Dynamic Analysis and Control System Design of Automatic Transmissions
Other SAE books of interest:

(Product Code: AE-29)

Innovations in Automotive Transmission Engineering
By Martin G. Gabriel
(Product Code: T-109)

Continuously Variable Transmission (CVT)
By Bruce D. Anderson and John R. Maten
(Product Code: PT-125)

For more information or to order a book, contact SAE International at

400 Commonwealth Drive,
Warrendale, PA 15096-0001, USA;

phone 877-606-7323 (U.S. and Canada only) or 724-776-4970 (outside U.S. and Canada);

tax 724-776-0790;

email CustomerService@sae.org;

Dynamic Analysis and Control System Design of Automatic Transmissions

By Shushan Bai, Joel Maguire, and Huei Peng
Contents

Introduction ................................................................. ix

Chapter 1 Automatic Transmissions ........................................ 1
  1.1 Powertrain system .................................................. 2
  1.2 Why is a transmission necessary? .................................. 2
    1.2.1 First perspective: wheel power ................................. 4
    1.2.2 Second perspective: engine operation ......................... 5
  1.3 Different types of automatic transmissions ....................... 6

Chapter 2 Mechanics of Planetary Gear Automatic Transmissions ...... 9
  2.1 Torque converter ................................................... 11
    2.1.1 Description of torque converter ............................... 11
    2.1.2 Dynamic model of engine and torque converter system .... 14
    2.1.3 Backward calculation of torque converter variables ......... 18
  2.2 Planetary gear trains ............................................... 21
    2.2.1 Planetary gear set ............................................. 21
    2.2.2 Planetary gear train ........................................... 23
    2.2.3 Static analysis of planetary gear trains: algebraic method 26
    2.2.4 Static analysis of planetary gear trains: lever analogy method 29
    2.2.5 Static analysis of planetary gear trains: matrix method .... 33
    2.2.6 Gear-shifting mechanics ....................................... 37
    2.2.7 Frictional clutches and their mathematical models .......... 45
    2.2.8 Dynamic equations of simple planetary gear sets ............ 47
    2.2.9 Dynamic equations and simulation model of planetary gear trains 49
    2.2.10 Generic dual-clutch model ................................... 57
    2.2.11 Matrix dual-clutch model .................................... 60
    2.2.12 Inertia balancing ............................................. 62
    2.2.13 Six- and eight-speed planetary automatic transmissions .... 65
Chapter 3  Control of Planetary Gear Automatic Transmissions  ........... 71

3.1 Electrohydraulic pressure control system ................................. 72
  3.1.1 Hydraulic pressure control system and its simulation models .... 73
  3.1.2 Detailed model of PPC solenoids ..................................... 80
  3.1.3 High-flow, direct-acting pressure control valves .................. 81
  3.1.4 Pulse width modulated (PWM) solenoid ............................ 82
  3.1.5 Analytical study of hydraulic clutch control systems .......... 84

3.2 Clutch-to-clutch gear-shift control ...................................... 105
  3.2.1 Gear-shifting mechanics from a control perspective ............. 105
  3.2.2 Hydraulic control system for clutch-to-clutch shift controls ... 110
  3.2.3 Dynamic simulation model for studying clutch-to-clutch shift controls ... 110
  3.2.4 Control of power-on up-shifts ....................................... 110
  3.2.5 Control of power-on down-shifts ................................... 112
  3.2.6 Hydraulic clutch control system design ............................ 112
  3.2.7 Clutch fill detection .................................................. 114
  3.2.8 Acceleration estimator ................................................ 114
  3.2.9 Canceled shifts, transitional shifts, and double-transition shifts. .... 118

3.3 Electronic torque converter clutch control ................................ 121
  3.3.1 Hydraulic system for torque converter clutch control ........... 121
  3.3.2 Electronic control algorithm for torque converter clutch control ... 122

3.4 Dynamic analysis of torque converter clutch damper .................. 126

3.5 Friction launch control ...................................................... 129

3.6 Shift scheduling system ................................................... 135
  3.6.1 Shift map .............................................................. 135
  3.6.2 Dynamic-programming-based shift map generation ............... 137
  3.6.3 Artificial intelligence-based shift scheduling system .......... 142

3.7 Integrated powertrain controls for driveability and fuel economy .... 150
  3.7.1 Overall architecture of integrated powertrain control system ...... 150
  3.7.2 Power-based gear selection ......................................... 152
  3.7.3 Constant-output-torque power-on up-shift control ............... 154

3.8 Centrifugal pendulum vibration absorber ................................ 156
  3.8.1 Basic concept and various designs for CPVA ..................... 157
  3.8.2 Equations of motion of CPVA ...................................... 159
  3.8.3 Simulink model of CPVA .......................................... 161
  3.8.4 Tuning of CPVA ...................................................... 162
  3.8.5 Path of pendulum motion ......................................... 162

