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学 位 論 文 題 目　Nonlinear System Modeling and Predictive Control Based on Local Linearization Approaches

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論文内容の要旨

So far, significant advances have been made in linear system modeling and control theory. However, in fact, many systems are, in general inherently nonlinear. This, together with higher product quality specifications and increasing productivity demands, tighter environmental regulations and demanding economical considerations in the process industry and other fields, require operating systems closer to the boundary of the admissible operating region. In these cases, linear models are often inadequate to describe the system dynamics and nonlinear models have to be used. Therefore, the researches on nonlinear system modeling and control theory have become the focus of attention recently. It is difficult that one overall solution will be developed covering all nonlinear system possibilities. It is more likely that nonlinear modeling and control problems will be solved in stages by finding design approaches which are particularly suitable for certain classes of nonlinear systems.

This thesis focuses on the black-box nonlinear system modeling and control problems; it means that very little *prior* knowledge on the system being considered can be exploited for building a model to describe the system behavior. Statistical modeling methods are here applied to build a system model, and we then design a suitable controller on the basis of the identified model to implement high-performance control. There have been many models built by means of statistical methodology for complex nonlinear system modeling, which are mainly completely-nonlinear models including various parametric and nonparametric models (such as the bilinear model, the Hammerstein model, the Volterra series model and neural network models), and local linearization models (such as state-dependent AR model and piecewise linear model-set). A purely nonlinear model based controller design usually requires solving a nonlinear optimization problem online, which is still an unsolved problem particularly in the industrial application field. Local linearization modeling and controller design approaches based on the framework of relatively-matured linear system modeling and control theory have made many successful applications. However, some potential problems, for example, on-line parameter estimation failure in the approaches resorting to parameter estimation online, higher identification cost in the approaches using piecewise linear model-set, and so on, limit a wider application of those approaches.

This thesis presents the nonlinear modeling and control approaches for two kinds of nonlinear systems based on the proposed local linearization methodologies which avoid the drawbacks of classical local linearization techniques as is mentioned above. One is the complex industrial process, which has smooth nonlinear dynamics, and may be represented by a local linearization model. Other kind of nonlinear systems to be considered in this thesis are stochastic nonlinear financial processes, such as foreign currency exchange process and stuck index varying process. The details of the thesis are summarized as follows.

First, for the smooth nonlinear industrial process, a nonlinear modeling and model predictive control (MPC) scheme based on the exponential ARMAX (ExpARMAX) model is proposed. The ExpARMAX model is a locally-linear, globally-nonlinear NARMAX (nonlinear ARMAX) model, which may be applied to characterize a class of nonlinear systems having operating-point-dependent smooth dynamics, such as, the power plant temperature process and the nitrogen oxide (NO_x) decomposition process in thermal power plants. The ExpARMAX model with exponential coefficients depending on operating-point-state is identified off-line; its identification approaches are also presented both by an experience formula-based approach and a hybrid nonlinear optimization scheme. Based on the model, a long-range predictive control strategy without resorting to parameter estimation online is investigated. Simulation study to a multivariable power plant temperature control process utilizing the ExpARMAX model-based predictive control approach illustrates its effectiveness.

Secondly, we generalize the modeling framework using the local linearization-type operating-point-dependent autoregressive model to consider more general control-oriented modeling problems for non-stationary nonlinear systems whose dynamic characteristics depend on time-varying operating-points and may be locally linearized. It is proposed to describe the system behavior by the RBF-ARX model, which is a pseudo-ARX model with Gaussian radial basis function (RBF) neural network-style coefficients depending on working-points of the system. The RBF-ARX model is built as a global model, and is estimated off-line so as to avoid the possible failure of parameter estimation online while real time control. A significant advantage is that if using a RBF-ARX model in acceptable precision to represent a nonlinear process which is being controlled by an existing controller, such as PID controller, then model identification data (training data) may be obtained directly from the existing control system. It means that the usually high-cost industrial identification experiment may not be needed for identifying an RBF-ARX model. That has been verified in an industrial experiment of the RBF-ARX model-based predictive control of the nonlinear nitrogen oxide (NO_x) decomposition (de-NO_x) process, which is presented in Chapter 5. A structured nonlinear parameter optimization method (SNPOM) which is especially adapted to the RBF-ARX model parameter estimation is proposed in this thesis. This is an off-line nonlinear model parameter optimization method, depending partly on the Levenberg-Marquardt method (LMM) for nonlinear parameter optimization and partly on the Least Squares method (LSM) using SVD (singular value decomposition) for linear parameter estimation. Compared with some other algorithms, the SNPOM obviously accelerates the computational convergence of the parameter optimization search process of RBF-type models, and also improves the modeling precision. The usefulness of this method is illustrated by means of several examples.

Thirdly, we propose the RBF-ARX model-based nonlinear predictive control method (RBF-ARX-MPC) for the non-stationary nonlinear systems whose dynamic characteristics depend on time-varying working-points and may be locally linearized. The RBF-ARX model here is built as a global model which is estimated off-line, and the local linearization of the system being controlled is obtained from the global model at each sampling instant. Therefore, the use of nonlinear programming techniques to solve an optimization problem online with constraints in the RBF-ARX-MPC is avoided. Furthermore, the RBF-ARX-MPC considers the effect of a time-varying local mean of the model. A time-varying locally-linearized ARX model describing a non-stationary nonlinear process must necessarily include an offset term, so the RBF-ARX-MPC proposed may be considered a more general MPC scheme based on a locally linearized ARX model with or without a time-varying offset term. The nominal and robust stability analysis of the nonlinear predictive controller proposed is also given both in an unconstrained case and in the case with *ex post facto* input constraints.

