The First Korea-Japan Joint Seminar On Chemical Process Control

June 24, 2000
Institute of Chemical Processes
Seoul National University
Seoul, KOREA

Brain Korea 21: Chemical Engineering Part
Institute of Chemical Processes
Seoul National University

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Morning Program: 10:00 - 12:00 AM

Opening Remark Professor Hyun-Ku Rhee

Polymer Quality Control in a Polymerization Reactor Using On-line Measurement and Nonlinear Model Predictive Control

Professor Hyun-Ku Rhee and Boong-Goon Jeong
Seoul National University

Identification of Volterra Kernels of Nonlinear System by Use of Pseudo-Random M-sequence with Applications to Nonlinear Model Predictive Control

Professor H. Kashiwagi
Kumamoto University

Identification and Nonlinear Model Predictive Control of a Continuous Polymerization Reactor

Sang-Seop Na
Seoul National University

A Practical Method for Identification of Nonlinear Chemical Processes

Motoki Numata
Kumamoto University

Lunch: 12:00 - 1:30 PM

Afternoon Program: 1:30 - 3:00 PM

Constrained Linear Optimal Control

Professor Jin-Hoon Choi
Sogang University

Nonlinear Separation Model and Control on Chemical Process

Professor Masatoshi Nakamura
Saga University

Nonlinear Subspace-based Predictive Control in a Polymerization Reactor

Kee-Youn Yoo
Seoul National University

Closing Remark Professor H. Kashiwagi

Polymer Quality Control in a Polymerization Reactor Using On-line Measurement Data and Nonlinear Model Predictive Control

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Abstract

Our goal is to control the polymer qualities by employing the nonlinear model predictive controller (NLMPC) in a continuous polymerization reactor known as a hard nonlinear process. The essential issue in NLMPC implementation is a dynamic nonlinear model suitable for model predictive control. In this study, we use the models obtained from the first principles approaches as well as by the system identification.

In the case of first principles approach, a mathematical model is developed for a continuous reactor in which free radical polymerization of methyl methacrylate (MMA) occurs. Elementary reactions considered in this study were initiation, propagation, termination, and chain transfers to monomer and solvent. The reactor model takes into account the density change of the reactor content and the gel effect. Based on the first principle model, a control system is designed for a continuous reactor using extended Kalman filter (EKF) based nonlinear model predictive controller (NLMPC) to control both the conversion and the weight-average molecular weight of polymer product. Control input variables are the jacket inlet temperature and the feed flow rate.

In the case of system identification approach, a subspace-based identification method of the Wiener model, consisting of a state-space linear dynamic block and a polynomial static nonlinearity at the output, is used to retrieve the accurate information about the nonlinear dynamics of a polymerization reactor from the input-output data. The Wiener model may be incorporated into model predictive control (MPC) schemes in a unique way that effectively removes the nonlinearity from the control problem, preserving many of the favorable properties of the linear MPC. The control performance is evaluated by simulation studies for which the original first-principles model for a continuous MMA polymerization reactor takes the role of the plant while the identified Wiener model is used for the control purpose.

For the purpose of validating the control strategy, on-line digital control experiment was conducted with on-line densitometer and viscometer. In order to measure the conversion and the

weight-average molecular weight on-line, the on-line densitometer and viscometer were installed in such a way that the measured values of density were used to calculate the conversion and the viscosity measurement along with conversion data were used to determine the weight-average molecular weight. Control input variables were the jacket inlet temperature and the feed flow rate.

Despite the complex and nonlinear features of the polymerization reaction system, the EKF based NLMPC and Wiener MPC performed quite satisfactorily for the property control of the continuous polymerization reactor of the multiple-input multiple-output with input and output constraints.

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Identification of Volterra Kernels of Nonlinear System by use of Pseudo-Random M-sequence with Applications to Nonlinear Model Predictive Control

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Abstract

The author has been working on identification of Volterra kernels of nonlinear systems by use of M-sequence for about 7 years. The principle of the method of nonlinear system identification is first explained, and then its applications to MPC of nonlinear chemical processes are presented.

