Modern Flight Dynamics

Anderson Series

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ABOUT THE AUTHOR

David Schmidt was born in Lafayette, Indiana, and attended Purdue University where he received the B. S. degree, cum laude, in Aeronautical Engineering. He later received the M. S. degree from the University of Southern California and the Ph.D from Purdue, both in aerospace engineering. Prior to his graduate studies he served on the technical staff of the Douglas, and then the McDonnell Douglas Missiles and Space Corporation. After first supporting the Apollo program in the development of the Saturn booster, he became Engineering Lead in a preliminary vehicle-design group of the Advanced Systems and Technology Division. Upon completion of his graduate education, he served on the technical staff of the Stanford Research Institute, focusing on research in systems analysis and optimization of air transportation systems.

Dr. Schmidt's academic career began when he joined the faculty of the School of Aeronautics and Astronautics at Purdue, where he served as professor of aeronautics and astronautics for 14 years. He then joined the faculty of Arizona State University, where he served as professor of mechanical and aerospace engineering for six years. He later moved to the University of Maryland at College Park, where he served as professor of aerospace engineering for an additional six years. Lastly, he was invited to join the faculty at the University of Colorado, Colorado Springs, where he helped establish the brand new Department of Mechanical and Aerospace Engineering. He retired from the University of Colorado in 2006, and was appointed Professor Emeritus. While at Arizona State Dr. Schmidt served as the founding director of the Aerospace Research Center in the College of Engineering, and while at the University of Maryland he served as the founding director of the Flight Dynamics and Control Laboratory in the Department of Aerospace Engineering. His teaching was recognized at several of these institutions through many prestigious teaching awards.

In addition to his earlier industrial experience, in 1978 Dr. Schmidt was invited to serve as a summer faculty fellow at the USAF Flight Dynamics Laboratory, Wright-Patterson AFB, and in 1984–85 he served as a visiting sabbatical professor at NASA's Langley Research Center.

He has been an invited member of several national review panels, including the National Academy of Engineering's (NAE) National Research Council (NRC) Review Panel for a Decadal Study of NASA Aeronautics Research, the NAE's NRC Committee on Advanced Supersonic Technology, and the NAE's NRC Committee on High-Speed Research. Furthermore, he has served as an invited member of the USAF Scientific Advisory Board's Science and Technology Panel on Vehicles and Power. In 1996 he served as the General Conference Chair for the Guidance, Navigation and Control Conference of the American

Institute of Aeronautics and Astronautics (AIAA). In 1991–93 he also chaired the AIAA National Technical Committee on Guidance, Navigation, and Control.

Dr. Schmidt is the author of over 200 research articles on flight dynamics, air-traffic control systems, and man-machine control systems, and he has been invited to lecture worldwide on his research. From 2001–2009 he was a member of the AIAA's Education Editorial Board, and from 1988–1991 he was associate editor of the AIAA's *Journal of Dynamics, Guidance, and Control.* He is listed in *Who's Who in America,* and is a member of Tau Beta Pi and Sigma Gamma Tau engineering honor societies. In 1997, Dr. Schmidt received AIAA's highest honor in the field of flight dynamics and control when he was awarded the national Mechanics and Control of Flight Award. He is a fellow of the AIAA.

Dedication

To my parents
and to Karalee, my wife and my best friend

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I am indebted to many people who have greatly contributed to this effort, and I will not be able to mention them all. But to all of you, I am genuinely grateful. I would first like to acknowledge my colleagues and students, both graduate and undergraduate, at Purdue University. My knowledge of the subject of flight dynamics was greatly enhanced during my tenure there. I learned a great deal from my students, and I was constantly inspired by their dedication to learning and to aerospace engineering. Next I would like to acknowledge all my colleagues in the flight dynamics community, by whom I am always being educated. Thanks also to Professor John D. Anderson, Jr. for his first encouraging me to undertake writing this book and for his continued support.

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Finally, any errors remaining in the book are my responsibility alone. Instructors using the book who uncover errors or who have suggestions are asked to bring them to my attention at Schmidt.Flight.Dynamics@gmail.com. I would appreciate hearing from you.

