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Modeling with vortex lattice method and frequency sweep flight test for a fixed-wing UAV

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ABSTRACT

A complementary and systematic procedure, applied to a small fixed-wing UAV, is presented for modeling the flight dynamics. An analytical dynamic model is first constructed with the help of the vortex lattice method for the aerodynamics, and the frequency response is compared with the frequency sweep flight test. Next, the model is slightly modified based on the understood limitations of the analytical model. For the given UAV used in this work, the analytical model and the flight test are well matched for the elevator and aileron input responses with only a slight modification on the overall control power. For the rudder response, the propeller normal force effect is also taken into account in addition to the control power modification in order for the model to agree well with the flight test.

1. Introduction

There are many unmanned aerial vehicles (UAVs) operated for military or civilian applications, and recently small scale UAVs have drawn much attention as flight test platforms in the community of flight control research. Small scale UAVs are attractive due to their compact size and low cost. An important task in the flight control system development is to model the aircraft dynamics. However, with sophisticated wind tunnel tests unavailable at low cost, it is generally difficult to get accurate dynamic models for such UAVs. The lack of accurate models limits the ability to determine stability and performance properties.

Dynamic models of aircraft can be obtained either theoretically or experimentally. There are a few theoretical methods commercially available, such as those developed by Engineering Science Data Unit (ESDU) or DATCOM (Williams & Vukelich, 1979). These methods have evolved from decades of experience with manned aircraft. Another theoretical approach is to deploy sophisticated Computational Fluid Dynamics (CFD) (Babcock & Arena, 2004; Klausmeyer, 2004), which may be used to obtain stability and control characteristics of aircraft. But the main drawback of this method is the computational power required to compute the aerodynamic forces and moments acting on an entire aircraft.

Of the experimental methods, a number of identification techniques have been proposed in the past to model aircraft dynamics. Ljung (1999) provides a background for system identification theory. General aircraft modeling and the practical application of system identification is summarized in Klein and Morelli (2006). Over the recent decades a number of research institutes have been developing various techniques for aircraft system identification. Major contribution have been made by the NASA research centers Dryden (Iliff, 1979; Maine & Iliff, 1985; Wang & Iliff, 2004) and Langley (Klein & Morelli, 2006; Morelli & Klein, 2005), the U.S. Army Aeroflightdynamics Directorate at Ames (Tischler & Cauffman, 1992; Tischler & Remple, 2006), DLR (German Aerospace Center) (Jategaonkar, 2006; Jategaonkar et al., 2004). Many different methods have been developed. Of those, system identification techniques for unmanned aerial vehicles are well summarized in Carnduff (2008). The most commonly used methods for fixed-wing aircraft are the equation error formulation based on least-square method, and the output error formulation based on maximum likelihood estimation. These methods have been formulated in both the time and frequency domain. There is also a commercially available software tool Comprehensive Identification from Frequency Responses (CIFER) (Tischler & Remple, 2006), which was originally developed for rotorcraft system identification. In addition, various modeling methods and novel identification techniques have been published in recent literature (Dorobantu et al., 2011; Gremillion & Humbert, 2010; Mettler et al., 2002; Theodore & Tischler, 2004) for small fixed-wing and rotary-wing UAVs.

This paper reports a systematic procedure developed with a small scale fixed-wing UAV for modeling and identifying flight dynamics. The work presented in this paper takes a complementary approach, wherein an analytical dynamic model is first obtained with the help of the vortex lattice method (Anderson, 1991) for the aerodynamics, and its frequency response is compared with the frequency sweep flight test. The experimental frequency response is obtained simply by taking the ratio of the Fast