As is well known, a class of nonlinear control system can be expressed by use of Volterra kernel expansion. For example, a linear dynamical system followed by nonlinear static system is a typical nonlinear system which is represented by Volterra kernels. When we can obtain Volterra kernels of a nonlinear system, we can say the identification of the nonlinear system is successful.

The identification of Volterra kernels by use of white Gaussian signal was first proposed by Lee and Schetzen in 1965. Barker *et al.* used M-sequence instead of white noise for obtaining 2nd Volterra kernel of nonlinear systems. But their methods are limited to the measurement of Volterra kernels of up to 2nd order.

The authors proposed in 1993 a method of obtaining Volterra kernels of up to 3rd order by use of shift and add propery of pseudo-random M-sequence, and applied it to saturation-type nonlinear system, mechatronic system, and nonlinear chemical processes.

Once we can get Volterra kernels of nonlinear process, we can easily construct a model for the nonlinear process. This means that when we apply this nonlinear system identification to actual nonlinear processes, we get more accurate model for the process which means MPC for nonlinear process would be much better by use of identified model than linear approximated model.

The authors investigated the effects of nonlinear MPC using identified Volterra model in cooperation with Mitsubishi Chemical Corp. in Japan. The simulation results show that MPC by use of Volterra model is much better than in case of linear model.

Identification and Nonlinear Model Predictive Control of a Continuous Polymerization Reactor

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Abstract

The dynamics of polymerization reactors is known to be inherently nonlinear and thus the first-principles model usually takes a complex form and is involved with a number of kinetic parameters. These are neither readily found from the literature nor easily obtained from the laboratory or pilot plant work. Therefore, the implementation of a first-principles model based controller such as a nonlinear model predictive controller (NLMPC) may be difficult and less effective.

As an alternative to the first-principles model, various nonlinear input-output models have been proposed and applied to the control of chemical processes. However, the application to polymerization reactors has been rather scarce, and furthermore the optimization and control based on input-output models have been performed mainly by numerical simulation. Hence, there is a strong motivation for the experimental validation of the identification by the input-output data and control by using such an input-output model.

In continuous polymerization reactors, the existence of steady-state multiplicity and parametric sensitivity has been shown theoretically as well as experimentally by various researchers. In addition, these reactors often exhibit highly interactive nonlinear behavior, which becomes more apparent during the grade-transition period than during the steady-state operation. For this reason, the important control objective may become the minimization of grade-transition time. Therefore, a multivariable NLMPC may yield improved performance over a linear model predictive controller for grade-transition control in a continuous polymerization reactor.

To excite the polymerization reactor system, we use the pseudorandom multilevel input signal. The input variables are the jacket inlet temperature and the feed flow rate whereas the output variables are the monomer conversion and the weight-average molecular weight. The effect of the number of input levels and the switching probability on the identification of a polynomial autoregressive moving average model (ARMA) is investigated in the simulation study. And then, the experimental identification is conducted and the results are compared with those for the case of

the linear ARMA model.

Because the polynomial ARMA model may give an objective function of higher order in input variables, we design the multivariable NLMPC based on the identified model by using the successive linearization approach. Hence, the optimization problem can be solved via the quadratic programming. To validate the performance of the proposed NLMPC during the grade-transition period, control experiments for setpoint-tracking are conducted. In particular, the on-line measurement techniques of polymer properties are proposed and demonstrated in the experiments for the identification and control.

Despite the heavy nonlinear features of the polymerization reactor, the polynomial ARMA model is found to accurately describe the dynamic behavior of the nonlinear system. Also, the proposed NLMPC can satisfactorily control the polymer properties in the continuous polymerization reactor.

A Practical Method for Identification of Nonlinear Chemical Processes by Use of Volterra Kernel Model

Motoki Numata

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Technology Development Center, Mitsubishi Chemical Corporation, Kurosaki Plant

Abstract

The author has been working on chemical process control and process development / design for 18 years at Mitsubishi Chemical Corporation. In 1982-85, the author developed an optimum heating method for the coke oven process and implemented it using LQI control with preview action algorithm. In 1990-1, the authors applied 2x2 MPC integrated with "soft sensor" to the temperature profile control of a rotary dryer. In 1993-98, the author joined several APC (Advanced Process Control) projects for petrochemical processes. As the multivariable MPCs, DMC and similar controllers (ex. SMCA) are mainly used for the projects and most of them are leading profitable results. Recently, such "nonlinear" MPCs are widely applied to the industrial chemical processes by using MPC software packages.

