Nonlinear Modelling and Control for a Mechatronic Protection Valve

Theses of Ph.D. dissertation

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1 Motivation and Aim

Recently, there has been a growing need to further increase the integration level, together with a strong driver for cost reduction, in the pneumatic brake systems of commercial vehicles.

This general trend has also influenced the foundation of electronic air management systems in pneumatic brake systems. The task of the electronic air management system is to control the air delivery (supplied by a compressor), the air quality (such as the humidity and the pollution level) and the air distribution into independent consumer units, also called circuits. These three basic functions of the air management units are now integrated into a single device (as of reducing the purchasing and mounting costs, moreover reliability is improved) unlike its conventional counterparts, where each of these functions are provided by different units (valves). The functions are covered now by an electronic control unit.

The air distribution part of the electronic air management system has to provide different pressure levels to the different consumer units as being a general requirement. This is often solved by applying mechanic pressure limiting valves into the affected circuits, although, many circuits have electronic actuators used for other functions, such as controlling the fill up sequence of the circuits or providing special protection in case of defect in any of the circuits. Such units of the distribution part of the electronic air management system are called mechatronic protection valves.

There is an obvious development opportunity for further cost reduction to use the mechatronic protection valve units of the air management system for circuit pressure limiting function as well, while omitting the mechanic pressure reduction valves. For this general task, the need to apply advanced control systems is also arisen.

Fortunately, at the same time, the area of control design methodology has significantly improved, and nonlinear techniques are gaining more and more ground in addition to the traditional linear methods. This development has special importance in case of switching or hybrid dynamic systems [7].

Based on these facts, the aim of the research work summarized in the dissertation was to investigate the possibility of designing a nonlinear pressure limiting controller satisfying a prescribed control specification for a mechatronic protection valve and to design and tune a possible nonlinear controller.

In order to reach the above described research aim, the dynamic model of the investigated mechatronic protection valve suitable for control purposes has to be developed, which is the subject of the first part of the dissertation. The model can be set up from thermodynamical, mechanical, electronic and magnetic first engineering principles including suitable constitutive relations by a systematic modelling procedure according to the scheme of the protection valve shown in Fig.1. (Chapter 2).

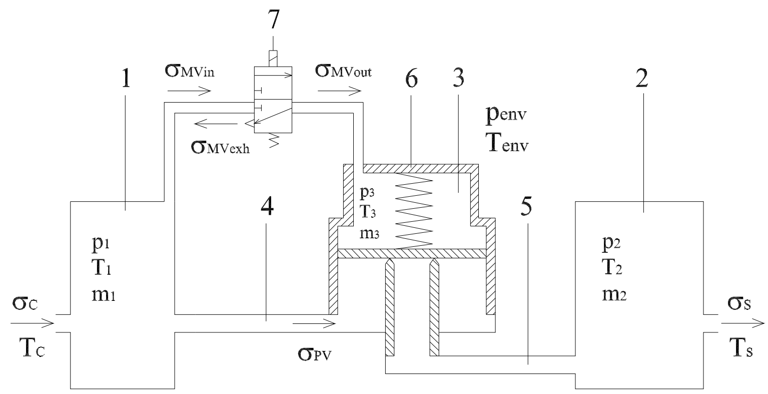

Figure 1: Schematic of the mechatronic protection valve

Dynamic system models derived from first engineering principles are sometimes too detailed and complex for control purposes. Therefore, a systematically derived model should often be simplified. The developed detailed model of the mechatronic protection valve has been considered for simplification to obtain a lower order model. For this purpose a simplification method has been developed for lumped parameter dynamic models and has been applied for the detailed model of the mechatronic protection valve (Chapter 3).

Having estimated the unknown parameters of the simplified model, the validation of the dynamic model was performed by independent measurements of the open loop system (Chapter 4).

The subject of the second part of the dissertation is the dynamic analysis of the mechatronic protection valve and its pressure limiting controller synthesis using the validated model.

The first step of controller design is the dynamic analysis of the developed model (Chapter 5). The dynamic analysis has identified that the general pressure limiting control problem is not causal. With supplying additional assumptions the problem has been converted to a causal one that has been investigated further.