PREFACE

On the Subject

For those who love flying machines, the study of *flight dynamics* is most exciting indeed. When introduced to the topic, at whatever age, students discover that flight dynamics is the essence of aeronautical engineering because it involves the study of the motion—the flight—of the vehicle. This motion defines the vehicle's performance, a topic of enormous significance to the ultimate success of the machine. Thus the excitement generated from the pursuit of this subject follows from both romantic as well as practical reasons.

Flight dynamics is also a study of the complete vehicle, rather than just a component of a vehicle. Hence it is fundamentally the study of a multicomponent system and its dynamics. This study is by necessity multidisciplinary, as depicted in Figure 1. When first introduced to the subject, students may see how some of the other disciplines they've been asked to master actually fit together. Thus it also provides an integrating function.

Although flight dynamics is multidisciplinary, it is still a basic aerospace science. The study is relatively new, compared to aerodynamics, for example. But it has become quite clear that the study of aeronautical or aerospace engineering is incomplete without the thorough treatment of flight dynamics. Many more traditional undergraduate and post-graduate aeronautical engineering curricula have been modified over the last several years to reflect this fact.

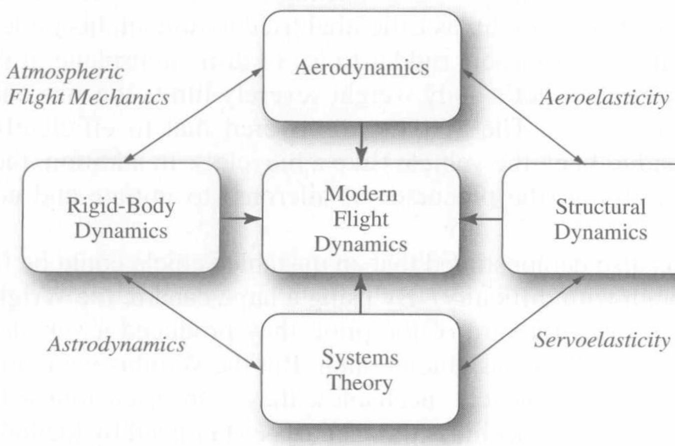

Figure 1 Components of modern flight dynamics.

The theories and methodologies developed in modern flight dynamics are critical in several aspects of flight-vehicle design and development. Notable among these are the determination of the vehicle's configuration, or geometry, the tailoring of its dynamics, especially its handling characteristics (i.e., its "controllability" on the part of a pilot or autopilot), and the design of the autopilot itself.

On the Wrights

The subject of flight dynamics goes back to the Wright brothers, who may be considered the fathers of airplane flight dynamics. When the Wrights developed their revolutionary aircraft, reciprocating engines had already been developed, and the aerodynamics (lift, drag) of airfoils was fairly well understood. (Aerodynamics had been studied by the French and Germans, for example, for quite a while.) The tremendous breakthrough made by the Wrights was how to control the vehicle in flight. In the words of Wilbur Wright[1] two years before their first powered flight:

> Men already know how to construct wings or aeroplanes, which when driven through the air at sufficient speed, will not only sustain the weight of the wings themselves, but also that of the engine, and of the engineer as well. Men also know how to build engines and screws of sufficient lightness and power to drive these planes at sustaining speed. . . . Inability to balance and steer still confronts students of the flying problem. . . . When this one feature has been worked out, the age of flying machines will have arrived, for all other difficulties are of minor importance.

Prior to the Wright's first flight, the only known ways to turn a vehicle were by using a rudder, as with ships, or by shifting the vehicle's center of mass by shifting the pilot's body weight, as Lilienthal tried to do with his gliders. But as we now know, if you only use a rudder to try to turn an airplane, it slips sideways. And shifting the pilot's body weight severely limits the size and maneuverability of the vehicle. The Wrights discovered that to efficiently turn an airplane, they had to bank the vehicle (like a bicycle!). In addition, the Wrights invented wing warping (the precursor of ailerons) to initiate and control the banking.

The Wrights also demonstrated that an unstable vehicle could be flown successfully (although with difficulty). By using a large canard, the Wright's pitch-control surface located forward of the pilot, they produced a vehicle that was neutrally stable, or slightly unstable in pitch. But the Wrights were not too concerned. Since they were bicycle mechanics, they were accustomed to dealing with unstable machines—machines that had to be stabilized by the human operating them! One wonders if the Wrights could have been as successful as they were, had they not been bicycle mechanics.

