GREY-BOX APPROACH FOR THE DIAGNOSIS, ANALYSIS AND CONTROL OF NONLINEAR PROCESS SYSTEMS

Theses of Ph.D. dissertation

written by
GÁBOR SZEDERKÉNYI

Supervisor: Professor Katalin Hangos

Information Science Ph.D. School

Department of Computer Science
University of Veszprém
Veszprém, Hungary

2002

1 Motivation and aim

Recently, there has been a growing need for the automation of increasingly complex plants in different branches of the industry. This presents a challenge for systems and conrol theory: how to cope with nonlinearity and complexity inherent in most of the industrial control problems. At the same time, the analysis and control of nonlinear systems is a rapidly developing area of systems and control theory using mainly advanced geometric and symbolic tools which are not suitable for complex systems of industrial size.

A possible remedy to bridge this gap between theory and industrial use is to utilize the special structure of the system in question. Process systems are special (often highly nonlinear) dynamic systems the behaviour of which is governed by the laws of thermodynamics. This implies a special structure which can be utilized to develop feasible and yet powerful nonlinear techniques for model analysis, diagnosis and control.

Topics covered by the dissertation are quite diverse in terms of the tools and techniques used. These are parameter estimation, model-based fault diagnosis, nonlinear and Hamiltonian analysis and control of dynamic models. However, a common idea is present throughout the work: how the special structural properties of process systems can be used to simplify these tasks. This approach is called grey-box modeling.

The first part of the thesis (Chapter 2) deals with model-based fault detection and isolation of process systems. There is a growing demand for fault detection and diagnosis in order to provide safe and continuous operation in dynamic process plants [1]. Dynamic modeling of the equipments, called operating units is a well developed area, and model based diagnostic methods can therefore be efficiently and relatively easily applied.

The usual design goal of process systems is to create energy and/or cost optimal systems which is often a highly complicated problem. Most often, linearized models are used for model analysis and controller design. However, the dynamic behaviour of process systems is known to be nonlinear in most cases due to the complex thermodynamic relations, reaction kinetics etc. On the other hand, more and more theoretically well-grounded mathematical tools for studying nonlinear systems have become available recently [2], [3]. The natural form of a process model is a nonlinear state space model with clear engineering meaning [4]. Therefore, the aim of the second part of the work (Chapters 3, 4 and 5) was to apply the tools of nonlinear model analysis and control to relatively simple but practically important process system classes.

2 New scientific results

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

Thesis 1 *Model-based fault diagnosis of process systems* (Chapter 2) (**[P1], [P5], [P6], [P7], [P11]**)

A method has been developed for the model-based fault detection and diagnosis of nonlinear process systems. Physical model has been used for the description of the process dynamics and semi-empirical models have been applied for fault modeling.

1. It has been shown that the performance of the fault detection and isolation algorithms is improving with the increasing level of detail of the process models. A method has been worked out for the spatial localization of the faults using measured signals belonging to different spatial locations of the system.
2. It has been shown that safe simultaneous fault detection and isolation is possible using the grey- or white-box models of the faults together with the process model.

The results have been illustrated on the example of countercurrent heat-exchangers. The known process dynamics have been used as a filter for extracting characteristic fault-relevant information from the measurement data. Recursive parameter estimation and signal-change detection methods have been applied for fault detection and diagnosis.

Thesis 2 *Nonlinear model analysis of process systems* (Chapter 3) (**[P2], [P8], [P9], [P12], P[13]**)

The analysis of nonlinear process systems given in nonlinear input-affine state space form has been performed using linear and nonlinear methods. Conclusions have been drawn from the comparison of the linear and nonlinear analysis methods on the example of fermentation processes.

1. Exploiting the special structural properties of process models, the generally highly complicated nonlinear reachability analysis becomes analytically computable. On the example of continuous fermentation processes it has been shown that the singular points obtained from the reachability analysis have clear physical meaning.

