need to be embedded in the robot's structure and morphology, and which need to be implemented through software control, thus allowing for diverse behavior patterns. Second, novel feedback laws must be developed that work in concert with—and not against—the natural dynamics of the system in achieving stability and robustness of the implemented behaviors.

As soon as enough actuation is included to allow both slow and fast walking, walking on flat ground, climbing and descending stairs, running, and transitioning among these modes, nonlinear feedback control can play a key role in achieving stable, elegant, energy-efficient gaits [3], [5]–[8].

—Reviewed by Jessy Grizzle and Ioannis Poulakakis

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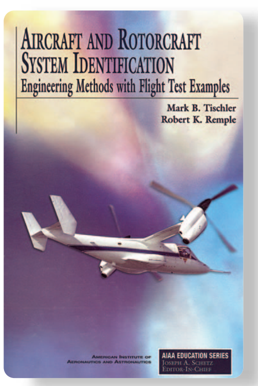

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Aircraft and Rotorcraft System Identification: Engineering Methods with Flight Test Examples

by MARK B. TISCHLER and ROBERT K. REMPLE

I have always been amazed at the volume of quality research devoted to the synthesis of feedback control systems. There are many elegant theories for control designers to choose from, and virtually all of these theories begin with a model of system dynamics. In control theory, the plant dynamics are simply a given, a starting point for the successful design of a control system. But in the world of aircraft flight dynamics and control, development of the dynamic model is not at all trivial. Aircraft dynamics are driven by complex aerodynamic forces, and accurate models based on fundamental physics are not easily derived. Experimental data from wind tunnel testing and other sources is a valuable tool in dynamic model development, but quality test data are typically expensive and almost always incomplete. Some might even say that knowledge of the aircraft dynamics is more than half the journey toward the design and implementation of a successful control system.

System identification is the process of deriving a dynamic model through experimentation. Known inputs provide excitation of the system, outputs of the system are measured, and a model is derived that best represents the experimental data. The methodology has been applied to many different engineering and nonengineering disciplines to model dynamic systems. System identification is now a vital aspect of aircraft flight control design and testing. In fact, identified models of aircraft have many applications beyond control design, including validation and refinement of flight simulation models, structural mode analysis, and flying qualities analysis. Several textbooks cover the most common algorithms used in system identification [1]–[4], which serve as both references for practicing engineers and as textbooks for graduate-level courses. However, none of these texts focus on the specific application of identification of aircraft dynamics. Additionally, there are unique challenges associated with the application of system identification to aircraft, not the least of which are related to the inherent cost and risk associated with flight testing. Intelligent and *efficient* application of system

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identification is absolutely critical for the method to be an integral part of aircraft design and development.

The American Institute of Aeronautics and Astronautics has recently published three textbooks dedicated to the topic of aircraft system identification. In addition to Tischler and Remple's book, they have published books by Klein and Morelli [5] and Jategaonkar [6]. The world of aircraft system identification is divided into two camps, namely, those who use time-domain methods and those who use frequency-domain methods. Jategaonkar's book is devoted to the time-domain method, and, while Klein and Morelli provide one chapter on frequency-domain methods, their text is also primarily focused on time domain. On the other hand, Tischler and Remple are firmly in the frequency-domain camp, and their entire book is dedicated to this approach to system identification.

A positive aspect of the book is that it presents numerous examples with real flight test data. The rotorcraft examples, which include the XV-15, UH-60, and AH-64, far outnumber the fixed-wing examples. This focus is not surprising considering Tischler's position with the U.S. Army Aeroflightdynamics Directorate, which has been involved in virtually every U.S. Army rotorcraft program over the last few decades as well as many U.S. Navy and civil rotorcraft programs. Since my experience is primarily with the rotorcraft industry, I know first hand that Tischler's frequency domain approach to system ID is prevalent throughout that industry. In particular, the software package Comprehensive Identification from Frequency Responses (CIFER), which was developed by Tischer's group, has seen wide usage throughout the rotorcraft industry.

It should be noted that the material in the book is inherently linked to the CIFER software. Several chapters have a direct correlation with specific components of the software, and virtually all of the example results are produced by CIFER. Although many of the methods presented in the text could be applied using other software tools, it would be difficult to reproduce the example results or do the end-of-chapter exercises without adopting the software along with the book. Fortunately, a student version of the software is provided free through AIAA. New users should be warned that there is a learning curve, but the user interface has improved significantly over the last few years and will hopefully continue to improve. Over the years I have reproduced some of the features of CIFER in Matlab code, but a complete reproduction requires a significant investment in time and access to the appropriate references cited in the book.

CONTENTS

Chapter 1 presents an overview of the aircraft system identification process, along with a review of basic concepts, a description of the frequency-domain method, and some history and background. Much of Chapter 1 is devoted to discussing the relative merits of frequency-domain versus time-domain methods for aircraft system identification. The authors make a strong case for the frequency-domain method, pointing out its ability to identify pure time delays, accommodate sensor biases and unstable systems, and efficiently estimate models for high-order systems. All of these features make the approach especially well suited for rotorcraft. The authors also indicate a few of the weaknesses of the frequency domain, including its inability to identify nonlinear models and the requirement for long flight test records. One issue not discussed is the fact that frequency-domain identification is essentially a batch process that is not well suited for online identification.

