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System Identification

Theory for the User

Second Edition

系统辨识 —— 使用者的理论（第2版）

LENNART LJUNG

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Second Edition

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国际知名大学原版教材

——信息技术学科与电气工程学科系列

出 版 说 明

郑大钟
清华大学信息科学与技术学院

当前，在我国的高等学校中，教学内容和课程体系的改革已经成为教学改革中的一个非常突出的问题，而为数不少的课程教材中普遍存在的“课程体系老化，内容落伍时代，本研层次不清”的现象又是其中的急需改变的一个重要方面。同时，随着科教兴国方针的贯彻落实，要求我们进一步转变观念扩大视野，使教学过程适应以信息技术为先导的技术革命和我国社会主义市场经济体制的需要，加快教学过程的国际化进程。在这方面，系统地研究和借鉴国外知名大学的相关教材，将会对推进我们的课程改革和推进我国大学教学的国际化进程，乃至对我们一些重点大学建设国际一流大学的努力，都将具有重要的借鉴推动作用。正是基于这种背景，我们决定在国内推出信息技术学科和电气工程学科国外知名大学原版系列教材。

本系列教材的组编将遵循如下的几点基本原则。(1) 书目的范围限于信息技术学科和电气工程学科所属专业的技术基础课和主要的专业课。(2) 教材的范围选自于具有较大影响且为国外知名大学所采用的教材。(3) 教材属于在近 5 年内所出版的新书或新版书。(4) 教材适合于作为我国大学相应课程的教材或主要教学参考书。(5) 每本列选的教材都须经过国内相应领域的资深专家审看和推荐。(6) 教材的形式直接以英文原版形式印刷出版。

本系列教材将按分期分批的方式组织出版，为了便于使用本系列教材的相关教师和学生从学科和教学的角度对其在体系和内容上的特点和特色有所了解，在每本教材中都附有我们所约请的相关领域资深教授撰写的影印版序言。此外，出于多样化的考虑，对于某些基本类型的课程，我们还同时列选了多于一本的不同体系、不同风格和不同层次的教材，以供不同要求和不同学时的同类课程的选用。

本系列教材的读者对象为信息技术学科和电气工程学科所属各专业的本科生，同时兼顾其他工程学科专业的本科生或研究生。本系列教材，既可采用作为相应课程的教材或教学参考书，也可提供作为工作于各个技术领域的工程师和技术人员的自学读物。

组编这套国外知名大学原版系列教材是一个尝试。不管是书目确定的合理性，教材选择的恰当性，还是评论看法的确切性，都有待于通过使用和实践来检验。感谢使用本系列教材的广大教师和学生的支持。期望广大读者提出意见和建议。

System Identification
—Theory for the User
Second Edition

影印版序

《System Identification—Theory for the User，Second Edition》（系统辨识——使用者的理论，第二版）一书是著名的系统辨识方面的权威、瑞典 Linköping 大学 L.Ljung 教授编著的。L.Ljung 教授现任瑞典皇家工程科学院院士、瑞典皇家科学院院士、IFAC 顾问、IEEE Fellow 及多家国际刊物编委等职，在国际上拥有很高的学术地位。L.Ljung 教授在系统辨识领域的贡献是世界公认的，可以说他及他所领导的“控制小组(the Control Group)”在辨识方面所做的工作代表着系统辨识学科的前沿，尤其在辨识模型和辨识方法的一般性框架、快速辨识算法、辨识收敛性分析、可辨识性理论及闭环系统辨识等方面所作的贡献都是具有前瞻性和开创性的。

本书第一版出版于 1987 年，该书是它的第二版，1999 年由 Prentice Hall 出版社出版，它是 Kailath 教授主编的“信息和系统科学丛书”中的一部重要著作。应该说，本书是一部理论性著作，但作者意味深长地提到过：副标题“使用者的理论”才是本书写作的初衷。也就是说，作者把重点放在使用者如何去理解和使用现有的系统辨识理论上，其目的是让读者在获得坚实的辨识理论基础后，有信心去处理和解决实际问题。本书第 3 篇“使用者的选择”，包括 6 章内容（选择与目标、实验设计、数据预处理、辨识准则的选择、模型结构选择与模型验证、系统辨识的实际应用），体现了作者的这种写作用心。