2. It has been shown that a large class of isotherm fed-batch fermentation processes is not reachable with the inlet feed flow rate, since the rank of the reachability distribution is less than the number of state variables in each point of the state space. The coordinates transformation suitable for transforming the state space model of fed-batch fermentation processes to controllability canonical form has been determined. It has been shown that the calculated coordinates transformation is independent of the source function (that is of the fermentation kinetics) in the model. Using the calculated coordinates-transformation the minimal state space realization of fed-batch fermentation processes has been given. A dimensionally homogenious conserved quantity has been determined which is a nonlinear combination of the state variables. The results have been generalized for the temperature-dependent (non-isotherm) case.
3. It has been shown that the zero dynamics of continuous isotherm fermentation processes is globally asymptotically stable with respect to the substrate concentration as output independently of the source function. This means continuous fermentation processes are globally minimum-phase systems with respect to the substrate concentration. Furthermore, if one involves the biomass concentration into the output, it makes the stability region of the zero dynamics narrower. This implies that the stability region of a controlled (closed loop) system is also narrower in this case.

Thesis 3 *Analysis based control structure selection* (Chapter 4) (**[P3], [P9], [P14]**)

The role of the nonlinear analysis results in control structure design has been investigated. Linear and nonlinear static controllers for the stabilizing control of continuous fermentation processes have been designed. The operation of the controllers have been compared based on their performance measures and recommendations for their use have been given.

1. A method for using the prior information from the nonlinear model analysis (stability region, reachability distribution, zero dynamics) in the design of nonlinear controllers has been developed.
2. Using theoretical analysis and simulation experiments it has been shown that the controllers designed on the basis of the nonlinear analysis results have more advantageous properties than the linear ones designed using the locally linearized model of the process.

3. A novel method for the design of a globally stabilizing controller for continuous fermentation processes has been worked out. The design parameter of the controller is the quadratic Lyapunov-function of the closed loop system.
4. A generally applicable method has been developed for the local stabilization of locally reachable nonlinear single-input input-affine state space models. The method creates a link between linear optimal control and nonlinear systems. Using the method it is possible to select those linear outputs that make the system at least locally minimum-phase.

Thesis 4 *Hamiltonian view on process systems* (Chapter 5) (**[P4]**)

Dynamic models describing a large class of process systems can be transformed into the so-called simple Hamiltonian form. Based on this simple Hamiltonian description nonlinear stabilizing and loop-shaping controllers can be designed for process systems.

1. A method has been worked out for the tuning of Hamiltonian stabilizing and loop-shaping controllers that is based on the global stability analysis of the closed loop system.
2. The condition of the simple Hamitonian description of process systems corresponding to the source function has been given. Based on this condition it has been shown that process systems not containing source or containing only one component can always be described in the simple Hamiltonian framework.

3 Publications related to the thesis

Journal papers

[P1] E. Weyer, G. Szederkényi, and K. M. Hangos. Grey box fault detection of heat exchangers. *Control Engineering Practice* 8:121-131, 2000. (**Thesis 1**)

[P2] G. Szederkényi, M. Kovács, and K. M. Hangos. Reachability of nonlinear fed-batch fermentation processes. *International Journal of Robust and Nonlinear Control*, in print, 2002. (**Thesis 2**)

[P3] G. Szederkényi, N. R. Kristensen, K. M. Hangos and S. B. Jorgensen. Nonlinear analysis and control of a continuous bioreactor. *Computers & Chemical Engineering*, in print, 2002. (**Thesis 3**)

[P4] K. M. Hangos, J. Bokor, and G. Szederkényi. Hamiltonian view on process systems. *AIChE Journal*, 47:1819-1831, 2001. (**Thesis 4**)

Conference papers

[P5] G. Szederkényi, E. Weyer, and K. M. Hangos. Simulataneous fault detection of heat exchangers. In *Proc. of the IFAC Workshop on Fault Detection and Supervision in the Chemical Process Industries*, P. S. Dhurjati, S. Cauvin (Eds.), (Lyon, France), pp. 1-6, June 1998. (**Thesis 1**)

[P6] K. M. Hangos and G. Szederkényi. Grey box process modeling for fault detection and isolation. In *Proc. of the European Control Conference (ECC'99)*, (Karlsruhe, Germany), (on CD), Aug. 1999. (**Thesis 1**)

[P7] L. Tesar, G. Dolanc, G. Szederkényi, J. Kadlec, D. Juricic, K. M. Hangos, and M. Kinnaert. A toolbox for model-based fault detection and isolation. In *Proc. of the European Control Conference (ECC'99)*, (Karlsruhe, Germany), (on CD), Aug. 1999. (**Thesis 1**)