Chapter 4  Metal Pushing V-Belt Continuously Variable Transmissions .... 167

4.1 Mechanics of metal pushing V-belt continuously variable transmissions ...... 168

4.2 Controls of metal pushing V-belt continuously variable transmissions .... 170

4.3 Comparison with other ratio control systems ........................... 173

4.4 Feed-forward/feedback control and its application to V-CVT ratio control .... 177
4.4.1 Introduction ................................................................. 177
4.4.2 Limitations of feedback controls ................................. 177
4.4.3 Feedback and feed-forward control systems ................ 179
4.4.4 Design of feed-forward controls ................................ 180
4.4.5 Application: direct pulley pressure control of V-CVT .... 181

Chapter 5 Dynamics and Controls of Dual-Clutch Transmissions ....... 185

5.1 Construction of dual-clutch transmissions ......................... 186
5.2 Synchronizer and its control ........................................... 187
5.3 Dual-clutch module ........................................................... 189
5.4 Control algorithms for DCTs ............................................ 192
5.5 Conclusion ................................................................. 193

References ................................................................. 195
Bibliography ................................................................. 197
Index ................................................................. 201
About the Authors ............................................................. 205
Introduction

Automatic transmissions for automobiles are not simply gearboxes, but have evolved into complex integrated mechanical/electrical/hydraulic/electronic systems for achieving optimal operation of vehicle powertrains. To achieve optimal design and control of modern automatic transmissions, adequate dynamic analyses and control system designs are indispensable. This book exclusively covers the topic of dynamic analysis and control system design of automatic transmissions.

Why is dynamic analysis indispensable for achieving optimal design of automatic transmissions? First, the gear shifting of automatic transmissions is a dynamic process, which involves synchronized torque transfer from one clutch to another, smooth engine speed change, engine torque management, and minimization of output torque disturbance. Dynamic analysis is required to gain the necessary understanding of gear shifting mechanics, and therefore to support the creation of an optimal design for gear shift control systems.

Hydraulic clutch control systems in automatic transmissions are highly dynamic systems. Good dynamic and steady-state behaviors such as response time, stability, repeatability, steady-state error, and robustness are the foundation for achieving premium gearshift quality. The ratio of the continuously variable transmission (CVT) is controlled by hydromechanical ratio feedback systems or electrohydraulic ratio feedback control systems. It is well known that dynamic analysis is absolutely necessary for achieving adequate designs of hydraulic control systems and feedback control systems.

In addition, an automatic transmission also provides isolation of engine torque pulsation to reduce torsional vibrations of the powertrain and driveline. This is achieved through torque converter clutch slip speed control and adequate design of the torque converter clutch damper. In recent years, as a result of pursuing higher engine fuel efficiency, the magnitude of the engine torque pulsation is increasing. To provide the required isolation for this higher level of engine torque pulsations, adequate design of torque converter clutch dampers and torque converter clutch control systems is necessary. This requires the use of dynamic-analysis-based system design as well.

The electronic control algorithms for automatic transmissions include gearshift control algorithms, gear schedule algorithms, torque converter clutch control algorithms, friction launch control algorithms, and integrated powertrain control algorithms. Good designs of such control algorithms must be based on a thorough understanding of the dynamic characteristics of the systems as well as the use of the relevant dynamic analysis and design methodologies.
Introduction

While the basic working principle and the mechanical construction of automatic transmissions has not changed significantly, in recent years the tightening requirements for performance, fuel economy, and drivability, as well as the increasing number of gears, have made the design of transmission controls more challenging. The recent emergence of new types of transmissions such as the Continuously Variable Transmission (CVT), Dual-Clutch Transmission (DCT), and hybrid powertrain has presented added challenges. To respond to such developments in automatic transmission technologies, this book will cover the broad topics of dynamic analysis and control system design of automatic transmissions.

The book starts with the basic mechanics of automatic transmissions, and then covers in detail topics of dynamics and controls of automatic transmissions. The topics covered include gear-shifting mechanics and controls, dynamic modeling of planetary automatic transmissions, design of hydraulic control systems, learning algorithms for achieving consistent shift quality, torque converter clutch controls, the centrifugal pendulum vibration absorber, friction launch controls, shift scheduling and integrated powertrain controls, CVT ratio controls, and DCT controls, to name a few.

The book strives to provide a good balance between theory and practice. For the beginner, the book will provide enough details to understand the basics of dynamics and controls of automatic transmissions. For experienced engineers, this book will provide sufficient theoretical discussions to help elevate the reader’s knowledge to a higher level. The book can be used as a reference handbook for engineers as well as a teaching tool for classrooms. In the sections that cover basic analytical skills, homework is provided for classroom usage.