本书基本上由四大部分内容构成：系统与模型、辨识方法、理论分析、使用者的选择。**系统与模型**部分主要论述线性时不变系统、线性时变系统和非线性系统的描述及其对应的模型结构。这部分内容在其他教科书里也是可以找到的，但是作者从系统辨识需要的角度来阐述系统及其模型，读起来别有体会。尤其在第 4 章第 2 节中，作者归纳性地论述了传递函数模型类的结构，包括等式误差模型、线性回归模型、ARMAX 模型、拟线性回归模型、DA(Dynamic Adjustment)模型、FIR 模型、输出误差模型、Box-Jenkins 模型、一般结构模型等，这使读者对辨识所用的模型类有一个完整的认识，非常有利于辨识方法的学习和应用。**辨识方法**部分主要论述各类模型参数辨识算法及其数值解方法，包括非参数时域与频域辨识方法、最小二乘辨识方法、线性回归辨识方法、预报误差辨识方法、子空间辨识方法、极大似然辨识方法、拟线性回归辨识方法、辅助变量辨识方法等。就辨识算法的递推形式而言，本书又分作递推预报误差方法、递推拟线性回归方法和递推辅助变量方法三种形式。值得指出的是，第 11 章第 4 节给出的预报误差递推辨识算法代表着辨识方法的一般性框架。**理论分析**部分主要讨论了基于数据集性质的辨识算法的一致性、收敛性、可辨识性和参数估计的渐近分布等问题。**使用者的选择**部分主要阐述辨识目的、开环辨识实验设计、闭环辨识实验设计、采样时间的选择、数据预处理、辨识准则的选择、模型结构辨识、模型验证、辨识软件工具、辨识应用中的一些实

际考虑和辨识应用等问题。这部分内容对使用者是十分实际和有用的。

纵观全书，作者要告诉读者什么？尤其对使用者来说，我想可以概括为：

(1) 懂得选择合理的模型类和合适的辨识方法。

(2) 理解辨识结果对数据、模型类和辨识准则的依赖。

(3) 学会利用数值方法去解决辨识估计的计算问题。

(4) 掌握辨识的实验设计、合理利用先验知识。

本书第二版修订离第一版出版相隔 12 年之久，这期间有关系统辨识的研究又有了显著的发展。作者在第二版中加进了许多新的研究成果和作者对这一时期系统辨识研究进展的见解。第二版中新增加的内容主要有非线性黑箱模型（如神经网络模型和模糊模型）、多变量状态空间模型的子空间辨识方法、非参数频域辨识方法、闭环辨识的综合性讨论、数据预处理等。第三篇“使用者的选择”多数内容重写了，更加突出了使用者的需要和应用上的技巧。

本书的主要特点：

(1) 体系结构上突出层次性，第一层面论述辨识所用的模型类，第二层面讨论辨识方法及其数值计算，第三层面是辨识的理论分析，第四层面阐述辨识使用者的选择。

(2) 强调辨识理论的应用，但论述辨识理论问题时又是十分严谨的，决不把理论的应用看作数学上可以草率敷衍的理由。

(3) 全书的论述是建立在概率框架的基础上的，非概率的解释有时可能也是有效的，但很少采用。

(4) 本书所引用的参考文献十分丰富，几乎包罗了系统辨识领域的许多重要文献和反映重要问题的原始文献。

(5) 每章后面的习题分四种类型。G 类习题即使不想做，也值得你去认真思考；E 类习题需要动手完成；T 类习题一般比较难，牵涉到较深的辨识理论问题；D 类习题是正文的一种补充和延伸。

阅读本书需要动态系统、线性代数和随机过程的知识。对辨识的实际工作者来说，如果不愿意硬啃本书中的一些理论问题，尤其是打“*”的内容，可以跳过。阅读完第 1 章后，可以直接去阅读第三篇“使用者的选择”，第 2~11 章只需阅读每章的小结，这样依然可以成功地应用辨识理论去解决实际问题。这也是作者的一种潜心安排。本书中的一些例子值得读者在计算机上仿照练习，其代码和数据可以从网页“http://www.control.isy.liu.se/~ljung/sysid”下载。各章后面的附录是一些定理的证明，跳过也无妨。

本书是世界多所知名大学，包括 Stanford 大学、MIT、Yale 大学、澳大利亚国立大学、瑞典 Linköping 大学和 Lund 大学，系统辨识课程的教材，也应该成为我国自动化专业控制科学与控制工程学科研究生系统辨识课程的教材或教学参考书。本书还适合于自学者、有关技术人员、高校教师参考。

