17th AIAA Aerodynamic Decelerator Systems Technology Conference and Seminar
19-22 May 2003, Monterey, California

AIAA 2003-2105

AIAA-2003-2105

ON THE DEVELOPMENT OF A SIX-DEGREE-OF-FREEDOM MODEL OF A LOW-ASPECT-RATIO PARAFOIL DELIVERY SYSTEM

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Abstract

The future of the Army's air delivery mission includes the use of precision-guided autonomous airdrop methods to resupply troops in the field. High-glide systems, ram-air parafoil-based, allow for a safe standoff delivery as well as wind penetration. This paper addresses the development of a six-degree-of-freedom model of a low-aspect ratio controllable parafoil-based delivery system. The model is equally suitable for modeling and simulation and for the design of guidance, navigation and control (GNC) algorithms. This gliding parafoil model was developed in the MATLAB/Simulink® environment. Apparent mass and inertia effects are included in the model. Initial test cases have been run to check model fidelity.

Introduction

The tempo of the battlefield in today's Army is extremely fast-paced. The Desert Storm war demonstrated the rapid pace at which a land battle can be executed. The Army's transformation initiatives are geared towards increasing the ability of the Army to respond rapidly and improve the agility and mobility of its forces. A key part of this transformation is the ability to get materiel where it needs to be, when it needs to be there. In addition, the US Air Force desires to improve the survivability of its air delivery aircraft by increasing the ability to drop payloads from higher altitudes than currently dropped from and further from the drop zones. Therefore, the services require the ability to deliver payloads from high altitude, with large standoff to achieve precision accuracies from the desired impact point.

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Numerous papers in the area of parafoil system design have been published over the past 50 years. They cover the following major topics:

- Advanced computational methods for the 3D flow simulation around the parafoil canopy;[1-3]
- Wind-tunnel experiments;[4-7]
- Real drop experiments.[8-18]

Although each of these papers topics addresses the problem differently, they all share an important feature - verification of corresponding mathematical models using real drop data.

Despite the 50-year research effort, the aerodynamics of a flexible body such as a parafoil canopy still contains some unknowns and uncertainties. For instance, because of the flexible nature of a parafoil's canopy, even aerodynamic experiments in wind tunnels[4] may provide variable data for both longitudinal and lateral channels, not explicitly applicable for the modeling.

Analysis of previous work[11-13,15,19-22] that addresses model verification leads to the conclusion that major differences between them lie in the way authors account for the influence of numerous interrelated parameters on the motion of entire system. This paper does not intend to discuss various numerical techniques of parameter identification (PID),[23] but briefly mentions the physical issues (multicriteria essence) behind the identification process. This paper employs the same methodology authors have already used for the PID of a controllable circular parachute.[24,25] The key feature of this original technique is to separate the influence of different dominant factors (apparent mass terms, aerodynamic coefficients) by employing different portions of the flight test data.

The paper is organized as follows. The background section of the paper reviews existing parafoil models and discusses several modeling issues not completely resolved to date. Formulation of the problem follows next. The paper then proceeds with a development of the mathematical model of a double-skin parafoil. This includes the basic equations of motion in matrix form convenient for further implementation within the

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **MAY 2003**	2. REPORT TYPE	3. DATES COVERED **00-00-2003 to 00-00-2003**

4. TITLE AND SUBTITLE **On the Development of a Six-Degree-of-Freedom Model of a Low-Aspect-Ratio Parafoil Delivery System**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Postgraduate School,Department of Mechanical and Astronautical Engineering,Monterey,CA,93943**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
see report

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**10**	

Mathworks MATLAB/Simulink environment. The apparent mass model is then presented. The following section provides analysis and computation of the aerodynamic forces and moments. The paper then contains examples of simulations including system response on certain control patterns. Preliminary results of the model's parameters identification based on comparison with the airdrop data available are also introduced. The paper ends with the summary of obtained results.

Configuration of the Descending System

The autonomously guided Pegasus delivery system is comprised of a ram-air canopy, a GPS-based guidance and control unit, and payload. A photo of the system is shown in Figure 1.