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[1] McFarland, M. W., ed., *The Papers of Wilber and Orville Wright,* Vol. 1, McGraw-Hill, 1953.

The Subject Revisited

Many years after the Wrights' historic flights, researchers began to develop an analytical theory of *flight dynamics.* Like the more classical aerospace sciences of aerodynamics and structures, modern flight dynamics has its genesis in dynamics, or mechanics, with the focus on the dynamics of nonlinear, multidimensional systems. So it is applied physics. But, with reference to Figure 1, it also relies heavily on the tools that have been developed in the area of mathematical systems theory. Furthermore, the subject deals not only with describing the vehicle's dynamics, but also with ways to affect these dynamics in some desired way—to tailor them. This is accomplished either through the art of vehicle-configuration design, or through the introduction of feedback control systems.

However, this "new" aerospace science is neither a subset of aerodynamics, nor of feedback-control theory. Though modern flight dynamics draws from these topics, they do not define the discipline. The definition of the discipline has been the source of confusion sometimes. Historically, when a airplane's dynamics were determined almost entirely by the aerodynamic forces acting on it, aerodynamicists coined the phrase *aerodynamic stability and control.* This topic <u>was</u> one aspect of applied aerodynamics. The focus was almost exclusively on the estimation of the aerodynamic forces and moments. The rigorous treatment of the system's rigid-body dynamics was absent, and there was no mention of feedback control or structural deformation.

Conversely, the majority of aerospace vehicles developed since around 1970 include some sort of active feedback-control system for flight guidance and/or attitude stabilization and control. Furthermore, the vehicle's dynamics are greatly affected, if not completely dominated, by the actions of such feedback systems. That is, the vehicle geometry alone no longer determines the dynamics of the vehicle, or its stability. Therefore, the topic of <u>modern</u> flight dynamics has evolved in large part due to the introduction of active feedback systems into the vehicle design.

Just as the subject of modern flight dynamics is not only applied aerodynamics, neither is it just applied control theory. According to the definitions from experts in the field, feedback control theory deals little, if at all, with defining (or modeling) the dynamics of the system to be controlled. Furthermore, in the feedback-control design problem defined in texts dealing with that subject, the system to be controlled is taken as a given. It cannot be changed. Only feedback loops can be added around it to augment its dynamics. And frequently the modeling of the dynamics of the system is performed independently from the design of the feedback loops.

However, in the design of modern aerospace vehicles, the entire system is being designed, both the vehicle to be controlled as well as its feedback loops. And the use of feedback expands the design space the vehicle designer has to work with. So in modern flight dynamics, the modeling and the control design are inexorably intertwined. The subject cannot be decoupled in some artificial way into pure aerodynamics, pure dynamics, pure vibrations, and pure feedback control, for modern flight dynamics lies specifically in the intersection of these areas. To force any decoupling—if you will—throws the baby out with the bath water.

On This Book

All these considerations have significantly influenced the writing of this book, which attempts to do justice to the beauty and uniqueness of the field of modern flight dynamics, while paying tribute to the rich history of the subject. The book is a result of the author's 30-years of experience in teaching flight dynamics, plus his years of experience as a practitioner and researcher in the field.

Most of the material herein arises from undergraduate and graduate courses developed by the author at Purdue University over several years. Portions of the material have also been presented by the author in courses at Arizona State University, the University of Maryland, College Park, and finally the University of Colorado, Colorado Springs. In addition to its use as a textbook, we intend the book to be a useful reference for the practicing engineer and researcher.

Since the thorough treatment of modern flight dynamics requires the student to have mastered prerequisite material in several areas, the material presented herein is intended for fourth-year undergraduates and/or graduate students in aerospace or mechanical engineering. We assume that undergraduate students have completed coursework in rigid-body dynamics and aerodynamics. Portions of the prerequisite subjects key to the development of modern flight dynamics are reviewed in early chapters and in several other sections of this book, but these are only reviews. In addition, key material with which undergraduate students may not have sufficient familiarity is presented in *just-in-time tutorials* immediately prior to the relevant topic.

With regard to the treatment of feedback control in this text, the approach to feedback-systems design is that of "dynamics-based" synthesis, as opposed to "algorithmic-based" synthesis. That is, the feedback control laws are synthesized based on an intimate knowledge and understanding of the vehicle's dynamics—its physics. The feedback systems are designed to act in concert with, and to naturally exploit and enhance, those dynamics. Frequency-domain tools are relied upon heavily, and the approach will appear to be quite "conventional," in the terminology of control theorists.