萧德云

清华大学自动化系教授

2001 年 12 月

To Ann-Kristin, Johan, and Arvid

Preface to the First Edition

System identification is a diverse field that can be presented in many different ways. The subtitle, *Theory for the User*, reflects the attitude of the present treatment. Yes, the book is about theory, but the focus is on theory that has direct consequences for the understanding and practical use of available techniques. My goal has been to give the reader a firm grip on basic principles so that he or she can confidently approach a practical problem, as well as the rich and sometimes confusing literature on the subject.

Stressing the utilitarian aspect of theory should not, I believe, be taken as an excuse for sloppy mathematics. Therefore, I have tried to develop the theory without cheating. The more technical parts have, however, been placed in appendixes or in asterisk-marked sections, so that the reluctant reader does not have to stumble through them. In fact, it is a redeeming feature of life that we are able to use many things without understanding every detail of them. This is true also of the theory of system identification. The practitioner who is looking for some quick advice should thus be able to proceed rapidly to Part III (User's Choices) by hopping through the summary sections of the earlier chapters.

The core material of the book should be suitable for a graduate-level course in system identification. As a prerequisite for such a course, it is natural, although not absolutely necessary, to require that the student should be somewhat familiar with dynamical systems and stochastic signals. The manuscript has been used as a text for system identification courses at Stanford University, the Massachusetts Institute of Technology, Yale University, the Australian National University and the Universities of Lund and Linköping. Course outlines, as well as a solutions manual for the problems, are available from the publisher.

The existing literature on system identification is indeed extensive and virtually impossible to cover in a bibliography. In this book I have tried to concentrate on recent and easily available references that I think are suitable for further study, as well as on some earlier works that reflect the roots of various techniques and results. Clearly, many other relevant references have been omitted.

Some portions of the book contain material that is directed more toward the serious student of identification theory than to the user. These portions are put either in appendixes or in sections and subsections marked with an asterisk (*). While occasional references to this material may be encountered, it is safe to regard it as optional reading; the continuity will not be impaired if it is skipped.

The problem sections for each chapter have been organized into four groups of different problem types:

- *G problems:* These could be of General interest and it may be worthwhile to browse through them, even without intending to solve them.
- *E problems:* These are regular pencil-and-paper Exercises to check the basic techniques of the chapter.
- *T problems:* These are Theoretically oriented problems and typically more difficult than the E problems.
- *D problems:* In these problems the reader is asked to fill in technical Details that were glossed over in the text.

Acknowledgments

Any author of a technical book is indebted to the people who taught him the subject and to the people who made the writing possible. My interest in system identification goes back to my years as a graduate student at the Automatic Control Department in Lund. Professor Karl Johan Åström introduced me to the subject, and his serious attitude to research has always been a reference model for me. Since then I have worked with many other people who added to my knowledge of the subject. I thank, therefore, my previous coauthors (in alphabetical order) Anders Ahlén, Peter Caines, David Falconer, Farhat Fnaiech, Ben Friedlander, Michel Gevers, Keith Glover, Ivar Gustavsson, Tom Kailath, Stefan Ljung, Martin Morf, Ton van Overbeek, Jorma Rissanen, Torsten Söderström, Göte Solbrand, Eva Trulsson, Bo Wahlberg, Don Wiberg, and Zhen-Dong Yuan.

The book has developed from numerous seminars and several short courses that I have given on the subject world-wide. Comments from the seminar participants have been instrumental in my search for a suitable structure and framework for presenting the topic.

Several persons have read and used the manuscript in its various versions and given me new insights. First, I would like to mention: Michel Gevers, who taught from an early version and gave me invaluable help in revising the text; Robert Kosut and Arye Nehorai, who taught from the manuscript at Stanford and Yale, respectively; and Jan Holst, who lead a discussion group with it at Denmark's Technical University, and also gathered helpful remarks. I co-taught the course at MIT with Fred Schweppe, and his lectures as well as his comments, led to many clarifying changes in the manuscript. Students in various courses also provided many useful comments. I mention in particular George Hart, Juan Lavalle, Ivan Mareels, Brett Ridgely, and Bo Wahlberg. Several colleagues were also kind enough to critique the manuscript. I am especially grateful to Hiro Akaike, Chris Byrnes, Peter Falb, Meir Feder, Gene Franklin, Claes Källström, David Ruppert, Torsten Söderström, Petre Stoica, and Peter Whittle.