Fourthly, for illustrating the feasibility and effectiveness of the RBF-ARX model-based nonlinear system modeling and MPC strategy to real problems, an application to the nitrogen oxide (NO_x) decomposition (de-NO_x) process in thermal power plants is carried out both by means of simulation study and industrial experiment. The de-NO_x process has the nonlinear behavior depending on the load demand of power plants. At a certain fixed operating point, the de-NO_x process may be represented using a linear model. However, if the load demand changes with time rapidly, a linear model or on-line estimated linear time-varying model is difficult to characterize the process. The real-data-used simulation studies and some industrial experiments utilizing the proposed RBF-ARX model-based modeling and MPC method to the process verify that the off-line identified RBF-ARX model can describe the global nonlinear property of the process over a wide region in acceptable precision, and the RBF-ARX model-based MPC exhibits much better control performance, compared with the well-tuned PID control which is now still widely used in this kind of process control, and the well-known on-line estimated time-varying linear ARX model-based generalized predictive control (GPC) approach.

Finally, on the basis of the market microstructure theory, the stochastic volatility microstructure models both in continuous-time form and in discrete-time form are proposed for describing the dynamics of some financial processes, and for implementing the asset allocation control. The estimates of two immeasurable state variables, which represent the market excess demand and liquidity respectively, may be obtained from the microstructure model proposed. A simple trading strategy for dynamic asset allocation, based on the indirectly obtained excess demand information instead of the prediction for price, is presented. Estimation approaches for the microstructure models, applying the local linearization scheme, the extended Kalman filtering and the maximum likelihood method, are investigated. Case studies on the JPY/USD currency exchange rate time series and the Japan TOPIX index time series show the effectiveness of the nonlinear stochastic process modeling and the asset allocation strategy presented in this thesis.

論文の審査結果の要旨

論文は非線形システムのモデリングと同定，及び同定された非線形モデルによる予測制御法の研究に関するものである．論文全体は７章に分けられ，第１章のイントロダクションの後，第２章では Exponential AR (ExpAR) モデルと呼ばれる非線形 AR モデルを拡張し，赤池・中村法と呼ばれる多変量 AR モデルによる予測制御手法を非線形システムに拡張する試みが提示されている．多変量の火力発電プラントのボイラーシステムの発生電力量に従属してシステム特性が変わる非線形性を ExpAR モデルの状態従属固有値の考えでモデル化し赤池・中村法型の制御系設計の考えを残しながら火力発電ボイラーの温度の非線形制御を具現化している．大規模シミュレータを使った検証も示されている．第３章では ExpAR モデルをさらに発展させた RBF-ARX (Radial Basis Function - ARX) モデルを導入しその推定法を議論している．RBF-AR モデルの特性を利用した新しい最適化法を導入しこれまでの方法と比較してその特長を議論している．第４章では RBF-AR モデルベースの非線形予測制御法の安定性が議論されている．RBF-AR モデルの特性が入力の制約無しの場合のフィードバックプロセスの安定性を保証することに役立っていることが示されている．第５章では RBF-AR モデルベースの予測制御法を脱硝システム制御へ応用した結果が示されている．発電プラントの排煙中の窒素酸化物の量を押さえる脱硝制御問題に関して，実機プラントの実験データを使ったモデル同定とモデルベースの予測制御の実際，その困難と解決法が他の方法による結果と比較しながら具体的に議論されている．第６章で金融のアセットアロケーション問題を金融システムのモデリングと制御の問題と捉えて論じている．連続時間確率微分方程式モデル，離散時間時系列モデル，それらの状態空間表現とカルマンフィルターによる白色化，状態推定，最尤法などを導入提示し，実際の円ドル為替データに適用し外貨のアロケーションに関する結果を出している．第７章で論文全体の総括がなされている．

火力発電所プラントなどのシステムを制御するために，線形モデルを用いた統計的制御ではなく非線形モデルを用いた統計的制御を行う必要があることに注目した研究である．非線形モデルとして ExpAR モデルとそれを発展させた RBF-ARX モデルを提案し，その安定性，同定可能性，パラメータ推定法と制御系の設計法について述べられている．RBF-ARX モデルを提案した業績のみでも高く評価できるが，彭氏は，線形の最小二乗法のみで推定できるパラメータと非線形最適化手法が必要なパラメータを有している提案モデルのパラメータ推定法についても従来の方法よりも収束が速い方法を見出している．シミュレータと実機試験で制御に用いることが可能であることも確かめている．本年６月，７月に実施された新大分火力発電所における実機試験について詳しい説明が論文発表会でなされた．国内外の学会等でもすでに理論的には高い評価を受けていたが，実用化も可能であることが必要であるという要求も満足したことになる．このように申請論文は，理論，実用の両面から非常に優れた論文であるとの評価を下すことができる．また，彭輝氏にはこれまでに 21 編の学術論文があり，その中で博士論文の内容に関係する論文は７編あり，すべて彭輝氏が第一著者である。

これらの結果，彭輝氏の博士申請論文は博士(学術)を授与するのに十分な内容を備えていると判断した．