
Preface

Discontinuous control systems are the oldest type of control system and the most widespread type of nonlinear control system. The theory of discontinuous control, and the theory of relay feedback systems in particular, is usually considered a mature subject. However, many problems in discontinuous control theory still remain open. One problem involves the input-output properties of these systems, knowledge of which is extremely important to every application.

Two types of discontinuous control systems are studied in this book. The first is the so-called relay feedback system, which normally encompasses relay servomechanisms, various on-off controllers, sigma-delta modulators, relay feedback tests used for process dynamics identification, and controller tuning. Relay systems are often considered the main type of nonlinear system, which is evident by the enormous amount of house temperature control systems (that are usually implemented as on-off controllers) that exist. The theory of relay systems is an old subject. The problem of analysis of relay feedback systems was first considered by L. MacColl in 1945 [71]; the study was motivated by the development of relay servomechanisms of missile thrusters on the one hand and vibrational voltage regulators on the other. MacColl's analysis was based on an approximate approach close to the describing function method. Later, exact methods of analysis of relay feedback systems were developed, the most well-known of which is the Tsytkin locus [94]. The exact approach developed by Tsytkin, however, did not consider the servo aspect of relay feedback control. Its purpose was limited to finding periodic motions that may occur in a relay system in an autonomous mode or under external excitation. The servo problem in relay feedback control has not received due attention since. In recent years, a relatively small number of publications on relay feedback systems theory have appeared, in which only autonomous modes, and not servo modes, were considered.

The second type of discontinuous control system considered in this volume is the so-called sliding mode control system, which includes the conventional first-order sliding mode control system and the second-order sliding mode

system. Sliding mode systems are a specific type of discontinuous control system. There are a number of references on sliding mode control (systems) devoted to this type of discontinuous control, the most well-known of which is by V.I. Utkin [97]. This subject has been an active research area during the past three decades. However, the present volume offers a different treatment of sliding modes than the traditional approach. The approach presented in this work allows accounting for the presence of so-called parasitic dynamics in control loops and uncovers mechanisms of chattering and non-ideal closed-loop performance in sliding mode control systems.

The purpose of this book is to present a new frequency-domain theory of discontinuous control systems in which the control systems are viewed and studied as servo systems. This theory involves a unified frequency-domain approach to both analysis of possible self-excited periodic motions and analysis of input-output properties of discontinuous control systems. The servo aspect of control is very important and was underestimated in the past. Knowledge of input-output properties is as important as knowledge of autonomous behavior in discontinuous control systems (self-excited oscillations). In fact, these two aspects complement each other. For example, in on-off house temperature control system design, it is equally important to know both the frequency of relay switching and how the average indoor temperature might change in response to the outdoor temperature. The latter problem can be solved only if the servo aspect of the system is considered.

The core approach in this present book is the frequency-domain method called the locus of a perturbed relay system (LPRS). This method offers an exact analysis of both oscillatory properties and servo properties of relay feedback systems. The method is analytical and very convenient for design applications, which is illustrated by the numerous examples provided. This approach is exact, which allows for overcoming the drawback of the well-known describing function method. Further, overcoming the constraint of the filtering hypothesis of the describing function method allows for extending the proposed theory to analysis of motion in sliding mode control systems, where the sliding mode itself is now considered as oscillations of either finite or infinite frequency. The analysis provided, however, is not merely another confirmation of available results in sliding mode control theory. The proposed approach offers a more precise treatment of sliding mode control systems than does classic sliding mode control theory. Thus, the proposed approach introduces the theory of *real* sliding mode control versus *ideal* classic sliding mode control.

This book is primarily a research monograph, as it is devoted only to frequency-domain theory of discontinuous control systems, and the theory presented in the book is novel. However, it also has many features of a textbook, as the theory presented covers a relatively large classic nonlinear control area. This theory is illustrated by a number of application examples from different areas of control engineering and is accessible to students with a background in linear control. The included MATLAB code can also make understanding

of the presented theory easy. The book, therefore, can be used by researchers, practitioners, and undergraduate and graduate students.

The material is organized into two parts and appendices. Part I is devoted to the theory of the locus of a perturbed relay system (LPRS) method, and Part II presents applications of the LPRS method. Part I comprises five chapters. Chapter 1 poses the problem and outlines the scope and method of analysis, which is presented in detail in the following chapter. In Chapter 3, the results obtained in Chapter 2 for slow inputs are extended to the analysis of the system response to relatively fast input signals. Chapter 4 presents frequency-domain theory of sliding mode control systems. The sliding mode analysis follows the methodology developed in the preceding chapters. Chapter 5 is devoted to an emerging area of sliding mode control — second-order sliding mode control systems analysis.

Part II gives a number of applications of LPRS theory. These applications include the electro-pneumatic servomechanism (Chapter 6), the relay feedback test and its application to process dynamics identification and controller tuning (Chapter 7), the sliding mode differentiator and dynamic compensator (Chapter 8), and the sliding mode observer (Chapter 9). Some of these applications have been in engineering practice for many years, and other applications are relatively new. In general, the material of each chapter in the second part of the book is independent and only makes general references to topics presented in the first part. The Appendix contains the derivations of the LPRS, the proofs of the theorems, and the MATLAB code used in the text for the LPRS computations.

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