Svante Gunnarsson and Sten Granath made the experiments described in Section 17.2, Bo Wahlberg contributed to the frequency-domain interpretations, and Alf Isaksson prepared Figure 13.9.

The preparation of the manuscript's many versions was impeccably coordinated and, to a large extent, also carried out by Ingegerd Stenlund. She had useful help from Ulla Salaneck and Karin Lönn. Marianne Anse-Lundberg expertly prepared all the illustrations. I deeply appreciate all their efforts.

Writing a book takes time, and I probably would not have been able to finish this one had I not had the privilege of sabbatical semesters. The first outline of this book was written during a sabbatical leave at Stanford University in 1980–1981. I wrote a first version of what turned out to be the last edition during a minisabbatical visit to the Australian National University in Canberra in 1984. The writing was completed during 1985–1986, the year I spent at MIT. I thank Tom Kailath, Brian Anderson and Sanjoy Mitter (and the U.S. Army Research Office under contract DAAG–29–84-K–005) for making these visits possible and for providing inspiring working conditions. My support from the Swedish National Board for Technical Development (STUF) has also been important.

Sabbatical or not, it was unavoidable that a lot of the writing (not to mention the thinking!) of the book had to be done on overtime. I thank my family, Ann-Kristin, Johan, and Arvid, for letting me use their time.

Lennart Ljung
Linköping, Sweden

Preface to the Second Edition

During the 10 years since the first edition appeared, System Identification has developed considerably. I have added new material in the second edition that reflects my own subjective view of this development. The new sections deal with *Subspace methods* for multivariable state-space models, with *Nonlinear Black-box models*, such as neural networks and fuzzy models, with *Frequency-domain methods*, with *input design, in particular periodic inputs*, and with more comprehensive discussions of *identification in closed loop* and of *data preprocessing*, including missing data and merging of data sets. In addition, the book has been updated and several chapters have been rewritten.

The new methods I have learnt directly from persons who have developed them, and they have also been kind enough to review my presentation: Urban Forssell, Michel Gevers, Alf Isaksson, Magnus Jansson, Peter Lindskog, Tomas McKelvey, Rik Pintelon, Johan Schoukens, Paul van den Hof, Peter Van Overschee, Michel Verhaegen, and Mats Viberg. The nonlinear black box material I learnt from and together with Albert Benveniste, Bernard Delyon, Pierre-Yves Glorennec, Håkan Hjalmarsson, Anatoli Juditsky, Jonas Sjöberg, and Qinghua Zhang as we prepared a tutorial survey for AUTOMATICA. The presentation in Chapter 5 is built upon this survey. Håkan Hjalmarsson and Erik Weyer have pointed out important mistakes in the first edition and helped me correct them. Pierre Carrette and Fredrik Gustafsson have read the manuscript and provided me with many useful comments. Ulla Salaneck has helped me keeping the project together and she also typed portions of the new material. I thank all these people for their invaluable help in my work.

I am grateful to SAAB AB and to Stora Skutskär Pulp Factory for letting me use data from their processes. My continued support from the Swedish Research Council for Engineering Sciences has also been instrumental for my work.

Software support is necessary for any User of System Identification. The examples in this book have been computed using MathWork's SYSTEM IDENTIFICATION TOOLBOX for use with MATLAB. Code and data to generate the examples can be found at the book's home page

`http://www.control.isy.liu.se/~ljung/sysid`

Readers are invited to this home page also for other material of interest to users of System Identification.

