氏　　　名	施　招雲
学位（専攻分野）	博士(学術)
学位記番号	総研大乙第61号
学位授与の日付	平成１１年3月２４日
学位授与の要件	学位規則第４条第２項該当
学位論文題目	Nonlinear time series analysis by the generalized exponentiol autoregressive model and its applications
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論文内容の要旨

Due to the complexity and nonlinear variety of the real world, nonlinear time series analysis has become one topics of the most popular interest. Accordingly, there are several nonlinear modeling approaches provided to tackle the complexity of nonlinear time series, the approaches can be generally divided into three categories: parametric, semi-parametric, and non-parametric model. Actually nonlinear statistical time series analysis started its research on parametric modeling about two decades ago for the motivation to overcome the limitations of the linear models in revealing nonlinear phenomena such as limit cycle. Two typical parametric nonlinear time series models are the exponential autoregressive (ExpAR) model and the threshold autoregressive model, they have been well-known in describing several typical nonlinear behaviors. However, it has been argued recently that the parametric models are hard to justify *a priori* the universal description appropriateness in most real applications to complex dynamic systems analysis. Moreover, the parametric modeling approach as the traditional statistical nonlinear time series analysis methodology has been faced with the serious challenges from neural network techniques and deterministic dynamic theory. In this situation, the non-parametric identification such as non-parametric density estimation of nonlinear time series became popular being an alternative paradigm of modeling in recent years. The non-parametric models allow for great flexibility without confining oneself to a special parametric model, however, this approach still has some drawbacks such as the curse of dimensionality, which hinder its wide application. Therefore the semi-parametric modeling is introduced in order to evade the limitations of non-parametric approach, although some of the semi-parametric models lose their generality simultaneously so that they seem limited to be applicable for some particular cases, and the boundary between parametric and some semi-parametric models become not sharp.

Since the parametric approach can be easily interpreted, and in turn the dynamic mechanism of the underlying systems can be looked for, this study focuses on nonlinear time series analysis by one of the parametric model, the exponential autoregressive model and its general version, with comparison to other approaches. The thesis gives a deep investigation into the properties of the model, and shows the performance of the ExpAR modeling in identification and prediction as two important issues in the statistical analysis of time series. The details of the thesis are summarized as follows.

First, the classic exponential autoregressive model is introduced to nonlinear time series analysis. The ExpAR model looks very simple in structure, it is basically the AR model but the state-dependent coefficients. Then the dynamics of the ExpAR model is investigated. By calculating the Lyapunov exponent and the bifurcation of the ExpAR model, it is found that even very simple ExpAR may behave very complicated dynamics such as fixed point, limit cycle and chaos. Several typical chaotic phenomena like period-double bifurcation, intermittency and synchronization occur in the simple ExpAR model too. So we can let the ExpAR model reveal rich different nonlinear behaviors just by controlling the parameters and the delay dimension. This can be a solid evidence to accept the ExpAR model to identify some complex data since the model is originally provided to model time series instead of as an analytical model like Logistic equation and others. However, from the standout of practitioner, the model estimate, as a nonlinear optimization problem, becomes obviously important since minor difference in the values of parameters may result in large different dynamics. Actually the ExpAR model estimate has not been yet well solved. In this study, the genetic algorithm is applied to solve this problem, and several procedures are provided. The procedures take mutual estimation, in which the first one is to use the genetic algorithm to determine the scaling parameter in the model, and then other linear weights are estimated by linear least squares. In another procedure, the genetic algorithm is used to optimize both the model structure and the nonlinear scaling parameter. We therefore name the procedures as the self-organization modeling. As a by-product of the self-organizing procedure, we can get a subset ExpAR model that is of importance to dimensionality reduction. The efficiency of the estimates is shown by the numerical examples.

Secondly, the investigation of applying the ExpAR model to machine tool chatter monitoring system design is carried out. According to the fact that machine tool chatter is a nonlinear self-excited oscillation of limit cycle type, we provide the limit cycle behavior to be the intrinsic index of chatter occurrence, and the ExpAR model is proposed to detect the index from on-line cutting signal. Consider the actual implementation of the proposal, a real-time estimation of the ExpAR model is provided to satisfy the needs of on-line monitoring system design. Actual cutting signal analysis shows the effectiveness of the proposal.