Based on the results of dynamic analysis, the specification of the control aim and input signal limitation, a nonlinear bang–bang type controller has been designed and tuned. Its performance, qualitative and quantitative properties have been evaluated by using computer simulations (Chapter 6).

2 Methods and Tools

The *model building* of the mechatronic protection valve has been carried out by executing a systematic modelling procedure [4]. First of all, the objective and the aim of modelling have to be defined, which highly influence the final form of the model. For dynamic models differential equations are required, which can be obtained from conservation balances, while they have to be supplemented with algebraic equations to obtain a solvable set of equations. The modelling assumptions have to be taken into consideration in a consistent way throughout the whole model development procedure.

A model for control purposes should retain all major dynamic characteristics of the real plant (such as its stability and main time constants, which are needed to be invariant under the simplification process) but omit all details that are weakly represented in the state variables and not related to the control aims.

Since the modelled object exhibits *switching or hybrid behavior*, the developed model has similar properties as well. To define the model equations a dedicated hybrid mode has been selected and the affected hybrid parts are exhaustively discussed separately [1, 12].

In order to obtain a state space model in its standard form, the possibility of substituting the algebraic equations into the differential equations has to be investigated. If all algebraic equations can be substituted into the differential equations, then the final result of the modelling is a set of differential equations, which can be transformed into a *nonlinear state space model in its input affine form.*

There are several methods proposed in the literature for performing *model simplification and reduction* in different ways to obtain a model with suitable size and complexity. These methods can be classified based on the underlying engineering knowledge used during model simplification.

The so called *model simplification* method uses engineering insight and operation experience to leave out state variables based on the dynamics of the original state variables with physical meaning [4, 9]. A similar method has been developed and applied to the model of the mechatronic protection valve.

The obtained simplified model includes parameters that are not exactly known at this stage of the model development. Information related to these parameters can be obtained from laboratory measurements [2, 10]. For this purpose a Knorr-Bremse electronic air management prototype unit has been installed on a test bench at the Knorr-Bremse R&D Center Budapest (see Fig.2).

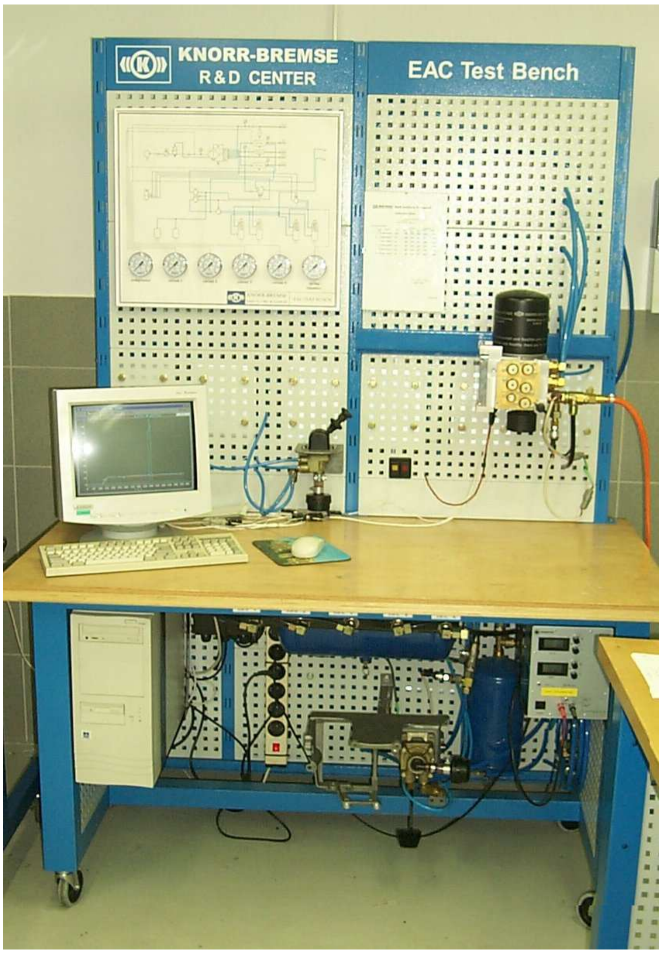

Figure 2: The pneumatic test bench

The data acquisition system provides the measurements of the dynamic transient processes. The measurable quantities for the *identification* have been the three chamber pressures (input–, output– and control chambers), electric current of the solenoid magnet valve and its input voltage. The mechatronic protection valve in circuit No.23 has been the subject of modelling and control design studies presented in this thesis.