However, in general, most of chemical processes exhibit nonlinear behavior. Especially, when we consider the process control strategy over the wide range of operations, such as plant startup, shutdown, batch processes and so on, nonlinear process identification and control study is very important to improve controller performance.

Since Kashiwagi has recently shown a method for measuring Volterra kernels up to third order using pseudo-random M-sequence signals, the authors choose Volterra kernel model as the nonlinear process model. However, for the identification, it is necessary to excite the process with a signal having wide range of frequency spectrum and high enough amplitude of input signals. In practice, it is not always possible to apply such input sequences to the actual plants. Even when we can apply such a pseudo-random signal to the process, it takes much time to obtain higher order Volterra kernels. Considering these problems, the authors propose a new method for practical identification of it by use of approximate ordinary differential equation model and simple plant test. Simulation results are shown for verifying the usefulness of our method.

Constrained Linear Optimal Control

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Abstract

In 1960, based on the state space approach, Kalman provided a complete Riccati equation based solution strategy of the infinite horizon linear quadratic optimal control problem [3]. However, constraints are always present in any practical control problems. For instance, the physical restriction of the actuator limits the value the input can assume. Moreover due to safety, environmental regulation and so on, the states of the plant are desired to lie within a designated area in the state space. Under the presence of these constraints, the closed loop system becomes nonlinear and the analysis by Kalman is no longer valid. However due to the difficulty caused by the nonlinearity, the constrained infinite horizon linear quadratic optimal control problem remained unsolved until Sznaier and Damborg [4] pioneered the area in 1987. Indeed, based on the fact that the constrained infinite horizon linear quadratic optimal control problem can be reduced to a finite dimensional quadratic program, they proposed a solution strategy based on a set of quadratic programs. Recently, Chmielewski and Manousiouthakis provided a computationally less demanding technique where only a linear program is required to find a finite dimensional quadratic program equivalent to the constrained infinite horizon linear quadratic optimal control problem [1].

Another important linear optimal control problem is the H_∞ optimal control problem proposed by Zames in 1980 [5]. Since it was first proposed in 1980, H_∞ optimal control problem has been the hottest research topic in control community. The solution of H_∞ optimal control problem has been initially sought within operator theoretic framework. However the resulting solution procedure was complicated. Later, using state space approach, a very simple and efficient solution technique based on Riccati equations has been obtained by Doyle, Glover, Khargonekar and Francis [2]. However, the ever existing constraints need to be addressed explicitly in the design step again. Again the explicit consideration of constraints makes the closed loop system nonlinear and, thus, the current

analysis is no longer valid. Due to the difficulty caused by the nonlinearity, the constrained H_∞ optimal control problem remained unsolved.

In this talk, the exponential stability properties of the mixed constrained linear quadratic optimal control are first presented based on the Lyapunov theory. Then, based on the exponential envelop associated with the exponential stability, it is shown that the constrained infinite horizon linear quadratic optimal control problem can be reduced to a finite dimensional quadratic program without on-line optimization. Moreover, we show that the constrained H_∞ optimal control is exponentially stable. Especially, if the plant is stable, the closed loop system is shown to be globally exponentially stable. The constrained H_∞ optimal control problem is a constrained infinite dimensional dynamic game problem where infinite number of variables and constraints exist. Hence the problem cannot be solved as it is. However we show that, for given the initial state, the constrained H_∞ optimal control problem is equivalent to another a constrained infinite dimensional dynamic game problem where only finite number of constraints exist. Then we establish that the latter problem can be reduced to a constrained finite dimensional dynamic game problem. Further reduction of this problem into a finite dimensional quadratic programming problem is also shown to be possible. The feedback implementation of proposed technique based on the quadratic programming problems is also discussed.