There are key reasons for taking this conventional, dynamics-based approach. First, a general consensus exists among modern flight dynamicists that this approach has been demonstrated over the years to work very well, and it is used throughout the industry. In fact, this design approach has been the basis for much if not all of the design of every operational aircraft's flight-control system. Other synthesis approaches have been attempted in research projects, but if the project led to flight of an actual vehicle, a great deal of conventional, dynamics-based control concepts were invariably relied upon in the development of its flight-control systems. So understanding this philosophy is critical to students, if they want to master this subject. Second, though they may not have used them, almost all undergraduate engineering students have been introduced to frequency-domain tools in their curriculum. So these tools are not foreign to them.

Finally, the decision to use English Engineering units in this book is based on the fact that these units are used exclusively in industry today. The historical databases so important in design, and legacy software packages for analysis, were all developed in English units, so there would be a tremendous cost involved with any organizationwide unit conversion. Thus there is an understandable reluctance on the part of the industry to such a conversion. Consequently, it is to the students' advantage to be familiar with working with these units, as they will certainly use them throughout their careers.

To the Instructor

This book could serve as the text for a two-course sequence in modern flight dynamics, the first an undergraduate course, the second at the undergraduate or graduate level. But other course usage is quite possible. The flowcharts in Figure 2 present possibilities for grouping the subject matter into three courses.

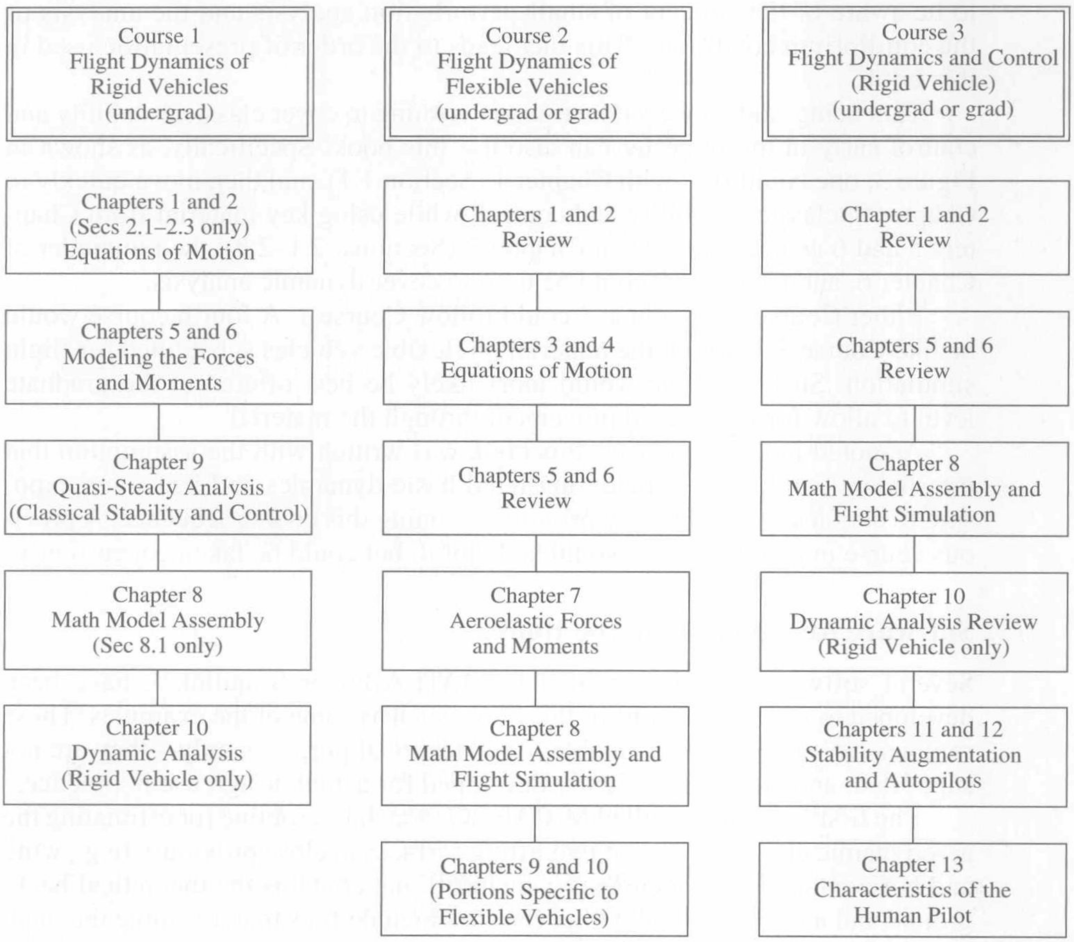

Figure 2 Possible course content.

