SYSTEM IDENTIFICATION OF POWERED PARAFoil-VEHICLE FROM FLIGHT TEST DATA

Gi-Bong Hur* and John Valasek†
Texas A&M University, College Station, Texas 77843-3141
http://flutie.tamu.edu/~fsl

ABSTRACT

The X-38/Crew Return Vehicle, a lifting body re-entry vehicle, has been developed as a lifeboat in case of emergency at the International Space Station. To simulate and verify the performance of the onboard Parafoil Guidance, Navigation and Control system, a commercial powered parafoil vehicle, known as Buckeye, was modified to accommodate the avionics and reduced-scale parafoil for aerodynamic similarity. Dynamic modeling and system identification results for the Buckeye are described in this paper. The vehicle dynamics are modeled as an eight degrees-of-freedom system comprising the six states for the parafoil and two states for the relative pitch and yaw angles of the vehicle with respect to the parafoil. Controllability and observability analyses are done using the Parafoil Dynamic Simulator, a six degrees-of-freedom nonlinear simulation code used prior to the actual flight tests. For system identification, the Observer/Kalman Filter Identification method is applied to reduce the flight test data, as well as simulated ones from the Parafoil Dynamic Simulator for small excitations. The identification results demonstrate that this approach works well for parafoil-vehicle system identification using flight data.

INTRODUCTION

Because of its low speed handling qualities and versatility of application for precision aerial delivery and recovery of payloads, the parafoil has been used in many areas from leisure to more sophisticated aerial recovery. Much research has been done at NASA Johnson Space Center to describe the dynamic behavior of the parafoil and to develop guidance and control algorithms using wind tunnel tests, ground tow tests and actual aerial drop tests.1,2,3,4 In Europe, the Institute of Flight Research of the German Aerospace Center (DLR) has conducted research to identify the dynamic behavior of a parafoil-load system and to investigate Guidance Navigation and Control (GNC) concepts.5,8 They used three degrees-of-freedom (DOF) and four-DOF models for their own parafoil-load system, ALEX-I and –II, to apply system identification algorithms and GNC designs.5 The ALEX system is to be dropped from a helicopter to acquire flight data. Meanwhile, NASA acquired a self-powered Buckeye parafoil-vehicle (Figure 1) as a test bed, which was modified by Southwest Research Institute (SwRI) to accommodate the Parafoil Guidance, Navigation and Control (PGNC) computer (Figure 2) as well as other avionics instruments.

Figure 1. Buckeye Unmanned Parafoil Test Bed in Flight
the early 1990’s, the method has been successfully employed to identify linear system models of flexible spacecraft structures and aircraft. Chen and Valasek applied the method for on-line system identification of six-DOF simulated aircraft dynamics, and found it is suitable for identification of linear aircraft models even without perfect trim conditions and in the presence of turbulence.

In this paper, the dynamics of the Buckeye vehicle are modeled with eight degrees-of-freedom: six for the parafoil, and two for the relative pitch and yaw attitudes of the vehicle. Instrumentation was installed to measure the states that describe eight-DOF motion, including an Inertial Measurement Unit (IMU) for attitudes and body-rate data, and a multifunction Aeroprobe flow sensor which measures angle-of-attack, sideslip angle, and static and dynamic pressures (Figure 3). Optical position sensing techniques such as the VisNav vision-based relative position sensor and video camera imaging systems were not selected for calculating the relative yaw angle because of availability and/or post processing requirements. Instead, a series of accelerometers are installed in the mid-section of the parafoil. Relative yaw angles are then calculated from side velocity by integrating the lateral accelerometer outputs.

Prior to flight testing, the OKID method was evaluated via simulation using the 8-DOF Parafoil Dynamic Simulator (PDS) code, and with previously recorded Buckeye flight data. Identification results of these evaluations for longitudinal and lateral/directional motions are presented in this paper.

**BASIC FORMULATIONS**

Although the OKID method has been well described in references, a brief summary of the underlying principles are presented here. Based on the concept of stochastic Kalman filter estimation and the techniques of deterministic Markov parameter identification, OKID generates a state-space discrete linear model representation directly in the time-domain. For lightly damped systems and modes, such as the phugoid mode of longitudinal aircraft dynamics, OKID can artificially improve system damping, thereby making the system deadbeat after just a few steps. This significantly reduces the required data record, storage space, and computation time. In practice, ideal linear system identification is almost impossible when external disturbances, often unknown, act on the system. A variant of the OKID algorithm developed to solve this problem by Chen and Valasek is applied to the Buckeye parafoil-vehicle simulation and flight test data. The discrete-time linear state-space perturbation model of the trimmed nonlinear parafoil-vehicle dynamics is assumed to have the form:

\[
X(k+1) = AX(k) + Bu(k) \tag{1}
\]

\[
y(k) = CX(k) + Du(k)
\]

where \(X(k) \in \mathbb{R}^n\), \(y(k) \in \mathbb{R}^m\), \(u(k) \in \mathbb{R}^r\), are state, output and control inputs with dimension of \(n\), \(m\), and \(r\) respectively. Following the development of Juang, solving for the output \(y(k)\) with zero initial condition from equations (1) in terms of the previous inputs \(u(i)\) \((i = 0,1,2,\ldots,k)\) yields
Writing Eqs. (2) in matrix form, we have
\[
Y = [D \ CB \ CAB \ \cdots \ CA^{i-2} B] \ \text{where}
\]
\[
U = \begin{bmatrix}
  u(0) \\
u(1) \\
u(2) \\
\vdots \\
u(l-3) \\
\end{bmatrix}
\]
and \( D, CB, CAB, \cdots, CA^{k-1}B \) are called Markov Parameters, and are commonly used as the basis to identify mathematical models for linear dynamic systems. Markov parameters generate linear state-space models by forming a Hankel matrix.\(^9,13\) For non-zero initial conditions, the following derivation is used:
\[
x(k+1) = \overline{A}x(k) + \overline{B}v(k),
x(k+2) = \overline{A}x(k+1) + \overline{B}v(k+1)
= \overline{A}^2x(k) + \overline{A}\overline{B}v(k) + \overline{B}v(k+1),
\]
\[
x(k+p) = \overline{A}^p x(k) + \overline{A}^{p-1} \overline{B}v(k) + \cdots + \overline{A} \overline{B}^v(k+p-1) + \overline{B}v(k+p-1)
\]
where \( \overline{A}, \overline{B}, \overline{C}, \) and \( \overline{D} \) are the observer Markov parameters. Through manipulation, system Markov parameters can then be recovered from the observer Markov parameters \( \overline{Y} \) through partition of \( \overline{Y} \) as:
\[
\overline{Y} = [D \ CB \ CAB \ \cdots \ CA^{(p-1)} B]
\]
for \( k = 1, 2, 3, \cdots \) Based on the definition of system Markov parameters, the system Markov parameters are
\[
Y_i = C(A + GC)^{k-1}(B + GD) - C(A + GC)^{k-1}G
\]
and the desired discrete system realization \([A, B, C, D]\) is obtained from the system Markov parameters.
parameters from a singular value decomposition (SVD) of the Hankel matrix.

\[
H(k-1) = \begin{bmatrix}
Y_k & Y_{k+1} & \cdots & Y_{k+\beta-1} \\
Y_{k+1} & Y_{k+2} & \cdots & Y_{k+\beta} \\
\vdots & \vdots & \ddots & \vdots \\
Y_{k+\alpha-1} & Y_{k+\alpha} & \cdots & Y_{k+\alpha+\beta-2}
\end{bmatrix}
\]

\[
H(0) = R_{n}\Sigma_n
\]

\[
\hat{A} = \Sigma_{n}^{-1/2} R_{n}^{T} H(1) \Sigma_{n}^{-1/2}
\]

\[
\hat{B} = \Sigma_{n}^{1/2} S_{n}^{T} F_e, \quad \hat{C} = E_{m}^{T} R_{n} \Sigma_{n}^{-1/2}
\]

where

\[
E_{e} = [I_{n}, O_{n}, \cdots O_{n}]
\]

\[
E_{e}^{T} = [I, O, \cdots O]
\]

With the control inputs and perturbation outputs data, the perturbation linear model can be identified using a OKID approach:

\[
X(k+1) = AX(k) + Bu(k)
\]

\[
y(k) = X(k)
\]

**PARAFOIL-VEHICLE SIMULATION MODEL**

The Buckeye parafoil-vehicle is a two-body system composed of a parafoil and a hanging vehicle. To apply OKID to simulation results, the same equations of motion from the PDS\(^{15,16}\) are adopted in this paper. From flight test observations, relative roll motion is ignored and relative pitch and yaw motions are assumed to exist. The parafoil and vehicle are assumed to be rigid bodies, which are connected by a universal joint at the confluence point (Figure 4). The eight degrees-of-freedom are composed of three positions and three attitudes for the parafoil, and two for pitch and yaw motions of the vehicle with respect to the parafoil. All external forces and moments are either aerodynamic or inertial. After evaluation of identification results from flight test data, a more detailed dynamic model can be applied for matching dynamic responses.