Thirdly, the generalized exponential autoregressive modeling is considered to complex time series analysis. The classic ExpAR model is actually a kind of state-dependent AR model in which only the amplitude is taken as the state. However, it can be imagined that the coefficients of the model are not necessarily dependent on one state, for some complex data, the coefficients of ExpAR model should be dependent on several states, say state vector. Therefore we introduce state vector-based ExpAR model, namely generalized ExpAR model, to nonlinear time series analysis, in which the coefficients are Gaussian-product functions (Gaussian radial basis function) of state vector. We prove that the geometric ergodic condition of the generalized exponential autoregressive model is still the same as that of the classic ExpAR model since factorizable property of the Gaussian radial basis function. Thus the stability of the model can be expected. For the estimate of the generalized ExpAR model, we provide a mutual estimating procedure which hybridizes the multi-agent random optimization algorithm namely evolutionary programming with the ordinary least squares to estimate the unknown parameters in the model. Simulations show the efficient ability of the generalized ExpAR model to dynamics reconstruction and prediction error reduction.

Finally, empirical investigation of statistical identification of several actual nonlinear time series is given. We introduce three typical models respectively belonged to non-parametric conditional mean estimator (Nadaraya-Watson estimator), semi-parametric model (radial basis function network) and local linearization model (generalized exponential autoregressive) to analyze the epilepsy EEG (spike and wave) and human pulse wave (quasi-periodicity). Empirical comparisons show that the non-parametric estimator is of advantage to dynamics reconstruction, the local linearization model is good at forecasting for short term horizon, and the semi-parametric model has its site between the above models.

論文の審査結果の要旨

博士論文の審査の申請のあった施招雲氏の論文の審査を行った結果、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。判断理由を以下に示す。

論文は６章からなりそれぞれ次のような内容である。

第１章では線形時系列モデルや非線形モデルについて概説することにより新しい非線形時系列モデルの必要性について述べている。また、従来の非線形モデルを紹介するとともに、第２章以降で論じている申請者が提案している非線形時系列モデルに関する基礎となるニューラルネットワークモデル、ノンパラメートリック推定の説明を行い、申請者の新しいモデルの理論的背景を明らかにしている。

第２章では指数型 AR モデル(exponential autoregressive model)について論じている。指数型 AR モデルは尾崎統氏により発案されたものであるが、スケーリングパラメータの推定に困難が伴うことが多かった。遺伝的アルゴリズムを用いてそのパラメータを推定する方法を提案することにより、この問題を解決できることを示している。スケーリングパラメータのみならずモデル構造も遺伝的アルゴリズムを用いて推定する方法も提案し、サブセット指数型ＡＲモデルについて数値例を用いて論じている。

第３章では指数型 AR モデルを工作機械のびびり振動の問題に応用している。工作機械の切削状態をモニタリングし制御することは工業的に重要なことであることにより、意義ある応用例であると言うことができる。

第４章では RBF(radial basis function) と遺伝的プログラミングを用いて AR 係数が状態に依存するような場合にＡＲ係数を推定する方法を提案している。この RBF-AR モデルは指数型 AR モデルを一般化したものとみなすことができる。RBF ニューラルネットワークモデルと RBF-AR モデルとの比較も行っている。

第５章では指数型 AR モデル、RBF-AR モデル、ノンパラメートリック AR モデルの比較を行っている。癲癇脳波データ(epilepsy EEG)、人の脈波データを例として用いている。

第６章では結論とこれらの発展について述べている。

申請者は制御工学・時系列解析を学び、新しい非線形時系列モデルについて研究している。遺伝的アルゴリズムや RBF という計算機指向型の時系列モデルを研究・提案しており、今後のモデリングに対しての方法性についても研究・提案しているとみなすことができる。また、学術雑誌に掲載された論文数は 13、口頭発表のプロシーティング数は 13 であり、国内外の国際シンポジウム等での発表経験も豊富である。研究成果は高く評価されており、特に RBF-AR モデルは申請者の独創性によるものである。