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Jinkun Liu
Xinhua Wang

机械系统先进滑模变结构控制

设计、分析及MATLAB仿真

Advanced Sliding Mode Control for Mechanical Systems

Design, Analysis and MATLAB Simulation

清华大学出版社
Springer

内 容 简 介

本书从 MATLAB 仿真角度系统地介绍了机械系统先进滑模变结构控制的基本设计方法，是作者多年来从事控制系统教学与科研工作的结晶，同时融入了国内外同行的新近成果。

全书共分 12 章，包括滑模变结构控制基本设计方法、基于名义模型的滑模控制、基于线性矩阵不等式和反演的滑模控制、离散滑模控制、动态滑模控制、自适应滑模控制、终端滑模控制、基于观测器的滑模控制、模糊滑模控制、神经网络滑模控制以及针对机器人和飞行器的滑模控制。每种控制方法都通过 MATLAB 仿真程序进行了仿真分析。

本书适于从事生产过程自动化、计算机应用、机械电子和电气自动化领域工作的工程技术人员阅读，也可作为大专院校相关专业学生的参考教材。

图书在版编目(CIP)数据

机械系统先进滑模变结构控制：设计、分析及MATLAB仿真＝Advanced Sliding Mode Control for Mechanical Systems: Design, Analysis and MATLAB Simulation: 英文/刘金琨，王新华著. --北京：清华大学出版社，2011.11
ISBN 978-7-302-24827-9

I.①机…　II.①刘…　②王…　III.①机械系统-变结构控制器-研究-英文　IV.①TM571.6

中国版本图书馆 CIP 数据核字(2011)第 033028 号

责任编辑：赵彤伟
责任校对：刘玉霞
责任印制：李红英
出版发行：清华大学出版社　　**地　　址**：北京清华大学学研大厦 A 座
http://www.tup.com.cn　　**邮　　编**：100084
社 总 机：010-62770175　　**邮　　购**：010-62786544
投稿与读者服务：010-62776969，c-service@tup.tsinghua.edu.cn
质 量 反 馈：010-62772015，zhiliang@tup.tsinghua.edu.cn
印 装 者：北京雅昌彩色印刷有限公司
经　　销：全国新华书店
开　　本：153×235　**印　张**：23　**字　数**：515 千字
版　　次：2011 年 11 月第 1 版　　**印　　次**：2011 年 11 月第1 次印刷
印　　数：1～1000
定　　价：89.00 元

产品编号：033911-01

Preface

In the formulation of any control problem there will be typical discrepancies between the actual plant and the mathematical model developed for the controller design. This mismatch may be due to unmodelled dynamics, variation in system parameters or the approximation of complex plant behavior by a straightforward model. The engineer must ensure the practical applicability of the resulting controller to produce the required performance levels despite such plant /model mismatches. This has led to an intense interest in the development of robust control methods to solve this problem. One particular approach to robust controller design is the sliding mode control methodology.

One of the most intriguing aspects of the sliding mode is the discontinuous nature of the control action. The primary function of each of the feedback channels is to switch between two distinctively different system structures (or components) such that a new type of system motion called the sliding mode exists in a manifold. This peculiar system characteristic is claimed to result in superb system performance which includes insensitivity to parameter variations and complete rejection of disturbances.

Sliding mode control is a specific type of variable structure control. The control systems are designed to drive and then constrain the system state to lie within a neighborhood of the switching function. There are two main advantages to this approach. Firstly, the dynamic behavior of the system may be tailored by the particular choice of switching function. Secondly, the closed-loop response becomes totally insensitive to a particular class of uncertainty. The latter invariance property clearly makes the methodology appropriate for robust control. Additionally, the ability to specify performance directly makes the sliding mode control attractive from the design perspective.

The sliding mode design approach consists of two components. The first involves the design of a switching function so that the sliding motion satisfies design specifications. The second is concerned with the selection of a control law to make the switching function attractive to the system state. Note that this control law is not necessarily discontinuous.