Chapter 2 presents a more detailed overview of the frequency-domain method, defining fundamental concepts and presenting some introductory examples, including identification of the XV-15 tilt-rotor aircraft in both the hover and cruise flight conditions. Chapter 3 presents more detailed descriptions of the example cases used throughout the text, including the XV-15 cases and a simple pendulum example, while Chapter 4 gives an overview of the CIFER software. Although the authors claim this book is not intended to be a user's manual, Chapter 4 would certainly suffice as a quick reference guide for CIFER, since it includes screen shots, description of menu items, and even a summary of function keys. This chapter would be of no value to someone not using the software.

Chapters 5 and 6 focus on the details of collecting and validating flight test data. Chapter 5 may be most valuable to flight test engineers who support the system identification process. This chapter essentially provides guidelines for the flight testing procedure such as recommendations on instrumentation and techniques for producing desirable pilot-generated or automated inputs. These guidelines are the lessons learned over many years of flight testing experience and thus cannot be derived from theory or found in software manuals. Reading the chapter could help engineers get the most out of the precious flight time they are allotted for system identification. Chapter 6 discusses methods for checking data consistency and reconstructing data contaminated with measurement errors and thus is useful for the flight test engineer who finds large portions of data contaminated by dropouts and other errors.

Chapters 7–12 present the theory and implementation of the frequency-domain identification methods incorporated in the CIFER software, with most of the chapters having a direct correspondence to a specific component of the software. Chapter 7 covers methods for deriving frequency responses of single-input, single-output (SISO) systems using fast Fourier transform (FFT) and chirp-Z transforms. Chapter 8 discusses the implications of identifying frequency responses of closed-loop systems. The placement of the chapter seems odd, but much of the material is useful for illustrating the concept of input correlation, and thus is a good transition to the extensions to MIMO systems presented in Chapter 9. Chapter 10 discusses a composite windowing averaging method, which is useful for obtaining smooth and accurate frequency responses over a wide range of frequencies. Finally, chapters 11 and 12 deal with fitting dynamics models to represent the identified frequency responses using optimization, with Chapter 11 dealing with transfer function models of SISO systems and Chapter 12 dealing with state space models of multi-input, multi-output (MIMO) systems. Chapter 12 also presents Cramer-Rao bounds and alternative metrics for measuring accuracy of the identified models.

Chapter 13 continues the discussion of state-space models by showing how the model can be related to the physical properties of the aircraft. This chapter shows how to select the structure for the state-space model and how some known parameters can be fixed or constrained to make the identification process more efficient and accurate. The chapter discusses useful guidelines that will be helpful for engineers who are first attempting one of the most difficult tasks in the identification process. The state-space model tends to be overparameterized, and novices are prone to constructing models that have little correlation to the physical properties of the aircraft. Many of the potential pitfalls of system ID can be avoided by carefully studying this chapter.

The material in chapters 7–13 is not intended to constitute a rigorous theoretical formulation of the methods but instead provide reasonable background for engineers who want to apply the method. In other words, although readers should not expect to be able to produce their own code to perform frequency domain ID using only the equations presented in this book, the text cites references that can be used to find more theoretical detail on the algorithms. I found [7] to be particularly useful for reproducing some of the features of CIFER in the Matlab environment.

Chapter 14 discusses time-domain verification of the identified model by comparing the response of the linear model to that of flight test using standard inputs such as doublets. It is a relatively trivial step, but the chapter allows the authors to show how a model's fit to frequency-domain data can be independently tested using time-domain results. Chapter 15 discusses issues relating to the development of high-order dynamic models of rotorcraft, and, in particular, models that involve rotor-body coupling. This chapter is of great significance to engineers designing high-bandwidth flight control systems for rotorcraft, but much of it may be difficult to follow without some background in rotorcraft flight mechanics.

CONCLUSIONS

There is no question that *Aircraft and Rotorcraft System Identification* is an essential reference for those working in system identification of rotorcraft and obviously to anyone who is using CIFER. Frequency-domain identification is a powerful and simple concept in theory, but it is a multistep process with myriad details and potential pitfalls when put into practice. The book contains many of the helpful guidelines and rules of thumb that have been acquired from thousands of hours of experience with control design and flight test programs. These guidelines, along with the inclusion of real flight test examples, are the most powerful feature of the text. The main limitation of the book is its tie-in to a specific software package that has not been universally adopted across the aerospace community. In my opinion, a Matlab toolbox based on these methods would go a long way toward generalizing the audience for this book and the software.

The real question is: Will the text be useful to a more general audience? Will engineers who are working with fixed-wing aircraft and have no intention of using CIFER find the book useful? My feeling is that the book is definitely worth reading if an engineer is considering the use of frequency-domain methods for system identification. I expect it is increasingly common for those in the fixed-wing aircraft industry to have to deal with issues such as higher order dynamics associated with structural modes or inherently unstable airframes, and they may find the frequency-domain identification methods presented in this book to be useful. The book could also potentially serve as a textbook for a special topics course on frequency domain identification of aircraft or even as a supplemental text for a course on rotorcraft flight dynamics. However, instructors would need to integrate the student version of CIFER into their course and be prepared to deal with the overhead of teaching the software as part of the course.

—Reviewed by Joseph F. Horn

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