Since the dynamic model of the mechatronic protection valve has unknown dynamic parameters in nonlinear form the general parameter estimation problem has to be solved. It is based on solving an optimization problem using a suitable method, for example the Nelder-Mead simplex search algorithm [11].

Finally, the validation of the dynamic model has to be performed. It means, that the identified model has to be checked against independent measurements.

The *dynamic analysis* of the prepared model has primary importance in control design. Dynamic analysis means checking of basic dynamic properties of the system: such as state controllability, state– and disturbance observability, input–output relative degrees and stability. Moreover, the hybrid reachability property needs to be checked as of having a mode switching model. In case of nonlinear state space models the dynamic properties can be different in different regions of the state space [6].

Due to the complex nonlinear model structure of the mechatronic protection valve, the controllability and observability properties have been investigated in *structural sense*, i.e. the particular properties may not hold on some null measure sets. The *hybrid reachability property* and the *relative degrees* have been checked using graph theoretic methods [4].

The *stability* of the open loop system has been investigated in *BIBO sense* by checking the physical bounds of the outputs and in *local linear asymptotic sense* in typical operation points of the pressure limiting controller by evaluating the eigenvalues [3].

Considering the control aims, the limitation of the input signal and the additionally supplied assumptions on the time function of the external air consumption disturbance signal, that converted the problem into a causal one, a *nonlinear bang–bang type controller* has been designed and tuned. The controller includes three modules: a disturbance observer (because the main disturbance signal is not measurable), a fixed programme feedforward module and a model predictive feedback module [5, 8].

The complete modelling and controller design procedure has been carried out in the *MATLAB/Simulink environment* [13].

3 New Scientific Results

The main scientific contributions of the dissertation are summarized in the following theses.

Thesis 1 *Nonlinear dynamic model of the mechatronic protection valve* (Chapter 2) ([**P1**], [**P2**])

The nonlinear dynamic model of the mechatronic protection valve considered as a mixed thermodynamical, mechanical and electro–magnetic system has been built and verified using a systematic modelling methodology. It has been shown that the model exhibits the following special properties:

1. The dynamic model of the mechatronic protection valve is given by a set of nonlinear differential–algebraic equations. *The differential equations are balance equations for the mass and internal energy of the gas in the chambers as balance volume, for conservation of the mechanical energy of the moving parts and conservation of the magnetic linkage for the solenoid magnet valve.*
2. It has been shown that the 11 state equations of *the nonlinear dynamic model can be rewritten into standard input affine form.*

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}) + \mathbf{g}(\mathbf{x})\mathbf{u}, \qquad \mathbf{y} = \mathbf{h}(\mathbf{x}).$$

3. The coordinate functions of the nonlinear model have the following properties:
   (a) *The coordinate function* $\mathbf{f}(\mathbf{x})$ *depends also on the disturbance vector* $\mathbf{d}$ *and includes hybrid modes:* $\mathbf{f}(\mathbf{x}) = \mathbf{f}(\mathbf{x}, \mathbf{d}, r)$, where $r\colon \mathbb{R}^n \to \mathbb{N}$ is a piecewise constant switching function mapping from the state space to the finite integer set $\mathbb{N} = \{1, 2, \ldots, 960\}$ and $\mathbf{x}$ is the state vector.
   (b) *The coordinate function* $\mathbf{g}(\mathbf{x})$ *is affine with respect to the state vector*, i.e. $\mathbf{g}(\mathbf{x}) = \mathbf{B}\mathbf{x} + \mathbf{b}$ with $\mathbf{B}$ being a constant matrix and $\mathbf{b}$ a constant vector.
   (c) *The output equation has the following form:* $\mathbf{h}(\mathbf{x}) = \mathbf{C}\mathbf{x} + \mathbf{e}(\mathbf{d})$, where $\mathbf{C}$ is a constant matrix and $\mathbf{e}$ is a nonlinear function of the disturbance vector $\mathbf{d}$.