The chattering phenomenon is generally perceived as a motion which oscillates about the sliding manifold. There are two possible mechanisms which produce such a motion. Firstly, in the absence of switching nonidealities such as delays, i.e., the switching device is switching ideally at an infinite frequency, the presence of a parasitic dynamics in series with the plant causes a small amplitude high-frequency oscillation to appear in the neighborhood of the sliding manifold. These parasitic dynamics represent the fast actuator and sensor dynamics. Secondly, the switching nonidealities alone can cause such high-frequency oscillations.

It is our goal to accomplish these objectives:

- Provide reasonable methods of the chattering phenomenon alleviating;
- Offer a catalog of implementable robust sliding mode control design solutions for engineering applications;
- Provide advanced sliding mode controller design methods and their stability analysis;
- For each sliding mode control algorithm, we offer its simulation example and Matlab program.

This book provides the reader with a thorough grounding in the sliding mode controller design. More advanced theoretical results are developed on the basis. Typical sliding mode controller design is emphasized using Matlab simulation. In this book, concrete case studies, which present the results of sliding mode controller implementations are used to illustrate the successful practical application of the theory.

The book is structured as follows. Chapter 1 introduces the concept of sliding mode control and illustrates the attendant features of robustness and performance specification using a straightforward example and graphical exposition, several typical sliding mode controllers for continuous system are introduced, and concrete stability analysis, simulation examples and Matlab programs are given. Chapter 2 introduces several normal sliding mode controllers design, including sliding mode control based on nominal model, global sliding mode control, sliding mode control based on linearization feedback technology and sliding mode control based on low pass filter. Chapter 3 introduces two kind of advanced sliding mode controllers design, including sliding mode control based on LMI technology and sliding mode control based on backstepping technology. Chapter 4 introduces discrete sliding mode controller design, including discrete sliding mode controller design analysis and a kind of discrete sliding mode controller design based on disturbance observer. Chapter 5 introduces a kind of dynamic sliding mode controller design. Chapter 6 introduces a kind of adaptive sliding mode controller design for mechanical systems. Chapter 7 introduces three kind of terminal sliding mode controllers design, including a typical terminal sliding mode controller design, a nonsingular terminal sliding mode controller design and a fast terminal sliding mode controller design. Chapter 8 introduces sliding mode control based on several observers; four kinds of observers are used, including high gain observer, extended state observer, integral-chain differentiator, disturbance observer and delayed output observer. Chapter 9 introduces four kinds of fuzzy sliding mode controllers design, including fuzzy sliding mode control based on equivalent control, sliding mode control based on fuzzy switch-gain regulation, sliding mode control based on fuzzy system approximation and adaptive fuzzy control based on fuzzy compensation for manipulator. Chapter 10 introduces two kinds of neural network sliding mode controllers design, including sliding mode controller design based on RBF neural network approximation and adaptive RBF network sliding mode control for manipulator. Chapter 11 introduces three kinds of sliding mode controllers design for robot, including sliding mode controller design based on input-output stability, sliding mode controller design based on computed torque method and adaptive sliding mode controller design for manipulator. Chapter 12 introduces two kinds of sliding mode controllers design for aircraft, which are sliding mode control for helicopter and sliding mode control for an uncertain VTOL aircraft.

Welcome to find and download the simulation programs of the book from http://ljk.buaa.edu.cn/ or email to ljk@buaa.edu.cn.

Contents

1 Introduction

Jinkun Liu
Beijing University of Aeronautics and Astronautics
P.R.China
E-mail: ljk@buaa.edu.cn

Xinhua Wang
National University of Singapore
Singapore
E-mail: wangxinhua04@gmail.com

Abstract This chapter introduces the concept of sliding mode control and illustrates the attendant features of robustness and performance specification using a straightforward example, several typical sliding mode controllers for continuous system are given, a concrete stability analysis, simulation examples and Matlab programs are given too.

Keywords sliding mode control, sliding surface, Reaching Law, quasi-sliding mode, equivalent control

One of the methods used to solve control problems are the sliding mode techniques. These techniques are generating greater interest.

This book provides the reader with an introduction to classical sliding mode control design examples. Fully worked design examples, which can be used as tutorial material, are included. Industrial case studies, which present the results of sliding mode controller implementations, are used to illustrate successful practical applications of the theory.