Operators and Notational Conventions

$\arg(z)$ = argument of the complex number z

$\arg\min f(x)$ = value of x that minimizes $f(x)$

$x_N \in AsF(n, m)$: sequence of random variables x_N converges in distribution to the F-distribution with n and m degrees of freedom

$x_N \in AsN(m, P)$: sequence of random variables x_N converges in distribution to the normal distribution with mean m and covariance matrix P; see (I.17)

$x_N \in As\chi^2(n)$: sequence of random variables x_N converges in distribution to the χ^2 distribution with n degrees of freedom

$\text{Cov}\, x$ = covariance matrix of the random vector x; see (I.4)

$\det A$ = determinant of the matrix A

$\dim \theta$ = dimension (number of rows) of the column vector θ

Ex = mathematical expectation of the random vector x; see (I.3)

$\overline{E}x(t) = \lim_{N\to\infty} \frac{1}{N} \sum_{t=1}^{N} Ex(t)$; see (2.60)

$O(x)$ = ordo x: function tending to zero at the same rate as x

$o(x)$ = small ordo x: function tending to zero faster than x

$x \in N(m, P)$: random variable x is normally distributed with mean m and covariance matrix P; see (I.6)

$\text{Re}\, z$ = real part of the complex number z

$\mathcal{R}(f)$ = range of the function f = the set of values that $f(x)$ may assume

$\mathbf{R}^d$ = Euclidian d-dimensional space

$x = \text{sol}\{f(x) = 0\}$: x is the solution (or set of solutions) to the equation $f(x) = 0$

$\text{tr}(A)$ = trace (the sum of the diagonal elements) of the matrix A

$\text{Var}\, x$ = variance of the random variable x

A^{-1} = inverse of the matrix A

A^T = transpose of the matrix A

A^{-T} = transpose of the inverse of the matrix A

$\overline{z}$ = complex conjugate of the complex number z

(superscript * is not used to denote transpose and complex conjugate: it is used only as a distinguishing superscript)

$y_s^t = \{y(s), y(s+1), \cdots, y(t)\}$

$y^t = \{y(1), y(2), \cdots y(t)\}$

$U_N(\omega)$ = Fourier transform of u^N; see (2.37)

$R_v(\tau) = \overline{E}v(t)v^T(t-\tau)$; see (2.61)

$R_{sw}(\tau) = \overline{E}s(t)w^T(t-\tau)$; see (2.62)

$\Phi_v(\omega)$ = spectrum of v = Fourier transform of $R_v(\tau)$; see (2.63)

$\Phi_{sw}(\omega)$ = cross spectrum between s and w = Fourier transform of $R_{sw}(\tau)$; see (2.64)

$\hat{R}_s^N(\tau) = \frac{1}{N}\sum_{t=1}^N s(t)s^T(t-\tau)$; see (6.10)

$\hat{\Phi}_u^N(\omega)$ = estimate of the spectrum of u based on u^N; see (6.48)

$\hat{v}(t|t-1)$ = prediction of $v(t)$ based on v^{t-1}

$\frac{d}{d\theta}V(\theta)$ = gradient of $V(\theta)$ with respect to θ: a column vector of dimension $\dim\theta$ if V is scalar valued

$V'(\theta)$ = gradient of V with respect to its argument

$\ell'_\varepsilon(\varepsilon, \theta)$ = partial derivative of ℓ with respect to ε

δ_{ij} = Kronecker's delta: zero unless $i = j$

$\delta(k) = \delta_{k0}$

$\mathcal{B}(\theta_0, \varepsilon)$ = ε neighborhood of θ_0 : $\{\theta \,|\, |\theta - \theta_0| < \varepsilon\}$

$\triangleq$ = the left side is defined by the right side

$|\cdot|$ = (Euclidian) norm of a vector

$\|\cdot\|$ = (Frobenius) norm of a matrix (see 2.91)

SYMBOLS USED IN TEXT

This list contains symbols that have some global use. Some of the symbols may have another local meaning.

$D_{\mathcal{M}}$ = set of values over which θ ranges in a model structure. See (4.122)

D_c = set into which the θ-estimate converges. See (8.23)

$e(t)$ = disturbance at time t; usually $\{e(t), t = 1, 2, \ldots\}$ is white noise (a sequence of independent random variables with zero mean values and variance λ)

$e_0(t)$ = "true" driving disturbance acting on a given system S; see (8.2)

$f_e(x)$, $f_e(x, \theta)$ = probability density function of the random variable e; see (I.2) and (4.4)

$G(q)$ = transfer function from u to y; see (2.20)

$G(q, \theta)$ = transfer function in a model structure, corresponding to the parameter value θ; see (4.4)

$G_0(q)$ = "true" transfer function from u to y for a given system; see (8.7)

$\hat{G}_N(q)$ = estimate of $G(q)$ based on Z^N

$G^*(q)$ = limiting estimate of $G(q)$; see (8.71)

