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Edited by M. Thoma and A. Wyner

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Lj. T. Grujić, A. A. Martynyuk, M. Ribbens-Pavella

Large Scale Systems Stability under Structural and Singular Perturbations

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To Aleksandr Mikailovich Liapunov
(1857 - 1918)

PREFACE

This book constitutes an up to date presentation and development of stability theory in the Liapunov sense with various extensions and applications.

Precise definitions of well known and new stability properties are given by the authors who present general results on the Liapunov stability properties of non-stationary systems which are out of the classical stability theory framework.

The study involves the use of time varying sets and is broadened to time varying Lur'e-Postnikov systems and singularly perturbed systems.

A remarkable contribution is proposed by the authors who establish necessary and sufficient conditions, similar to Liapunov's one, for uniform absolute stability of time varying Lur'e-Postnikov systems.

Comparison systems and comparison principle are studied, in general and particular forms, and applied to large scale systems.

In that sense various forms of large-scale systems aggregation are studied and various stability criteria are established under different hypotheses : with invariant structure, with Lur'e-Postnikov form and with singularly perturbed properties. Proposed results are broadened to structural stability analysis aimed at studying stability properties under unknown and unpredictable structural variations. The criteria are developed both in algebraic and frequency domains. They essentially reduce the order and complexity of stability problems.

A number of various aggregation-decomposition forms are also considered for power systems from the large scale systems stand point. Precise definitions are introduced by the authors for various stability domains with application to large-scale systems in general and more specifically to power systems. Stability properties and domains of disturbed power systems are established.

A number of examples and applications presented throughout this book illustrate the various results.

According to the amount and importance of definitions and stability criteria presented I consider that this book initially published in Russian, represents the most complete one on stability theory proposed at this date. It interests all people concerned with stability problems in the largest sense and with security, reliability and robustness.

Professor Pierre BORNE
Lille, France

FOREWORD

Poincare's daring idea to obtain qualitative information on motion directly from the differential equation describing it, i.e. without integration, was realized by Liapunov (1892). With his absolute completeness and irreproachable strictness, Liapunov laid the foundations of a conceptually new approach to the qualitative methods of the theory of differential equations. Nowadays, Liapunov's methods are recognized to be among the most powerful means of stability analysis in exact sciences. These, along with the many extensions further developed, contributed to broaden substantially the classes of problems able of being effectively analyzed by the direct method.

The present book contains an essay of development of the general theory of stability in the sense of Liapunov, elements of the stability theory of comparison systems (systems of ordinary differential equations with monotonous right-hand parts), presentation of the general methods for the analysis of structural stability of large-scale systems, including systems with singular perturbations. The Liapunov functions (scalar, vector and matrix) and his direct method for the stability analysis of the unperturbed motion are used throughout the book. Some of the obtained stability results are applied to the analysis of large-scale electric power systems. The stability of these systems is a very important particular case for which the direct criteria show extremely useful.

The Russian version of this monograph was completed in 1982, the 125th anniversary of Liapunov's birthday. Since, new results of the authors have been added and included in the present version. More specifically Chapter V has been thoroughly revised and completed. Overall, this English version is more than a mere translation of the Russian one.

Our permanent concern has been to write up in a clear, easy to comprehend, way, readable for both engineers who need convenient mathematical machinery for large-scale system stability analysis, and mathematicians who are interested in new problems of the qualitative theory of differential equations.

We have tried to do justice to scientists who the first obtained results in various areas of the large-scale systems stability theory, and to refer to their original papers. It is reflected in the Bigliographies which include more than 400 references. Certainly, even such a list is still incomplete. This can be partly explained by the intensive research efforts and developments in the area, and by the extremely wide domains of its application, beginning with technology and finishing with the problems of populational dynamics. We apologize to all those whose work was not cited or properly described.

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Academicians Yu.A. Mitropolsky and Ye.F. Mishchenko, Associate Member of Academy of Sciences of the USSR, V.I. Zubov and Professor Yu.A. Ryabov have got acquainted with the Russian manuscript of the book. Their detailed remarks were extremely valuable. Many conversations of A.A. Martynyuk with Professor A.B. Zhishchenko greatly influenced the presentation of problems connected with the algebraic type of the obtained results.

Collaborators of the Processes Stability Department of the Institute of Mechanics of the Ukrainian Academy of Sciences, I.Yu. Lazareva, Ye.P. Shatilova have contributed much in the course of the technical work on the manuscript. Mrs. M.B. Counet-Lecomte did an outstanding job in typing the final English version. The quality of this camera-ready presentation owes enormously to her expertise.