Typically, discrepancies may occur between the actual plant and the mathematical model developed for the controller design. These mismatches may be due to various factors. The engineer's role is to ensure required performance levels despite such mismatches. A set of robust control methods have been developed to eliminate any discrepancy. One such approach to the robust control controller design is called the sliding mode control (SMC) methodology. This is a specific type of variable structure control system (VSCS).

In the early 1950s, Emelyanov and several co-researchers such as Utkins and Itkis[1] from the Soviet Union, proposed and elaborated the variable structure control

(VSC) with sliding mode control. During the past decades, VSC and SMC have generated significant interest in the control research community.

SMC has been applied into general design method being examined for wide spectrum of system types including nonlinear system, multi-input multi-output (MIMO) systems, discrete-time models, large-scale and infinite-dimension systems, and stochastic systems. The most eminent feature of SMC is it is completely insensitive to parametric uncertainty and external disturbances during sliding mode[2].

VSC utilizes a high-speed switching control law to achieve two objectives. Firstly, it drives the nonlinear plant's state trajectory onto a specified and user-chosen surface in the state space which is called the sliding or switching surface. This surface is called the switching surface because a control path has one gain if the state trajectory of the plant is "above" the surface and a different gain if the trajectory drops "below" the surface. Secondly, it maintains the plant's state trajectory on this surface for all subsequent times. During the process, the control system's structure varies from one to another and thereby earning the name variable structure control. The control is also called as the sliding mode control[3] to emphasize the importance of the sliding mode.

Under sliding mode control, the system is designed to drive and then constrain the system state to lie within a neighborhood of the switching function. Its two main advantages are (1) the dynamic behavior of the system may be tailored by the particular choice of switching function, and (2) the closed-loop response becomes totally insensitive to a particular class of uncertainty. Also, the ability to specify performance directly makes sliding mode control attractive from the design perspective.

Trajectory of a system can be stabilized by a sliding mode controller. The system states "slides" along the line $s=0$ after the initial reaching phase. The particular $s=0$ surface is chosen because it has desirable reduced-order dynamics when constrained to it. In this case, the $s=cx_1+\dot{x}_1$, $c>0$ surface corresponds to the first-order LTI system $\dot{x}_1=-cx_1$, which has an exponentially stable origin. Now, we consider a simple example of the sliding mode controller design as under.

Consider a plant as

$$J\ddot{\theta}(t)=u(t) \tag{1.1}$$

where J is the inertia moment, $\ddot{\theta}(t)$ is the angle signal, and $u(t)$ is the control input.

Firstly, we design the sliding mode function as

$$s(t)=ce(t)+\dot{e}(t) \tag{1.2}$$

where c must satisfy the Hurwitz condition, $c>0$.

The tracking error and its derivative value are

$$e(t)=\theta(t)-\theta_{\mathrm{d}}(t),\ \ \dot{e}(t)=\dot{\theta}(t)-\dot{\theta}_{\mathrm{d}}(t)$$

where $\theta(t)$ is the practical position signal, and $\theta_{\rm d}(t)$ is the ideal position signal.

Therefore, we have

$$\dot{s}(t) = c\dot{e}(t) + \ddot{e}(t) = c\dot{e}(t) + \ddot{\theta}(t) - \ddot{\theta}_{\rm d}(t) = c\dot{e}(t) + \frac{1}{J}u - \ddot{\theta}_{\rm d}(t) \tag{1.3}$$

and

$$s\dot{s} = s\left(c\dot{e} + \frac{1}{J}u - \ddot{\theta}_{\rm d}\right)$$

Secondly, to satisfy the condition $s\dot{s} < 0$, we design the sliding mode controller as

$$u(t) = J(-c\dot{e} + \ddot{\theta}_{\rm d} - \eta\,\mathrm{sgn}(s)),\ \ \mathrm{sgn}(s) = \begin{cases} 1, & s > 0 \\ 0, & s = 0 \\ -1, & s < 0 \end{cases} \tag{1.4}$$

Then, we get

$$s\dot{s} = -\eta \,|\, s \,| < 0$$

A simulation example is presented for explanation. Consider the plant as

$$J\ddot{\theta}(t) = u(t)$$

where $J = 10$.