Thesis 2 *Simplification of the mechatronic protection valve model* (Chapter 3) ([**P3**], [**P4**])

A systematic model simplification method has been developed and applied to the nonlinear dynamic model of the mechatronic protection valve to obtain a lower order model suitable for control design purposes. The obtained simplified model has the following properties:

1. *The input affine structure of the state equation has been retained. The dimension of the state vector has been reduced from 11 to 7. The dimension of the disturbance vector has been cut to 3 from the original 5.*
2. Equation forms have become much simpler. *The finite integer set* $\mathbb{N} = \{1, 2, \ldots, 960\}$ *of the hybrid modes of the coordinate function* $\mathbf{f}$ *has been reduced significantly to have* $\mathbb{N} = \{1, 2, \ldots, 54\}$.
3. *The input and output vectors have been invariant under the simplification process.*
4. *All retained system variable entries (state-, input-, disturbance- and output variables) have preserved their physical meaning.* Some model parameters have changed slightly their meaning caused by lumping effects.

Thesis 3 *Identification of the mechatronic protection valve* (Chapter 4) ([**P5**], [**P6**])

The unknown parameters of the simplified model of the mechatronic protection valve have been estimated and the model has been validated against independent measurements by performing the following non–standard steps:

1. With help of parameter sensitivity analysis the candidate unknown parameters have been selected for identification. *In conclusion five parameters have been retained and the parameter vector has been formed as follows:*

$$\theta = [\ \alpha_{MV\text{in}} \ \ \alpha_{MV\text{exh}} \ \ \alpha_{PV} \ \ R_{ML} \ \ R_{MV}\ ]^T.$$

The last member (R_{MV}), being originally a known static parameter, has been included due to its time dependent behavior.

2. *One of the five retained parameters (R_{ML}) is included into the model in a nonlinear way, the others enter linearly.* They have been identified by solving the general parameter estimation problem *with L_2 prediction error norm utilizing the simplex direct search optimization method, where a continuous time model has been used with discrete time samples.*
3. The identified model has been validated against independent measurements. *It has been found that it is able to describe the dynamic behavior of the investigated system within the predefined tolerance limit of 10% for the pressure limiting controller design application aim.*

Thesis 4 *Specification of the pressure limiting control problem and design of the nonlinear pressure limiting controller for the mechatronic protection valve* (Chapter 6) ([**P7**], [**P8**], [**P9**], [**P10**])

1. *The circuit pressure limiting control problem using a mechatronic protection valve with respect to arbitrary external air consumption as a disturbance signal has been found not causal.*
2. *With the following additional assumptions to the external air consumption the control problem can be converted to a causal one:*
   (a) *The external air consumption is a constant function of time.*
   (b) *The duration of the consumption is constant.*
3. With the above assumptions and respecting the constraint of two level input signal, a nonlinear bang–bang controller has been designed and tuned that contains a disturbance observer, a fixed programme disturbance feedforward- and a model predictive feedback module. *The properties of the closed loop system investigated by simulation experiments have lead to the following observations:*
   (a) *The controller fulfils the predefined pressure overshoot and break down requirements.*

(b) *The residual error of the performance output and the pressure break down during the presence of the external air consumption can be decreased by means of increasing the number of intervals of the fixed programmes within the actuation time.*

(c) *The controller fulfils the requirements on the number of the magnet valve actuation.*

4 Publications Directly Related to the Thesis

The results of this thesis have been presented at conferences and published or accepted in journals and research reports as follows (in parenthesis the relevant **Thesis** is indicated):

[P1] H. Németh, P. Ailer, and K. M. Hangos. Nonlinear hybrid model of a single protection valve for pneumatic brake systems. Technical Report SCL-002/2002, Computer and Automation Research Institute, Budapest, Hungary, 2002.
`http://daedalus.scl.sztaki.hu`. (**Thesis 1**)

[P2] H. Németh, P. Ailer, and K. M. Hangos. Nonlinear modelling and model verification of a single protection valve. *Periodica Polytechnica, Ser. Transportation Eng.*, 30(1–2):69–92, 2002. (**Thesis 1**)