References

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Nonlinear Separation Model and Control on Chemical Process

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1. General Information

In these four years of the joint research among Kumamoto University, Mitzubishi Chemical Industry and our Saga University, our laboratory published the following refereed papers and conference papers which related to the chemical process control.

Refereed papers

(1) Masatoshi NAKAMURA, Satoru GOTO and Takenao SUGI: A Methodology for Designing Controllers for Industrial Systems Based on Nonlinear Separation Model and Control, Journal of IFAC, Control Engineering Practice, Vol. 7, No. 3, 347/356, March 1999

(2) Masatoshi NAKAMURA, Kenta SHIRAMASA, Takenao SUGI, Satoshi OHYAMA and Morimasa OGAWA: Nonlinear Statics Compensated PID Based on Nonlinear Separation Control: Chemical Reactor Control, Transactions of the Society of Instrument and Control Engineers, Vol 35, No. 3, 363/369, March 1999 (in Japanese)

Conference papers

(3) Masatoshi NAKAMURA, Takenao SUGI, Morimasa OGAWA and Toshiaki ITOH: Controller Design for Nonlinear Chemical Reaction System by Separating Nonlinear Statics and Linear Dynamics, The 15th SICE Kyushu Branch Annual Conference, 135, 87/90, November 1996 (in Japanese)

(4) Takenao SUGI, Masatoshi NAKAMURA, Satoshi OHYAMA and Morimasa OGAWA: Nonlinear Separation Control of Chemical Reactors for Changing Production Conditions, The 16th SICE Kyushu Branch Annual Conference, 405, 301/304, November 1997 (in Japanese)

(5) Masatoshi NAKAMURA, Kenta SHIRAMASA, Takenao SUGI, Satoshi OHYAMA and

Morimasa OGAWA: Nonlinear Separation Control Designing Noise Restraint for Chemical Reactors, Proceedings of the 42nd Annual Conference of the Institute of Systems, Control and Information Engineers, ISCIE, 6006, 517/518, May 1998 (in Japanese)
(6) Masatoshi NAKAMURA and Toshihiro IMAYOSHI: Nonlinear Separation Model and Control for Density and Level of Tanked Slurry in Chemical Plant, The 39th SICE Annual Conference, July 2000 (to be presented)(in Japanese)

As seen in the titles of the above papers, we had developed a methodology of 'Nonlinear Separation Model and Control', and adopted and modified it to chemical process control problems.

In our Systems Control Laboratory of Saga University, I and Dr. Sugi(research associate, his main field is biomedical systems control) and Mr. Imayoshi (master course student) are involving in this field.

At the first seminar, I will introduce 'Nonlinear Separation Model and Control' based on the contents of the paper [1]. Following is the abstract and introduction (with a small modification) of the paper [1].

2. Abstract of the reference

A feasible method of controller design for industrial nonlinear dynamic systems is proposed, by separating the nonlinear dynamic system into nonlinear static parts and a linear dynamic part. The proposed method of industrial controller design reduces the existing gaps between the control theory and the actual field. In the controller construction procedure of a system, the nonlinearities are eliminated by using the inversion functions of the nonlinear static parts. Any conventional control theory is ideally applicable to a linear dynamic part of the system. Based on the proposed method of nonlinear separation, controllers were constructed for three different systems: a chemical reactor, a temperature level-controlled tanked water system, and the contour-following control of an articulated robot arm. Some encouraging control performances, superior to those of other existing controllers, showed its significant potential for application to industrial systems with nonlinearities.

3. Introduction of the reference

Controller design for industrial nonlinear dynamic systems is not an easy task. In some cases, the controllers are designed using standard linear control techniques (Kalman, 1960), but the resulting linear controller can only be expected to function well in a restricted neighborhood of the operating point of the nonlinear system. If a disturbance acts on the system so that it strays far from the operating point, it becomes unstable. Further, to keep the operating points, tuning procedures are necessary, but these tunings are generally based on empirical techniques, and consistency and repeatability in terms of controller performance cannot be ensured. Due to these limitations of the linear control theory, a need has been found to incorporate knowledge about the inherent plant nonlinearities into the model structure, and hence a new era of controller design has been started with nonlinear control (Kano, 1988, Goodhart et al., 1994; Astrom et al., 1977; Richalet et al., 1978). Those nonlinear controllers are complicated, and face many problems when being implemented in an actual industry. The complexity of these controllers still gives rise to a requirement for appropriate controller design methods for nonlinear systems, in order to bridge the gaps between theory and practice.