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Nomenclature

b	wing span
$\bar{c}$	mean aerodynamic chord
f_0	initial frequency of the frequency sweep input signal
f_1	final frequency of the frequency sweep input signal
g	gravitational acceleration constant
l	rolling moment
m	pitching moment
n	yawing moment
p	roll rate
q	pitch rate
r	yaw rate
t	time
u	velocity component in the x-axis of body fixed frame
u_0	trim condition for the velocity component in the x-axis of body fixed frame
w	velocity component in the z-axis of body fixed frame
A_y	y-axis specific force
A_z	z-axis specific force
C	aerodynamic coefficient
D	drag
I_{xx}	moment of inertia about x-axis of body fixed frame
I_{yy}	moment of inertia about y-axis of body fixed frame
I_{zz}	moment of inertia about z-axis of body fixed frame
I_{xz}	product of inertia about x- and z-axis of body fixed frame
L	dimensional derivative for the rolling moment
M	dimensional derivative for the pitching moment
N	dimensional derivative for the yawing moment
Q	dynamic pressure
S	wing area
T_f	total time range of the frequency sweep input signal
U_k	discrete-Fourier-transformed variable for input signal
X	dimensional derivative for the force along the x-axis of body fixed frame
Y	dimensional derivative for the force along the y-axis of body fixed frame
Y_k	discrete-Fourier-transformed variable for output signal
Z	dimensional derivative for the force along the z-axis of body fixed frame
α	angle-of-attack
β	sideslip angle
δ_a	aileron deflection angle
δ_e	elevator deflection angle
δ_r	rudder deflection angle
ζ	damping ratio
θ	pitch angle
τ	time constant
ϕ	roll angle
Δt	sampling interval

Fourier Transforms (FFT) of the sampled input and output signals without further post-processing. Next, the model is slightly modified based on the understood limitations of the analytical model. The vortex lattice method uses simple computational fluid dynamics (CFD) for the 3D lifting surfaces. The method is based on the potential flow theory. As a result, a slight over-estimation is typical for the effectiveness of control surfaces where viscous effects may be important (Mason, 1998). With that in mind, for the test bed UAV used in this work, once a small modification was made on the control surface effectiveness, the dynamic model and the flight test were well matched for the elevator and aileron input responses. For the rudder response, the propeller normal force effect was also taken into account as well as the control power modification in order for the model to agree well with the flight test. The main attraction of the proposed method is that it first obtains the frequency response analytically based on the simple CFD, vortex lattice method. Yet, the limitation of the analytical approach is overcome by the relatively simple experimental procedure.

In what follows, Section 2 describes the test bed UAV used in this work and discusses the dynamic modeling of the aircraft wherein the aerodynamic component of the model is obtained using the vortex lattice method. Section 3 describes the frequency sweep experimental method. The frequency response is obtained by taking the Fast Fourier Transform (FFT) of the sampled input and output signals. Section 4 describes the applications of the frequency sweep experiment to the servo motor of the test bed UAV in order to get the actuator dynamics for the control surfaces. Section 5 reports the flight test wherein the frequency sweep experiment is applied in the aircraft level to get the frequency responses to each control surface command. Then, the analytical model is compared with the flight test to be modified accordingly. Section 6 provides a brief description on the application of the obtained model to the controller design and the associated closed-loop flight test. Finally, a brief conclusion is provided in Section 7.

2. Modeling of the test bed aircraft

The test bed UAV used in this work is shown in Fig. 1. The aircraft is equipped with the standard aerodynamic control surfaces including elevator, aileron, and rudder. The vehicle is powered by an electric motor to drive a propeller. The UAV has a total mass of 3.0 kg with a wing span of 1.54 m. The moments of inertia are found to be I_{xx}=0.119, I_{yy}=0.339, I_{zz}=0.415, and I_{xz}= 0.0163 in [kg m^2].

The UAV is equipped with avionics including flight sensors and a flight control computer. The core of the sensor suite is an MTi-G sensor package from Xsens Technologies (2009). It is an integrated Global Positioning System (GPS) and Attitude-Heading Reference System (AHRS) which provides position, velocity, attitude, angular rates, and accelerometer outputs. Also a pitot-static tube is installed to measure the airspeed. The test bed UAV has been used to demonstrate flight control research at Korea Aerospace

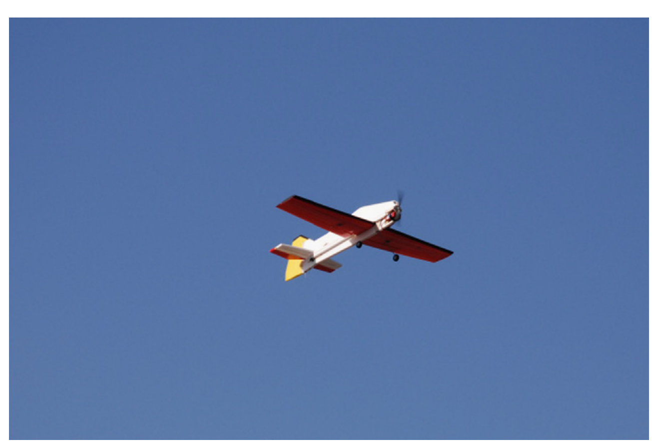

Fig. 1. Test bed UAV.