[P3] H. Németh, L. Palkovics, and K. M. Hangos. Model simplification of a single protection valve; a systematic approach. Technical Report SCL-004/2002, Computer and Automation Research Institute, Budapest, Hungary, 2002.
`http://daedalus.scl.sztaki.hu`. (**Thesis 2**)

[P4] H. Németh, L. Palkovics, and K. M. Hangos. Unified model simplification procedure applied to a single protection valve. *Control Engineering Practice*, 2004, Exeter, Devon, UK. In Press. (**Thesis 2**)

[P5] H. Németh, L. Palkovics, and K. M. Hangos. System identification of an electro-pneumatic protection valve. Technical Report SCL-001/2003, Computer and Automation Research Institute, Budapest, Hungary, 2003.
`http://daedalus.scl.sztaki.hu`. (**Thesis 3**)

[P6] H. Németh and K. M. Hangos. Elektro-pneumatikus védőszelep rendszeridentifikációja. *Gép*, 56(3–4):33–42, 2003. (In Hungarian). (**Thesis 3**)

[P7] H. Németh, L. Palkovics, and J. Bokor. Electro-pneumatic protection valve with robust control for commercial vehicle air supply systems. In I. Kageyama, T. Fujioka, and T. Takahashi, editors,

6^{th} *International Symposium on Advanced Vehicle Control '02*, volume 1, pages 757–762, Hiroshima, Japan, Sept. 2002. Society of Automotive Engineers of Japan. (**Thesis 4**)

[P8] H. Németh and K. M. Hangos. Nonlinear control of an electro-pneumatic protection valve for circuit pressure limiting. Technical Report SCL-005/2003, Computer and Automation Research Institute, Budapest, Hungary, 2003. `http://daedalus.scl.sztaki.hu`. (**Thesis 4**)

[P9] H. Németh, L. Palkovics, and K. M. Hangos. Feedforward bang-bang control design for electro-pneumatic protection valves. *Periodica Polytechnica, Ser. Transportation Eng.*, 32(1–2):1–18, 2004. (**Thesis 4**)

[P10] H. Németh, L. Palkovics, and K. M. Hangos. Feedforward Pressure Limiter Control for Mechatronic Air Management Systems. 7^{th} *International Symposium on Advanced Vehicle Control '04*, Arnhem, The Netherlands, Accepted. (**Thesis 4**)

5 Publications Partially Related to the Thesis

[O1] F. Varga, I. Wahl, and H. Németh. Definite project plan of electro-pneumatic braking, hardware-in-the-loop simulation model. Technical report, Department of Automobiles, Technical University of Budapest, 1997.

[O2] F. Varga, L. Kádár, I. Wahl, and H. Németh. Kísérő Gépjármű Kifejlesztése. Technical report, Department of Automobiles, Technical University of Budapest, 1997. In Hungarian.

[O3] H. Németh. Hygrometric measurement and error estimation for electronic air treatment systems of commercial vehicles. *Járművek*, 11–12:315–318, 2001.

[O4] B. Istók, J. Vad, Zs. Szabó, T. Gáspár, H. Németh, and G. Lóránt. On the resonance effects of pneumatic unloader valves. In 3^{rd} *International Fluid Power Conference*, volume 2, pages 581–592, Aachen, Germany, 2002.

6 Application Aspects

The modelling, parameter estimation and controller design methods used for the investigated mechatronic protection valve can be applied to other electro–pneumatic valves of the commercial vehicle brake system with different types and constructions with more complicated structures in a relatively straightforward way. In case of other designs, however, the modelling equations may be changed, the number of equations might increase.

Moreover, the presented methods can be used to investigate the enhancement possibilities of an existing electro–pneumatic valve to improve the control performance. The dynamic model of the mechatronic protection valve provides an effective way to improve the mechanic design of the valve such that its response is more optimal for the circuit pressure limiting function.

The developed model simplification method can be applied to other lumped parameter dynamic models. The necessary preparatory steps that one should perform on the actual system are (i) to construct the model hierarchy structure diagram, (ii) to perform a model parameter sensitivity analysis to pre-select model elements from the hierarchy to be omitted and (iii) to define model performance criteria that is used as decision criterion selection according to the application aim.

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