Fig. 1 Pegasus parafoil (from Ref. 26)

The main canopy is an eleven-cell ram-air design. It is made of 1.1-ounce F-111 nylon with cotton reinforcement. The rectangular planform is 575 *sq.ft* with a wingspan of 40 *ft*. The 2D airfoil shape is a customized proprietary design developed by FXC Corporation. The system payload can be varied from 400 to 600 *lbs* without exceeding the performance range of the ram-air canopy. Under the current test configuration, the payload is a wooden rectangular box, rigged to 500 *lbs*.

The guidance and control unit is suspended between the canopy and the payload. It consists of an airborne computer with embedded control logic, GPS receiver, IMU and compass. Two control actuators provide control inputs to the control lines attached to the left and right trailing edges of the canopy. The control surfaces of the canopy can be deflected symmetrically (up to 18 *inches*) for pitch control and asymmetrically for lateral control.

Parafoil Model

The model was derived using general equations of fluid dynamics.[21,27]

The final form of the equations of motion of the whole system as a rigid parafoil-payload body[17,18] was written in matrix form

$$\dot{V}^{*T} = A^{-1}\left\{\begin{bmatrix} F \\ M \end{bmatrix} - (\Sigma + U)\,AV^{*}\right\} \tag{1}$$

where the following vector notation was used

$$V^{*} = \begin{bmatrix} V_1 & V_2 & V_3 & \omega_1 & \omega_2 & \omega_3 \end{bmatrix}^T \tag{2}$$

$$\dot{V}^{*} = \begin{bmatrix} \dot{V}_1 & \dot{V}_2 & \dot{V}_3 & \dot{\omega}_1 & \dot{\omega}_2 & \dot{\omega}_3 \end{bmatrix} \tag{3}$$

$$\begin{bmatrix} F \\ M \end{bmatrix} = A\dot{V}^{*T} + \Sigma AV^{*} + UAV^{*} \tag{4}$$

The matrices *A*, *Σ* and *U* were defined as follows

$$A = \begin{bmatrix} m+\alpha_{11} & 0 & \alpha_{13} & 0 & \alpha_{15}+mz_s & 0 \\ 0 & m+\alpha_{22} & 0 & \alpha_{24}-mz_s & 0 & \alpha_{26}+mx_s \\ \alpha_{13} & 0 & m+\alpha_{33} & 0 & \alpha_{35}-mx_s & 0 \\ 0 & \alpha_{24}-mz_s & 0 & I_{11}+\alpha_{44} & 0 & I_{13}+\alpha_{46} \\ \alpha_{15}+mz_s & 0 & \alpha_{35}-mx_s & 0 & I_{22}+\alpha_{55} & 0 \\ 0 & \alpha_{26}+mx_s & 0 & I_{13}+\alpha_{46} & 0 & I_{33}+\alpha_{66} \end{bmatrix} \tag{5}$$

$$\Sigma = \begin{bmatrix} 0 & -\omega_3 & \omega_2 & 0 & 0 & 0 \\ \omega_3 & 0 & -\omega_1 & 0 & 0 & 0 \\ -\omega_2 & \omega_1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -\omega_3 & \omega_2 \\ 0 & 0 & 0 & \omega_3 & 0 & -\omega_1 \\ 0 & 0 & 0 & -\omega_2 & \omega_1 & 0 \end{bmatrix} \qquad (6)$$

$$U = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -V_3 & V_2 & 0 & 0 & 0 \\ V_3 & 0 & -V_1 & 0 & 0 & 0 \\ -V_2 & V_1 & 0 & 0 & 0 & 0 \end{bmatrix} \qquad (7)$$

In these equations m is the total mass of the system, I_{ij} are the moments of inertia, α_{ij} are the apparent mass and inertia terms, V_i are the velocity components, ω_i - the angular velocities, z_s and x_s are the vertical and longitudinal moment arms from particular component from the origin of the body-fixed coordinate frame.

Implementation was carried out in the Mathworks MATLAB/Simulink environment similarly to how it was done for the circular parachute in a previous study.[20,21] The general view of the Simulink model is presented in Figure 2.

