal observer design approach is used for the extended system (one additional degree of freedom). It should be noted, that informations about the absolute velocity of the boogie are necessary (to calculate the slip).
The simulation program in written in FORTRAN77 and simulated on the DEC-ALPHA workstation pool of the BUGH Wuppertal.

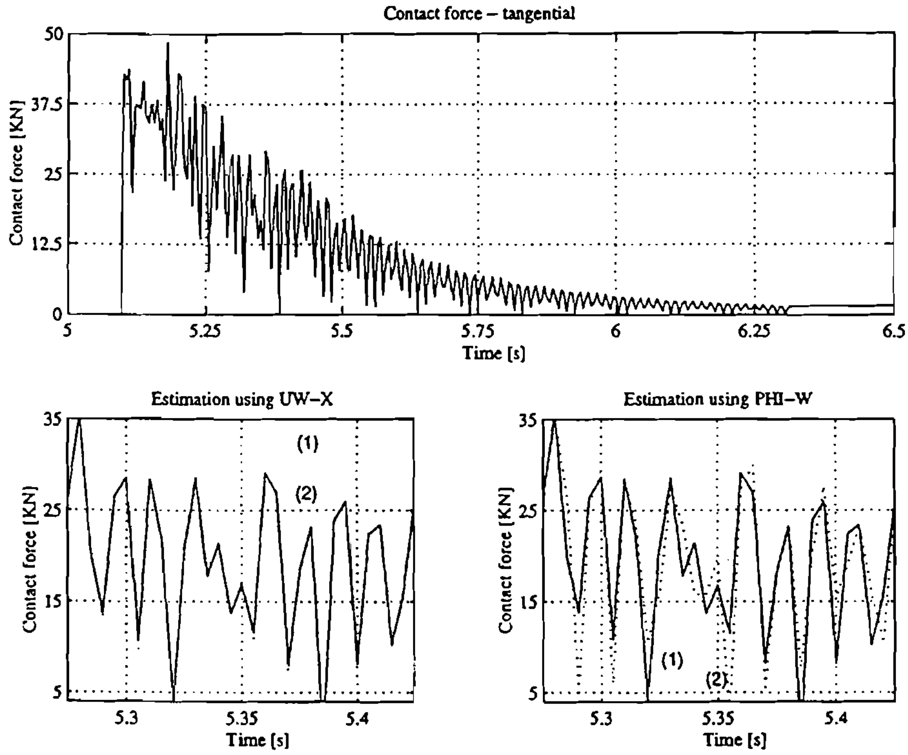

Fig. 4: Time behavior of the contact force:
Up: Contact force for a stepwise motormoment
Down: Estimation behavior of the PIO using diff. measurements
Graph (1): real value, Graph (2) estimation

To get realistic adhesion characteristics the friction coefficient μ itself and the switching condition (eq. 5-6) is stochastically modified. So a much more realistic characteristic as given by the Shen-Hedrick-Elkins model (eq. 4-6) is available. It should be noted that the PIO-design is independent from this structural and parametrical informations. The idea of the stochatical variation is shown in fig. 5.

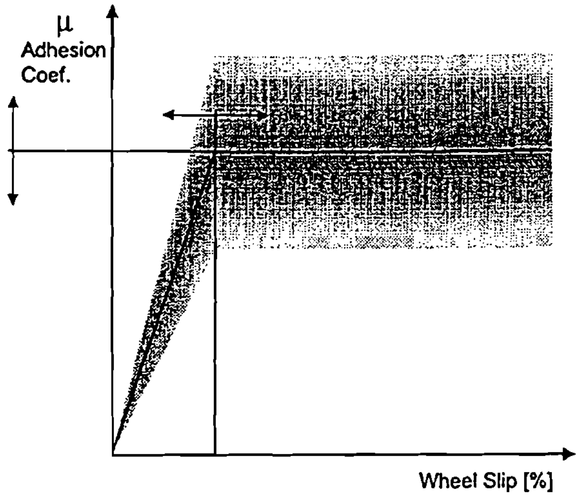

Fig. 5: Modified adhesion characteristic by stochastical variation of the Shen-Hedrick-Elkins model

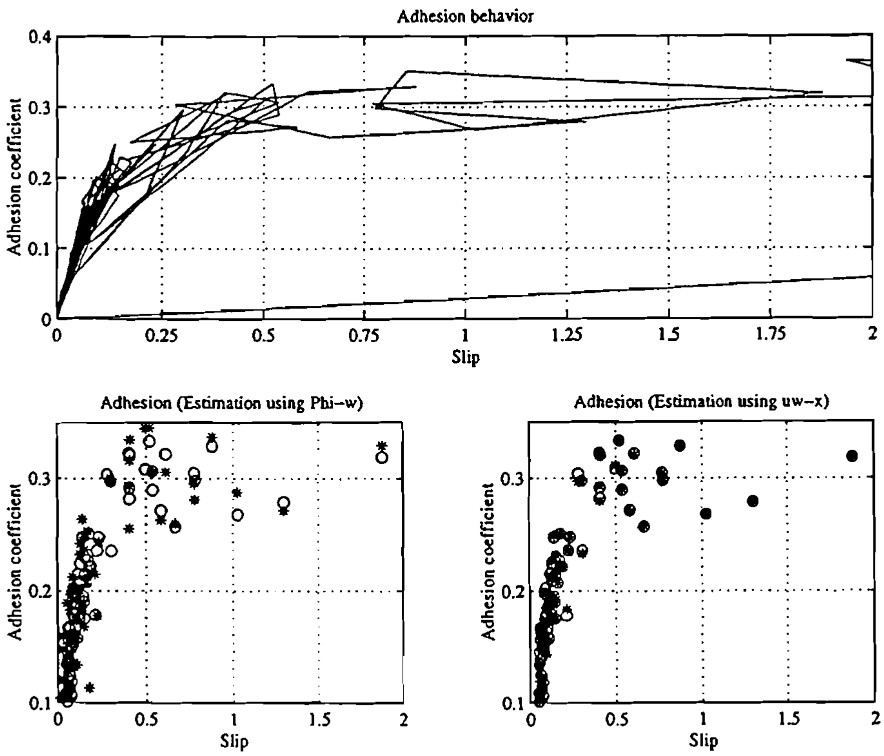

Fig. 6: Adhesion Charateristic of a step-wise maneuvre:
Up: Time-behavior of the adhesion situation
Down: Estimation behavior of the PIO using diff. measurements
o: real value, x: estimation

5 Concluding remarks and future aspects

In this contribution the application of the Proportional-Integral Observer (PIO) is shown.

Using a theoretical model of a elastic supported wheelset with a nonlinear contact model it can be shown by simulations that the linear PIO-scheme is able to estimate the nonlinear tangential contact forces. In this way using additional information about the absolute velocity an inside view to the actual adhesion situation is possible. Therefore the actual friction coefficient is calculated using the ratio of tangential contact force to the (dynamical) normal load and the actual slip.
This inside view into the unmeasurable contact situation gives the base for advanced adhesion control strategies. It should be noted that the proposed approach is independent from details of the contact itself. This feature is called robustness.

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