The initial state is set as [0.5 1.0] after choosing the position ideal signal $\theta_{\rm d}(t) = \sin t$. Using controller Eq. (1.4) wherein $c = 0.5$, $\eta = 0.5$ the results are derived as shown in Fig. 1.1 – Fig. 1.3.

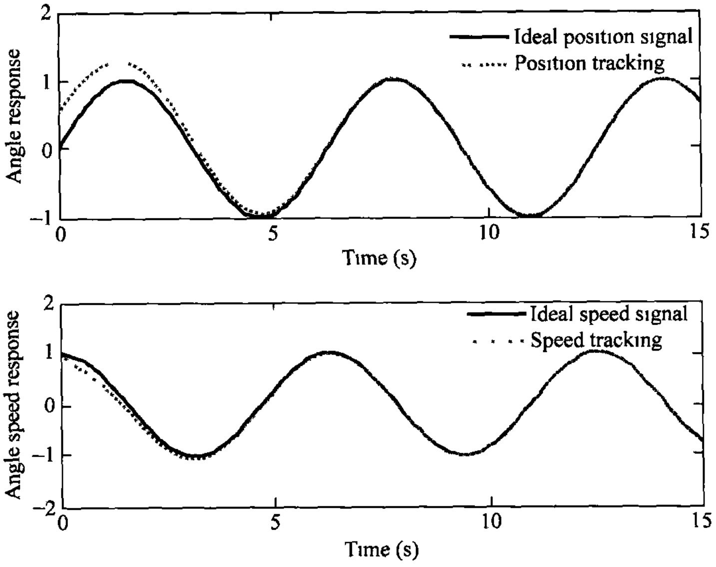


Figure 1.1 Position and speed tracking

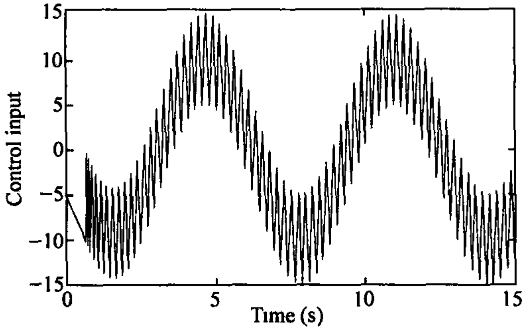


Figure 1.2 Control input

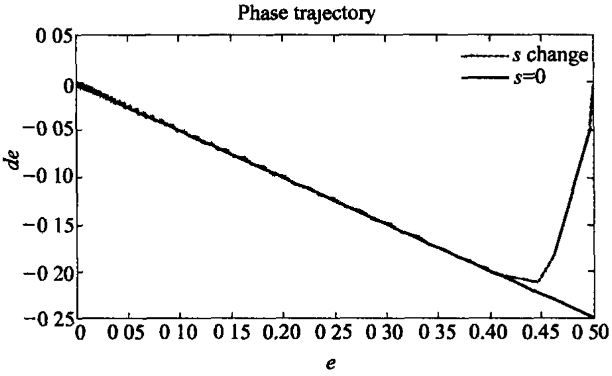
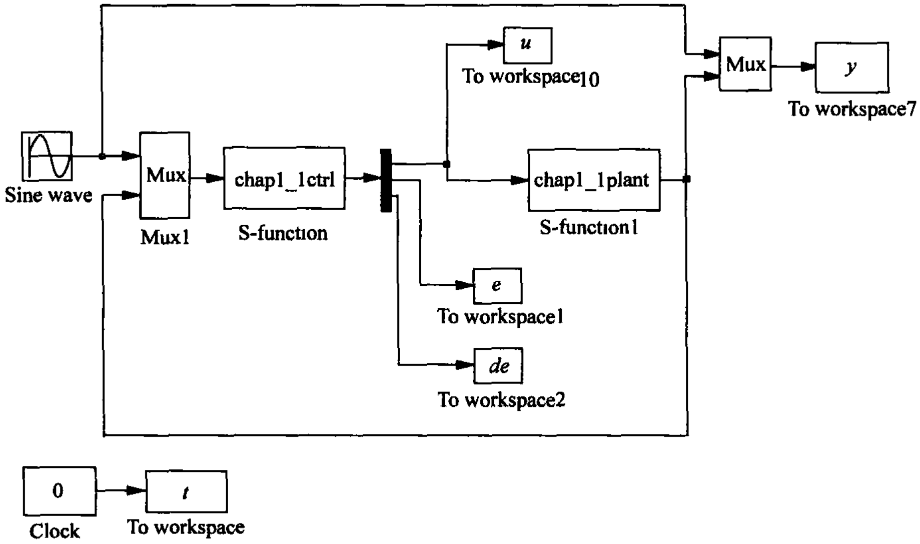