[P8] K. M. Hangos, J. Bokor and G. Szederkényi. Grey box characterization of nonlinear process systems. In *Proc. of the 9th Nordic Process Control Workshop*, (Copenhagen, Denmark), pp. 89-106, Jan. 2000. (**Thesis 2**)

[P9] G. Szederkényi, N. R. Kristensen, K. M. Hangos, and S. B. Jorgensen. Nonlinear analysis and control of a continuous fermentation process. In *Proc. of the 11th European Symposium on Computer Aided Process Engineering (ESCAPE-11)*, R. Gani, S.B. Jorgensen (Eds.), (Kolding, Denmark), pp. 787-792 May 2001. (**Thesis 2, Thesis 3**)

[P10] G. Szederkényi, K. M. Hangos, J. Bokor, and T. Vámos. Linear output selection for feedback linearization. In *Proc. of the 15th IFAC World Congress on Automatic Control*, (Barcelona, Spain), accepted, July 2002. (**Thesis 3**)

Research reports

[P11] G. Szederkényi. Simultaneous fault detection of heat exchangers. *Research report of the Systems and Control Laboratory SCL-5-1998.* Budapest, MTA SZTAKI, 1998. 39 p. (**Thesis 1**)

[P12] K. M. Hangos, G. Szederkényi, and J. Bokor. Grey box characterization of nonlinear process systems. *Research report of the Systems and Control Laboratory SCL-1-1999.* Budapest, MTA SZTAKI, 1999. 17 p. (**Thesis 2**)

[P13] K. M. Hangos, J. Bokor, and G. Szederkényi. Analysis and control of nonlinear process systems. *Research report of the Systems and Control Laboratory SCL-3-2000.* Budapest, MTA SZTAKI, 2000. 115 p. (**Thesis 2**)

[P14] G. Szederkényi. Analysis and control of nonlinear fermentation processes. *Research report of the Systems and Control Laboratory SCL-1-2001.* Budapest, MTA SZTAKI, 2001. 53 p. (**Thesis 3**)

Publications partially related to the thesis

[P15] P. Ailer, I. Sánta, G. Szederkényi, and K. M. Hangos. Nonlinear model-building of a low power gas turbine. *Periodica Polytechnica*, in print, 2002.

[P16] P. Ailer, G. Szederkényi, and K. M. Hangos. Parameter estimation and model validation of a low power gas turbine. In *Proc. of the IASTED International Conference on Modeling, Identification and Control (MIC'2002)*, (Innsbruck, Austria), accepted, Feb. 2002.

[P17] P. Ailer, G. Szederkényi, and K. M. Hangos. Model-based nonlinear control of a low power gas turbine. In *Proc. of the 15th IFAC World Congress on Automatic Control*, (Barcelona, Spain), accepted, July 2002.

References

[1] Rolf Isermann. *Process fault diagnosis based on dynamic models and parameter estimation methods*. Prentice Hall, 1989.

[2] Alberto Isidori. *Nonlinear control systems*. Springer, Berlin, 1995.

[3] Arjan van der Schaft. *L2-gain and passivity techniques in nonlinear control*. Springer, Berlin, 2000.

[4] K.M. Hangos and I.T. Cameron. *Process modelling and model analysis*. Academic Press, London, 2001.

[5] L. Ljung. *System identification - theory for the user*. University of Linköping, Sweden, Linköping, 1984.

[6] M. Basseville and I.V. Nikiforov. *Detection of abrupt changes. Theory and practice*. Prentice Hall, London, 1993.

[7] T. Kailath. *Linear systems*. Prentice Hall, Englewood Cliffs, 1980.

[8] J. La Salle and S. Lefschetz. *Stability by Liapunov's direct method*. Academic Press, New York, London, 1961.

[9] K. M. Hangos, A. A. Alonso, and J. Perkins. A thermodynamic approach to the structural stability of process plants. *AIChE Journal*, 45:802–816, 1999.

[10] C. A. Desoer and M. Vidyasagar. *Feed-back systems: input-output properties*. Academic Press, New York, 1975.

[11] C. I. Byrnes, A. Isidori, and J. C. Willems. Passivity, feedback equivalence and the global stabilization of minimum-phase nonlinear systems. *IEEE Trans. Aut. Contr.*, AC-36:1228–1240, 1991.