In addition, a "Chapter Road Map" has been included at the beginning of each chapter. The primary purpose of this road map is to indicate to the student and the instructor which sections in that chapter should be covered if the course is a first course in flight dynamics.

The author has presented a course similar to Course 1 at the undergraduate level for many years. With regard to the order of the material in Course 1, the author is fully aware of a conundrum faced by many instructors teaching the subject to undergraduates. This issue has greatly influenced the writing of this book. The conundrum deals with the fact that frequently the students need to be introduced to "classical static stability and control" early in the semester, to support their senior design course. And yet, it has been the experience of the author having taught such a course for 30 years, that if these classical topics are presented first, the students frequently don't understand where the concepts stem from. That is, they don't have a context to help them see how flight dynamics fits any logical framework. Hence, the student needs to be aware of the concept of small-perturbation analysis and the analysis of the equilibrium conditions. This fact leads to the order of presentation used in this book.

That being said, however, instructors wishing to cover classical stability and control early in the semester can also use this book. Specifically, as shown in Figure 3, one could start with Chapter 1 (Section 1.1), and then move quickly to Chapter 9, classical stability and control, while using key material from Chapters 5 and 6 as necessary. Then Chapter 2 (Sections. 2.1–2.3), the remainder of Chapter 6, and Chapter 10 could be used to cover dynamic analysis.

Either Course 2 or Course 3 could follow Course 1. A fourth course would be like Course 3, but with the material on flexible vehicles substituted for flight simulation. Such a course would most likely be best offered at the graduate level to allow for more rapid movement through the material.

As noted in several places, this book was written with the assumption that the student would have already mastered basic dynamics and had some exposure to classical control theory prior to beginning this course sequence. A previous course in aerodynamics would be helpful, but could be taken concurrently.

Software Accompanying the Book

Several software modules, written in MATLAB® or Simulink®, have been developed to support sections of this book, such as some of the examples. These routines have been made available for educational purposes only—they are not supported, and are not sufficiently developed for actual design use in practice.

The first is a module called MATAERO, which is a routine for estimating the aerodynamic characteristics of two lifting surfaces in close proximity (e.g., wing and horizontal tail). A document is included that contains the theoretical background and a user's manual. Other routines include files that assemble the math

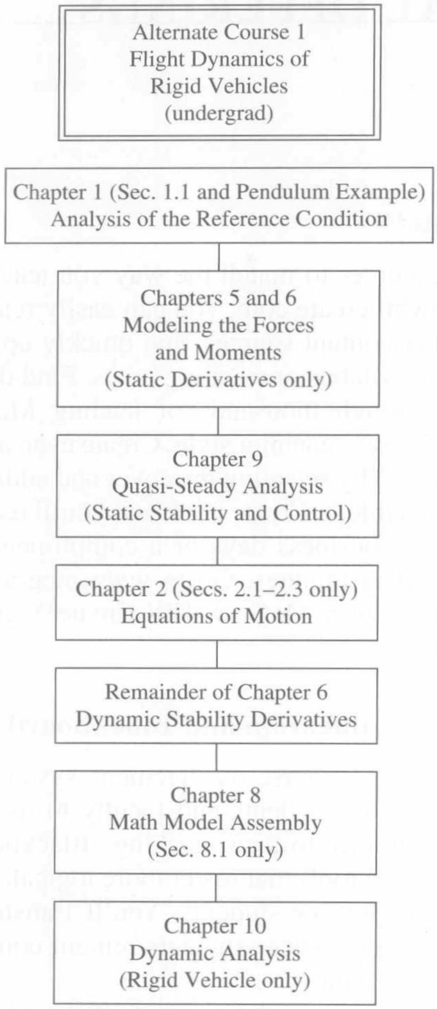

Figure 3 Reordering the sequence in Course 1.

models for several aircraft, using the data in Appendix B, while still others include the development of control laws discussed in several examples in the book. All these modules are identified in a file named "Read Me," and are available from the book's website at www.mhhe.com/schmidt.