The authors are cordially thankful to all of them.

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September 1987.

LIST OF BASIC SYMBOLS

All symbols are fully defined at the place where they are first introduced. As a convenience to the reader we have collected some of the more frequently used symbols in several places. The largest collection is the one given below. Additional list for later use can be found in the introduction to Chapter V.

$\mathcal{A}, \mathcal{B}, \mathcal{C}, \ldots$	upper case boldface Script letters denote sets
$\mathcal{A} \setminus \mathcal{B}$	a difference between sets $\mathcal{A}$ and $\mathcal{B}$
$\mathcal{A} \cup \mathcal{B}$, $\mathcal{A} \cap \mathcal{B}$	union, intersection of sets $\mathcal{A}$ and $\mathcal{B}$
$\mathbf{A}, \mathbf{B}, \mathbf{C}, \ldots$	upper case boldface Gothic letters denote matrices with constant or functional entries except $\mathbf{V}$
$\mathbf{a}, \mathbf{b}, \mathbf{c}, \ldots$	lower case boldface Gothic letters denote vectors
$a, b, c, \ldots$	lower case letters denote scalars
$\mathcal{B}_{\Delta}(t_o) = \{\mathbf{x}: \lVert\mathbf{x}\rVert < \Delta(t_o)\}$	the hyperball with the center in the origin and radius equal to $\Delta(t_o)$
$C^{(i,j)}(\mathcal{T}_{\tau} \times \mathcal{N})$	the family of all functions i-times differentiable on $\mathcal{T}_{\tau}$ and j-times differentiable on $\mathcal{N}$
$C(\mathcal{T}_{\tau} \times \mathcal{N})$	the family of all functions continuous on $\mathcal{T}_{\tau} \times \mathcal{N}$
$C^{(i,j)}(\mathcal{T}_{\tau} \times \mathcal{N}, \mathcal{R}^k)$	the family of all functions mapping $\mathcal{T}_{\tau} \times \mathcal{N}$ into $\mathcal{R}^k$ which are in $C^{(i,j)}(\mathcal{T}_{\tau} \times \mathcal{N})$

$D^{+}v(t,\mathbf{x}) = \limsup \left\{\frac{v[t+\theta,\chi(t+\theta;t,\mathbf{x})]-v(t,\mathbf{x})}{\theta} : \theta\to 0^{+}\right\}$	the upper right-hand Dini derivative of v along χ at $(t,\mathbf{x})$
$D_{+}v(t,\mathbf{x}) = \liminf \left\{\frac{v[t+\theta,\chi(t+\theta;t,\mathbf{x})]-v(t,\mathbf{x})}{\theta} : \theta\to 0^{+}\right\}$	the lower right-hand Dini derivative of v along χ at $(t,\mathbf{x})$
$D^{*}v(t,\mathbf{x})$	denotes that both $D^{+}v(t,\mathbf{x})$ and $D_{+}v(t,\mathbf{x})$ can be used
$d(\mathbf{x},A) = \inf[\Vert\mathbf{x}-\mathbf{y}\Vert : \mathbf{y}\in A]$	a distance from $\mathbf{x}$ to A
$d(A,B) = \max\{\sup[d(\mathbf{x},A):\mathbf{x}\in B], \sup[d(\mathbf{x},B):\mathbf{x}\in A]\}$	a distance between A and B
$\mathbf{f}: R\times R^{n}\to R^{n}$	a vector function mapping $R\times R^{n}$ into R^{n}
I_{k}	the $k\times k$ identity matrix
$He(\cdot)$	the Hermitian part of a matrix $(\cdot)$
$i,j,k,\ldots,N$	integers
$j=\sqrt{-1}$	the imaginary unit
$K_{[0,\xi]}$	the class of comparison functions on $[0,\xi]$
N	a time-invariant neighbourhood of the origin of R^{n}, or the set of the first N natural numbers : $N = \{1,2,\ldots,N\}$
$N(t)$	a neighbourhood of the origin at $t\in R$
$N_{\tau} = \{(t,\mathbf{x}): t\in T_{\tau}, \mathbf{x}\in N(t)\}$	a neighbourhood of the origin of $R\times R^{n}$ over T_{τ}
$N = \{(t,\mathbf{x}): t\in R, \mathbf{x}\in N(t)\}$	a neighbourhood of the origin of $R\times R^{n}$
$O = \{\mathbf{x}: \mathbf{x}=\mathbf{0}\}$	the singleton containing the origin of R^{n}
R	the set of all real numbers
$R_{+} = [0,+\infty[\subset R$	the set of all non-negative numbers
$\mathring{R}_{+} =]0,+\infty[$	the set of all positive real numbers

