Control design of an Electro-mechanic Wedge Brake (EWB) for commercial vehicles

Theses

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Thesis 1 – Non-linear, dynamic hybrid electro-mechanic wedge brake model

The mechanic and mechatronic components and their prototype assembly simulation has been created based on the relating physical laws and modelling assumptions, which are dynamic in respect of the hybrid modes of the system.

1. The differential equations of the model are given by the conservation laws of the components' balance volumes, like:
    a. conservation of the momentum
    b. conservation of the magnetic linkage
2. The elements of the conservation equations are expressed by the constitutive physical relations considering the substitution assumptions of the unit properties via basic mechanical components, like:
    a. contacts as springs and dampers
    b. parts as mass points
    c. frictions as continuously speed and contact force dependent forces
    d. spindle as rigid motion translator
    e. semi-conductors as switches
    f. electric motor as rotating electric circuits
3. The equations of the hybrid items, like:
    a. non-continuous contacts
    b. frictions

    have been expressed in respect of the relating condition variations, which describe in their combinations the total possible 648 hybrid modes of the system.
4. The non-linear, hybrid dynamic model of the system has been formulated in standard input affine form, as follows:

$$\frac{\mathrm{d}\mathbf{x}}{\mathrm{d}t} = \mathbf{f}(\mathbf{x}, \mathbf{d}, r) + \mathbf{g}(\mathbf{x})\mathbf{u} ,$$

    in that the derivative of the 18 state variable are given by the
    a. function of the state variables, disturbances and hybrid modes, added to the
    b. multiplication of the function of the state variables and the inputs

    While the 5 measured outputs can be described as the function of the state variables and hybrid modes, the unique performance output is influenced by the disturbances as well:

$$\mathbf{y} = \mathbf{h}(\mathbf{x}, r) \qquad \mathbf{z} = k(\mathbf{x}, \mathbf{d}, r)$$

Thesis 2 – Simplification and identification of the wedge brake model

Systematic simplification steps have been applied on the electro-mechanic wedge brake model giving a 1DoF and a 2DoF model as result. The parameters of the simplified models have been identified via iterative optimisation and development of disturbance estimation methods.

1. The system model has been simplified step by step concentrating each time on one well specified subpart of the model in direction of:
    a. keeping 10% precision compared to the detailed model,
    b. keeping interfaces at the borders of the simplification subarea,
    c. keeping input-affine structure of the state equations,
    d. keeping the physical meaning of the model variables while effective parameters are created,
    e. reducing the dimension of the state vector from 18 to 2,
    f. reducing the dimension of disturbance vector from 7 to 3.

    The input of the model has been changed based on the one order of magnitude difference between the electric and mechanic dynamic.
2. The unknown parameters of the simplified models have been identified by independent measurement sequences via H2 norm based direct simplex search optimisation method in two main step:
    a. Constant parameter and disturbance evaluation applied on the following set:

    $$\mathbf{\Pi} = \begin{bmatrix} a_0 & \theta_m & k_m & \mu_2 & s_{10} & \delta_d \end{bmatrix}^{\mathrm{T}}$$

    b. Evaluation of constant model parameters, air gap and friction coefficient estimation parameters applied on the following sets:

    $$\mathbf{\Pi}_S^* = \begin{bmatrix} a_0 & s_{10} & x_{s10} & \mu_2^* & \delta_d \end{bmatrix}^{\mathrm{T}} \qquad \mathbf{\Pi}_P^* = \begin{bmatrix} a_0 & s_{10} & x_{s10} & P & \delta_d \end{bmatrix}^{\mathrm{T}}$$

    Two type of friction coefficient estimation method have been developed for the second step to be able to reproduce its value changes during the brake applications.
3. Verification test sequences have been applied on one of the simplified models setting the identified parameters and the proportional friction coefficient estimation method:
    a. the 18% model precision has been validated by 16% result,
    b. while excluding the error of the uncertainly measured internal forces, the 10% model precision has been determined by 13% verification result as acceptable.

Thesis 3 – Control property analysis of electro-mechanic wedge brake model

It has been proven that the structural controllability and observability of the electro-mechanic wedge brake and its 2DoF simplified model are ensured only in the hybrid mode related to the connected brake pad and disc. Eliminating the state variables of the brake pad tangential movement by the assumption used in the 1DoF model, the structural controllability and observability become unconditional in the whole working domain. The asymptotic stability condition, which is unique in such a self-energised system, has been expressed by the linearization of the 1DoF model around a dominating working point.

1. The g(x) input function and the system degree of freedom is independent of the hybrid modes, which means that the input is producible as the affine combination of state variables.
2. The simplified state space model is a set of ordinary differential equations, where all the state functions are explicitly defined in all the hybrid modes.
3. The 1DoF simplified model fulfils the structural observability and controllability rank condition applied on structural matrices, while the 2DoF is structurally neither observable, nor controllable in the air gap.
4. In the force trajectory following working domain, the most important stability condition is strongly related to the system self-energising property, and it exactly describes that the system is only stable in the friction coefficient range below of the so called self-locking condition as follows:

$$\tan(\alpha) > \mu_2$$

Thesis 4 – Control design and verification of electro-mechanic wedge brake

The structural design of the electro-mechanic wedge brake control has been created and verified in respect of the system application and based on the hybrid properties of the model using the sliding mode control theorem.

1. Based on the target application the functional, performance requirements and the control interfaces have been defined.
2. Considering the hybrid modes of the model and the brake application procedure, the control state machine has been created, which coordinates the transitions between the position and force adjusting.
3. In view of the computation costs and expected performance of the simplest known control methods, the sliding mode control theorem has been chosen to be applied due to the possibility given by the input-affine structure of the model.
4. The position and force adjusting equations have been expressed using the sliding mode control method on the same skeleton exploiting the possibilities and constrains given by the model.
5. The equations have been evaluated and the required sliding surfaces have been defined based on the model parameters and the mechanical and electrical limitations of the system.
6. The control algorithm has been implemented including the required disturbance observers. It has been verified in Software- and Hardware-in-the-loop environment based on the previously determined requirements, and compared to the conventional system. The 95% of requirements are fulfilled and the results are close the pneumatic system or rather better.