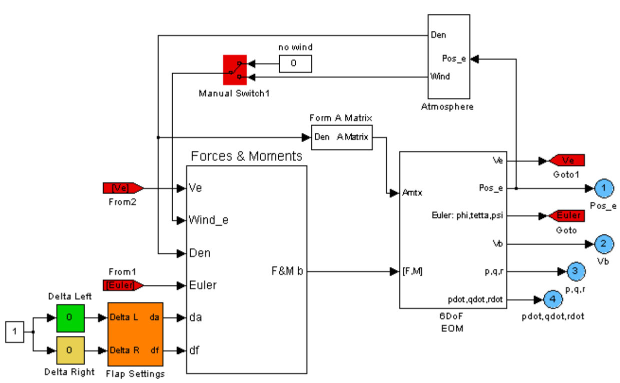

Fig. 2 Simulink model

Aerodynamics Model

The only available data on the aerodynamic coefficients was the wind tunnel data from Refs. 4 and 7 and computational fluid dynamics data obtained for the steady state turn in Ref. 28. However it was impossible to implement this data directly. While Refs. 7 and 28 contain the data just for one single point in terms of dependence on the angle of attack, the data in Ref. 4 despite of the richness of different dependences for three aspect ratios is somewhat incomplete and contradictory. Figures 3-7 give an example of the data on some lateral and longitudinal coefficients after some necessary corrections. It is seen, that the data is quite non-linear, non-consistent and obviously use the different scale for the angle of attack. After thorough analysis of the data it was assumed that a setup for the wind tunnel experiment included about 10º rigging angle so that the angle of attack axis for the longitudinal channel (Figures 6 and 7) should be shifted left by this angle.

Instead of modeling the aerodynamic coefficients along the full range of angles of attack ([-10 º,80 º]) it was suggested to replace them with the linear dependences within the operable range of angles of attack ([0 º,20 º]) as shown by appropriate formulas on Figures 3-7. Not only this provides a reasonable behavior and gives an acceptable accuracy but it also enables the use simple PID technique where only a few parameters for each dependence have to be optimized.

After careful analysis and preliminary simulation runs the applied aerodynamics model was developed as the database for all major aerodynamic coefficients expressed as functions of several input parameters. The longitudinal and lateral-directional aerodynamic coefficients depend on the angle of attack (α), sideslip angle (β), symmetrical flaps deflection ($\delta_f = \min(\delta_{left}, \delta_{right}) \in [0;1]$), and differential flaps deflection ($\delta_a = \delta_{left} - \delta_{right}$) as shown in the following equations.

$$C_D = 0.14 + (0.25 + 0.2\delta_f)\, C_L^2 \qquad (8)$$

$$C_Y = (-0.005 - 0.0001\alpha)\,\beta + (-0.007 + 0.0012\alpha)\,\delta_a \qquad (9)$$

$$C_L = 0.0375\left(\alpha + 10^o\right) + 0.1\left(2\delta_f + |\delta_a|\right) \qquad (10)$$

$$C_l = (0.005 - 0.0018\alpha)\,\beta - 0.0063\delta_a - \frac{b}{2|V|}(0.15p + 0.0775r) \quad (11)$$

$$C_m = -0.33 + \frac{dm_1}{m_1 + m_2}\left(\frac{1}{c} + \frac{\rho C_{B_o}}{2W/S}\right)\left(C_D \quad C_L\right)\begin{pmatrix}\cos(\alpha + 8^o)\\ -\sin(\alpha + 8^o)\end{pmatrix} - 6.39\frac{qc}{|V|} \quad (12)$$

$$C_n = (0.007 - 0.0003\alpha)\,\beta + (0.019 - 0.0008\alpha)\,\delta_a + \frac{b}{2|V|}(0.023p - 0.0936r) \quad (13)$$

where C_L, C_D, and C_Y are the lift, drag and side-force coefficients; C_l, C_m, and C_n are the rolling moment, pitch moment, and yawing moment coefficients; p, q, and r are the rolling, pitch, and yawing moments; b and c are the inflated span and chord; V is the total velocity; m_1 and m_2 are the payload and canopy masses, respectively. The rigging angle of 8° and $\alpha_{C_L=0} = -10°$ were applied.