R^k	k-th dimensional real vector space
$R \times R^n$	the cartesian product of R and R^n
S	a time-invariant subset of R^n
$S(t)$	a time-varying subset of R^n
S_s	a structural set of a system defining all system structural variations via structural matrices $\mathbf{S}$
$S_\tau = \{(t,\mathbf{x}): t \in T_\tau, \mathbf{x} \in S(t)\}$	a subset of $T_\tau \times R^n$ associated with $S(t)$
$S = \{(t,\mathbf{x}): t \in R, \mathbf{x} \in S(t)\}$	a subset of $R \times R^n$ associated with $S(t)$, $S_\tau = S$ iff $T_\tau = R$
$\operatorname{sign} \zeta = \zeta \lvert\zeta\rvert^{-1}$ iff $\zeta \neq 0$ and $\operatorname{sign} 0 = 0$	the signum type nonlinearity
$\bar{T}_o = [t_o, +\infty] = \{t: t_o \leq t \leq +\infty\}$	the largest time interval beginning with t_o
$T = [-\infty, +\infty] = \{t: -\infty \leq t \leq +\infty\}$	the largest time interval
$T_o^* =]t_o, +\infty] = \{t: t_o < t \leq +\infty\}$	the left semi-open unbounded time interval associated with t_o
$T_o = [t_o, +\infty[= \{t: t_o \leq t < +\infty\}$	the right semi-open unbounded time interval associated with t_o
$T_\tau = [\tau, +\infty[= \{t: \tau \leq t < +\infty\}$, $\tau \in R$	the right semi-open unbounded time interval associated with τ
$T_i \subseteq R$	a time interval of all initial moments t_o under consideration (or, of all admissible t_o)
$t \in R$	a time variable, instant
$t_o \in R$	an initial instant
$V_\zeta(t)$	is the largest connected neighbourhood of $\mathbf{x}=0$ associated with a positive definite v such that $v(t,\mathbf{x}) < \zeta$, $\forall \mathbf{x} \in V_\zeta(t)$
$\mathbf{x}(t)$	a state vector of a system at $t \in R$, $\mathbf{x} = (x_1, x_2, \ldots, x_n)^T$
$\alpha, \beta, \gamma, \ldots$	Greek letters denote scalars unless otherwise specified

$\Delta_M(t_o) =$ $\mathrm{Max}\ \{\Delta: \Delta=\Delta(t_o), \forall\rho>0, \forall x_o\in B_\Delta, \exists\ \tau(t_o, x_o, \rho)\in]0,+\infty[, \ni\chi(t;t_o,x_o)\in B_\rho, \forall t\in T_\tau\}$	the maximal Δ obeying the definition of attractivity
$\delta_M(t_o,\epsilon) =$ $\mathrm{Max}\ \{\delta:\delta=\delta(t_o,\epsilon)\ni x_o\in B_\delta(t_o,\epsilon) \Rightarrow \chi(t;t_o,x_o)\in B_\epsilon, \forall t\in T_o\}$	the maximal δ obeying the definition of stability
∂S	the boundary of a set S
$\bar{S}$	the closure of a set S
ϕ	empty set
$\tau_m(t_o,x_o,\rho) =$ $\mathrm{Min}\ \{\tau:\tau=\tau(t_o,x_o,\rho) \ni\chi(t;t_o,x_o)\in B_\rho, \forall t\in T_\tau\}$	the minimal τ satisfying the definition of attractivity
$\lambda_i(\cdot)$	the i-th eigenvalue of a matrix $(\cdot)$
$\Lambda_M(\cdot)$	the maximal eigenvalue of a matrix $(\cdot)$
$\lambda_m(\cdot)$	the minimal eigenvalue of a matrix $(\cdot)$
$\chi(t;t_o,x_o)$	a motion of a system at $t\in R$ iff $x(t_o)=x_o$, $\chi(t_o;t_o,x_o)\equiv x_o$
$\Rightarrow$	"implies"
$\Leftrightarrow$	"iff" ("if and only if")
$\forall$	"for every"
$\exists$	"there exist(s)"
$\nexists$	"there does (do) not exist"
$\ni$	"such that"
$\in$	"belongs to"
$\Vert\ \Vert$	the Euclidean norm
[ ]	denotes a closed interval
] [	denotes an open interval
( )	a general interval which can be semi-open, open, or closed.

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