$\tilde{G}_N(q)$ = difference $\hat{G}_N(q) - G_0(q)$; see (8.15)

$\mathcal{G}$ = set of transfer functions obtained in a given structure; see (8.44)

$H(q)$, $H(q, \theta)$, $H_0(q)$, $\hat{H}_N(q)$, $H^*(q)$, $\tilde{H}_N(q)$, $\mathcal{H}$: analogous to G but for the transfer function from e to y

$L(q)$ = prefilter for the prediction errors; see (7.10)

$\ell(\varepsilon)$, $\ell(\varepsilon, \theta)$, $\ell(\varepsilon, t, \theta)$ = norm for the prediction errors used in the criterion; see (7.11), (7.16), (7.18)

$\mathcal{M}$ = model structure (a mapping from a parameter space to a set of models); see (4.122)

$\mathcal{M}(\theta)$ = particular model corresponding to the parameter value θ; see (4.122)

$\mathcal{M}^*$ = set of models (usually generated as the range of a model structure); see (4.118).

P_θ = asymptotic covariance matrix of θ; see (9.11)

q, q^{-1} = forward and backward shift operators; see (2.15)

S = "the true system;" see (8.7)

$T(q) = [G(q)\ H(q)]$; see (4.109)

$T(q, \theta)$, $T_0(q)$, $\hat{T}_N(q)$, $\tilde{T}_N(q)$ = analogous to G and H

$u(t)$ = input variable at time t

$V_N(\theta, Z^N)$ = criterion function to be minimized; see (7.11)

$\overline{V}(\theta)$ = limit of criterion function; see (8.28)

$v(t)$ = disturbance variable at time t

$w(t)$ = usually a disturbance variable at time t; the precise meaning varies with the local context

$x(t)$ = state vector at time t; dimension = n

$y(t)$ = output variable at time t

$\hat{y}(t|\theta)$ = predicted output at time t using a model $\mathcal{M}(\theta)$ and based on Z^{t-1}; see (4.6)

$z(t) = [\,y(t) \quad u(t)\,]^T$; see (4.113)

$Z^N = \{u(0), y(0), \ldots, u(N), y(N)\}$

$\varepsilon(t, \theta)$ = prediction error $y(t) - \hat{y}(t|\theta)$

λ = used to denote variance; also, in Chapter 11, the forgetting factor; see (11.6), (11.63)

θ = vector used to parametrize models; dimension = d; see (4.4), (4.5), (5.66)

$\hat{\theta}_N$, θ_0, θ^*, $\tilde{\theta}_N$ = analogous to G

$\varphi(t)$ = regression vector at time t; see (4.11) and (5.67)

$\chi_0(t) = [\,u(t) \quad e_0(t)\,]^T$; see (8.14)

$\psi(t, \theta)$ = gradient of $\hat{y}(t|\theta)$ with respect to θ; a d-dimensional column vector; see (4.121c)

$\zeta(t)$, $\zeta(t, \theta)$ = "the correlation vector" (instruments); see (7.110)

$\mathbf{T}'(q, \theta)$ = gradient of $T(q, \theta)$ with respect to θ (a $d \times 2$ matrix); see (4.125)

ABBREVIATIONS AND ACRONYMS

ARARX: See Table 4.1
ARMA: AutoRegressive Moving Average (see Table 4.1)
ARMAX: AutoRegressive Moving Average with eXternal input (see Table 4.1)
ARX: AutoRegressive with eXternal input (see Table 4.1)
BJ: Box-Jenkins model structure (see Table 4.1)
ETFE: Empirical Transfer Function Estimate; see (6.24)
FIR: Finite Impulse Response model (see Table 4.1)
IV: Instrumental variables (see Section 7.6)
LS: Least Squares (see Section 7.3)
ML: Maximum Likelihood (see Section 7.4)
MSE: Mean Square Error
OE: Output error model structure (see Table 4.1)
PDF: Probability Density Function
PEM: Prediction-Error Method (see Section 7.2)
PLR: PseudoLinear Regression (see Section 7.5)
RIV: Recursive IV (see Section 11.3)
RLS: Recursive LS (see Section 11.2)
RPEM: Recursive PEM (see Section 11.4)
RPLR: Recursive PLR (see Section 11.5)
SISO: Single Input Single Output
w.p.: with probability
w.p. 1: with probability one; see (I.15)
w.r.t.: with respect to

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