The derivation of the formula for the coefficient C_m was based on the analysis presented in Ref. 19.

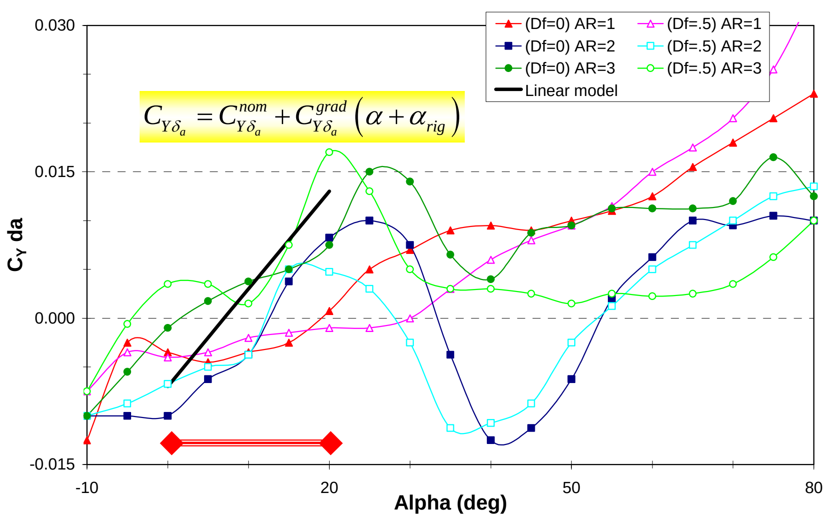

Fig. 3 Modeling of the coefficient $C_{Y\delta a}$

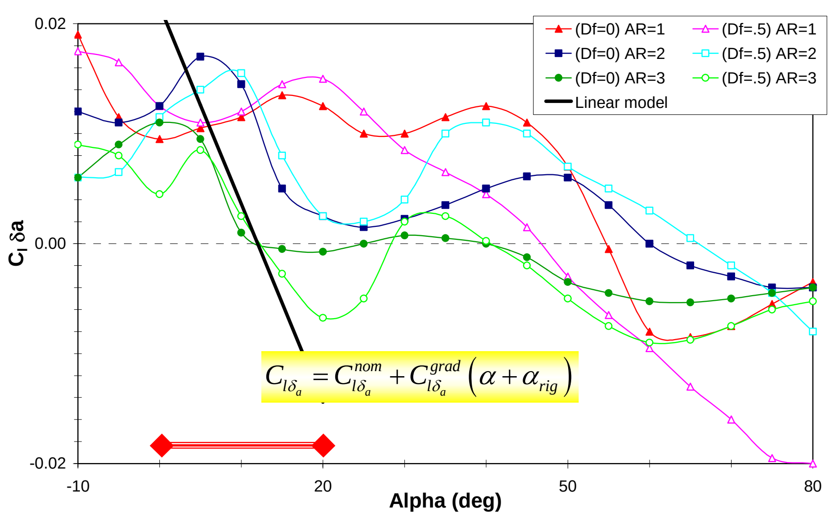

Fig. 4 Modeling of the coefficient $C_{l\delta a}$

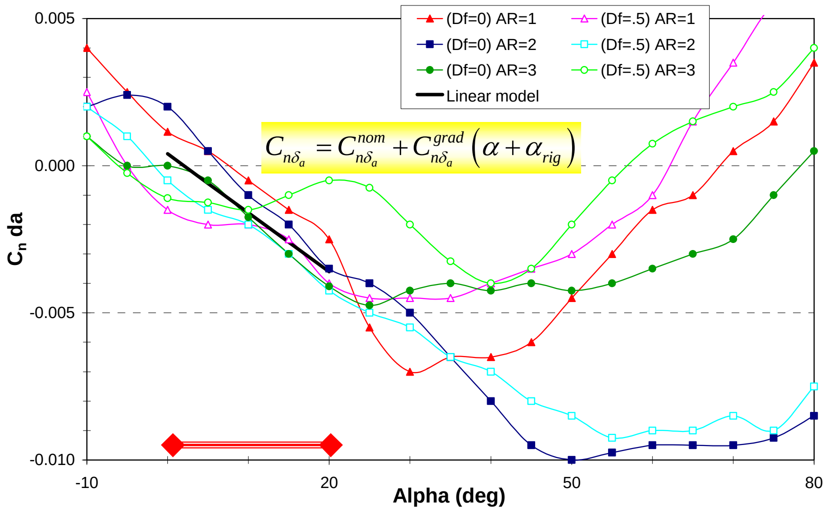

Fig. 5 Modeling of the coefficient $C_{n\delta a}$