The 8-DOF nonlinear equations of motion are described briefly as follows:

\[
\dot{X} = f_n(X, M, I, \Delta)
\]

where

\[
X = U, V, W, P, Q, R, Q, R_v
\]

and control

\[
\Delta = \{\text{winch\_left, winch\_right}\}
\]

which is applied simultaneously for longitudinal commands, and differentially for lateral/directional commands. \(M\) and \(I\) are the mass and moments of inertia for the combined parafoil and vehicle. Note that vehicle states are denoted by the subscript \(v\).

**NUMERICAL EXAMPLES**

A nonlinear, non-real-time 8-DOF simulation for the parafoil-vehicle is used to generate time history data streams for the OKID identification routine. As with identification for using actual flight test data, all states are stored at 50 Hz (\(T=0.02\sec\)), and appropriate inputs are introduced to properly excite the dynamical modes. The input types were selected and evaluated by simulation analysis so as not to excite motions outside the linear range.
This simulation is being used to survey and generate appropriate input amounts for the flight test evaluations. A controllability and observability analysis was also done using the identified state-space linear model.

As shown in Figure 5 (longitudinal states and control) and Figure 6 (lateral/directional states and control), the nonlinear simulation starts at the initial conditions and converges to steady-state. Note that all of the abscissas in the following simulation figures represent time in seconds.

After stabilization, a small input (symmetric for longitudinal and asymmetric for lateral/directional) is introduced for various time intervals. These figures show the accuracy of the identified linear model by comparing the nonlinear simulation histories and the linear model simulation, using the same inputs.

Results from the longitudinal identification in Figure 7 demonstrate that the OKID local linear model approximates the nonlinear dynamics very well. Figure 8 shows that the OKID identified lateral/directional model closely follows the responses of the nonlinear simulation model.
Figure 9 shows the identified linear model does not fully represent the nonlinear dynamic responses, due to an input which generated responses beyond the linear range. Figure 10 shows the effect of an excitation control input for the same flight condition, clearly demonstrating that inputs which generate large perturbations adversely affect fidelity of the identified linear model. For flight testing, the magnitude of the inputs must be properly scaled for better identification results.

Figure 9. Responses of Identified Longitudinal Linear Model and Nonlinear Simulation for Large Input

Figure 10. Responses of Identified Lateral/Directional Linear Model and Nonlinear Simulation for Large Input

FLIGHT TESTS
Unlike conventional aircraft, the parafoil-vehicle has only two control effectors, consisting of control lines attached to the starboard and port side trailing edges of the parafoil. Symmetric pulling of both control lines causes pitch motions, and asymmetric pulling generates lateral/directional motions. Asymmetric inputs generate directional motions from differential drag, caused by deflection of the trailing edges. Roll motions result mostly from the dihedral effect. This means that a trailing edge deflection mainly causes an increase in drag, but not much increase in lift. Glide slope changes due to L/D and directional changes are examples of major responses that can be controlled by inputs. For longitudinal excitations, a symmetrical pull of the control line is applied, and asymmetrical pulls are applied for lateral/directional excitations. To determine proper input commands for linear responses, various types and magnitudes of inputs are studied before conducting the actual flight tests.

Since the parafoil-vehicle is very vulnerable to gust and disturbances, and identification algorithms in general have trouble distinguishing between disturbance responses and pure responses, flight tests are conducted on calm days.

Current flight tests are ongoing as shown in Figure 11, and the results were not available at the time of publication, but will be reported at the conclusion of the test program.

Figure 11. Buckeye Flight Test Operations

SUMMARY AND CONCLUSIONS
A time domain identification method OKID has been applied to the two-body parafoil-vehicle dynamics identification problem. Dynamics of the parafoil-vehicle were modeled with eight degrees-of-freedom, including two degrees-of-freedom of hanging vehicle. Examples for longitudinal and lateral/directional system identification for nonlinear,
non real-time, eight degrees-of-freedom simulation results have been presented. The results demonstrate that the OKID method can identify the parafoil-vehicle dynamic system effectively, and accurately.

Further investigation will extend the OKID method to actual flight test data, which include sensor noise and disturbances, and employ more detailed and accurate dynamics.

ACKNOWLEDGMENTS
This research is funded by NASA Johnson Space Center under grant number NAG9-1268. The technical monitor is Alan Strahan. This support is gratefully acknowledged by the authors. The authors also thank colleagues in the Texas A&M Flight Mechanics Laboratory for their assistance and support.

REFERENCES