Figure 1.3 Phase trajectory

Simulation programs:

(1) Simulink main program: chap1_1sim.mdl



(2) Controller: chap1_1ctrl.m

```
function [sys,x0,str,ts] = spacemodel(t,x,u,flag)
switch flag,
case 0,
   [sys,x0,str,ts]=mdlInitializeSizes;
case 3,
   sys=mdlOutputs(t,x,u);
case {2,4,9}
   sys=[];
otherwise
   error(['Unhandled flag = ',num2str(flag)]);
end
function [sys,x0,str,ts]=mdlInitializeSizes
sizes = simsizes;
sizes.NumContStates  = 0;
sizes.NumDiscStates  = 0;
sizes.NumOutputs     = 3;
sizes.NumInputs      = 3;
sizes.DirFeedthrough = 1;
sizes.NumSampleTimes = 0;
sys = simsizes(sizes);
x0  = [];
str = [];
ts  = [];
function sys=mdlOutputs(t,x,u)
thd=u(1);
dthd=cos(t);
ddthd=-sin(t);

th=u(2);
dth=u(3);

c=0.5;
e=th-thd;
de=dth-dthd;
s=c*e+de;

J=10;
xite=0.50;
ut=J*(-c*de+ddthd-xite*sign(s));

sys(1)=ut;
sys(2)=e;
sys(3)=de;
```

(3) Plant: chap1_1plant.m

```
function [sys,x0,str,ts]=s_function(t,x,u,flag)
switch flag,
case 0,
   [sys,x0,str,ts]=mdlInitializeSizes;
case 1,
```

```
    sys=mdlDerivatives(t,x,u);
case 3,
    sys=mdlOutputs(t,x,u);
case {2, 4, 9 }
    sys = [];
otherwise
    error(['Unhandled flag = ',num2str(flag)]);
end
function [sys,x0,str,ts]=mdlInitializeSizes
sizes = simsizes;
sizes.NumContStates  = 2;
sizes.NumDiscStates  = 0;
sizes.NumOutputs     = 2;
sizes.NumInputs      = 1;
sizes.DirFeedthrough = 0;
sizes.NumSampleTimes = 0;
sys=simsizes(sizes);
x0=[0.5 1.0];
str=[];
ts=[];
function sys=mdlDerivatives(t,x,u)
J=10;
sys(1)=x(2);
sys(2)=1/J*u;
function sys=mdlOutputs(t,x,u)
sys(1)=x(1);
sys(2)=x(2);
```

(4) Plot program: chap1_1plot.m

```
close all;

figure(1);
subplot(211);
plot(t,y(:,1),'k',t,y(:,2),'r:','linewidth',2);
legend('Ideal position signal','Position tracking');
xlabel('time(s)');ylabel('Angle response');
subplot(212);
plot(t,cos(t),'k',t,y(:,3),'r:','linewidth',2);
legend('Ideal speed signal','Speed tracking');
xlabel('time(s)');ylabel('Angle speed response');

figure(2);
plot(t,u(:,1),'k','linewidth',0.01);
xlabel('time(s)');ylabel('Control input');

c=0.5;
figure(3);
plot(e,de,'r',e,-c'.*e,'k','linewidth',2);
xlabel('e');ylabel('de');
legend('s change','s=0');
title('phase trajectory');
```