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NOMENCLATURE*

Symbol	Definition (Typical Units)	Chapter Introduced
$\{\mathbf{1}\}$	Column of ones, rigid-body mode shape in vibration problem	3
a	Sonic velocity in air (fps)	5
ac	Aerodynamic center	5
$A = b^2/S$	Lifting-surface aspect ratio	5
$\mathbf{A}$	System matrix in state-variable description of system	8
b	Span of a lifting surface (ft)	5
$\mathbf{B}$	Control-distribution matrix in state-variable description of system	8
c	Airfoil section chord length (ft)	5
$\mathbf{C}$	Centripetal acceleration (vector) (ft/sec^2)	2, 9
$\mathbf{C}$	Constraint matrix in vibration problem	3
$\mathbf{C}$	Response matrix in state-variable description of system	8
$\bar{c}$	Mean aerodynamic chord length (ft)	5
$c_d = d/qc$	Aerodynamic 2-D section drag coefficient	5
c_p	Pressure coefficient	5
$C_D = D/q_\infty S$	Aerodynamic drag coefficient	5
C_{D_i}	Induced-drag coefficient	5
C_{D_P}	Parasite drag coefficient	5
$C_{D_\alpha} = \dfrac{\partial C_D}{\partial \alpha}$	Angle-of-attack drag effectiveness (/rad)	5, 6
$C_{D_{\dot\alpha}} = \dfrac{\partial C_D}{\partial \dot\alpha}$	Angle-of-attack-rate drag effectiveness (sec)	5, 6

* **Bold** indicates a vector or matrix quantity.

Symbol	Definition (Typical Units)	Chapter Introduced
$C_{D_{\delta_E}} = \dfrac{\partial C_D}{\partial \delta_E}$	Elevator drag effectiveness (/rad)	5, 6
$C_{D_{M_\infty}} = \dfrac{\partial C_D}{\partial M_\infty}$	Mach-number drag effectiveness	5, 6
$C_{D_q} = \dfrac{\partial C_D}{\partial q}$	Pitch-rate drag effectiveness (sec)	5, 6
$C_{D_u} = \dfrac{\partial C_D}{\partial u}$	Surge-velocity drag effectiveness (sec/ft)	5, 6
C_f	Aerodynamic friction coefficient	5
C_h	Hinge-moment coefficient for control surface	9
$C_{h_\alpha} = \dfrac{\partial C_h}{\partial \alpha}$	Angle-of-attack hinge-moment effectiveness (/rad)	9
$C_{h_\delta} = \dfrac{\partial C_h}{\partial \delta}$	Control-surface-deflection hinge-moment effectiveness (/rad)	9
$c_l = \dfrac{l}{qc}$	Aerodynamic 2-D section lift coefficient	5
$c_{l_\alpha} = \dfrac{\partial c_l}{\partial \alpha}$	Aerodynamic 2-D angle-of-attack lift effectiveness (/rad)	5
$c_{l_\delta} = \dfrac{\partial c_l}{\partial \delta_{\text{Flap}}}$	Aerodynamic 2-D flap lift effectiveness (/rad)	5
c_{l_0}	Aerodynamic 2-D section lift at zero angle of attack	5
$C_L = L/q_\infty S$	Aerodynamic lift coefficient	5
C_{L_0}	Aerodynamic lift coefficient at zero angle of attack	5
$C_{L_\alpha} = \dfrac{\partial C_L}{\partial \alpha}$	Angle-of-attack lift effectiveness (/rad)	5, 6
$C_{L_{\dot\alpha}} = \dfrac{\partial C_L}{\partial \dot\alpha}$	Angle-of-attack-rate lift effectiveness (sec)	5, 6
$C_{L_{\delta_E}} = \dfrac{\partial C_L}{\partial \delta_E}$	Elevator lift effectiveness (/rad)	5, 6
$C_{L_{M_\infty}} = \dfrac{\partial C_L}{\partial M_\infty}$	Mach-number lift effectiveness	5, 6
$C_{L_q} = \dfrac{\partial C_L}{\partial q}$	Pitch-rate lift effectiveness (sec)	5, 6