This paper proposes an important idea for use in controller design procedures for nonlinear dynamic systems in industry. In designing a controller for an actual system, the nonlinear dynamic system should, in almost all cases, be separated into a combination of several parts: the nonlinear static parts, and a linear or quasi-linear dynamic part. When the construction of the controller is based on the nonlinear separation model, the nonlinearities are eliminated by introducing the inversion characteristics of the nonlinear static parts, together with any type of conventional control theory such as a pole-assignment regulator (Ackerman, 1977), PID control (Kitamoti, 1980), fuzzy control (Mamdani, 1974), neural control (Bhat et al., 1990) or robust control (Doyle and Stein, 1981) can be ideally applied to the residual linear dynamic part. Based on the proposed method of nonlinear separation, a nonlinear chemical reactor, a temperature level-controlled tanked water system and an articulated robot arm system were appropriately modeled and controlled.

Nonlinear Subspace-based Predictive Control in a Polymerization Reactor

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Abstract

The control of polymerization reactors is an important subject which may be called 'polymerization reactor engineering' in a broad sense. This involves studies on the aspects of design, modeling, optimization and control of polymerization reactors. Control of polymerization reactors is an attractive and challenging problem due to its intrinsic characteristics.

In the industrial polymerization process, a typical operation task is involved with the manipulation of reactant concentrations, reactor temperature, and other adjustable variables to achieve desired targets for conversion, molecular weight, molecular weight distribution and residual impurities. These are actually indirect specifications of the end-use and processing properties needed by customer. Many end-use properties are correlated with the molecular weight averages (MWs) and molecular weight distribution (MWD), including tensile strength, impact strength, fatigue life, and melting point[1]. Molecular weight also affects the processing properties[2].

Hence, operating a polymerization process to achieve a specified average MW and MWD is highly desired. In this work, we assume that there are reliable methods available to measure the conversion and the weight average molecular weight in a polymerization reactor. The difficulties in designing an effective polymer quality control system for the polymerization reactor also arise from the nonlinear plant characteristics. With the advent of the current generation of high-speed computers, it is now conceivable that more advanced control strategies, not limited to PI/PID, can be applied in a realistic setting. Model predictive control is one of such controller design techniques which has gained wide acceptance in process control applications.

Our goal in this work is to study the control of polymer quality such as conversion and weight

average molecular weight in a continuous polymerization reactor. We use the feed flow rate and jacket inlet temperature as manipulated variables and apply the subspace-based predictive controller to control the polymer quality in a continuous polymerization reactor.

As an alternative to "full-fledged" nonlinear model predictive control, we introduce a different model predictive control algorithm that uses a linear-fractional linear parameter-varying (LF-LPV) prediction model[3] or a Wiener model originated from the subspace identification method. This approach allows us to avoid the stage of problem setup required in the standard nonlinear MPC approach, improve the computational efficiency significantly, and simplify the performance analysis. When compared with the standard local linearization-based model predictive control which uses linear time-invariant prediction models, the subspace-based predictive control using LF-LPV or Wiener prediction model provides more accurate approximation to the true nonlinear system, resulting in a performance closer to that of a nonlinear model predictive control.

The linear and nonlinear subspace-based predictive controllers have been applied to the styrene solution polymerization reactor. We observe that the set-point changes in the linear case cause offsets in the conversion as well as in the weight average molecular weight. This is because the linear subspace-based predictive controller cannot properly deal with the nonlinear features of the polymerization reactor system. It is observed that the LF-LPV and Wiener subspace-based predictive controllers perform satisfactorily for the control of the conversion and the weight average molecular weight (no offset) and the nonlinear model structure enables us to deal with the nonlinear characteristics of the polymerization reactor system.

References

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