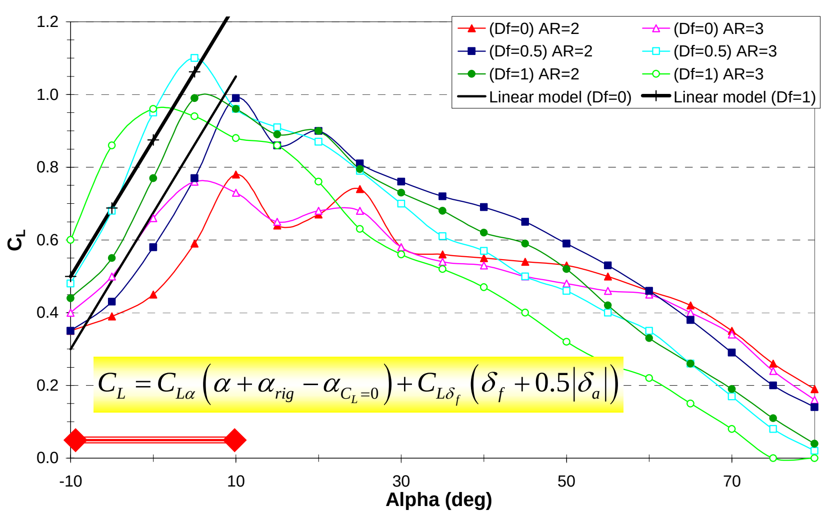

Fig. 6 Modeling of the coefficient C_L

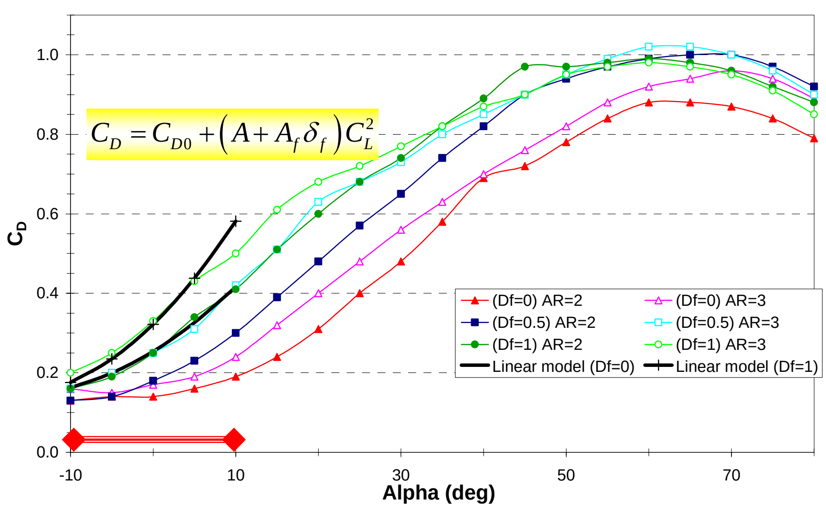

Fig. 7 Modeling of the coefficient C_D

Apparent Mass Model

In general the apparent mass tensor *A* (5) contains 36 elements that maybe unique in a real fluid. For ideal fluid, however, the tensor *A* has a symmetrical form, leaving a maximum of 21 distinct terms. In the case of a body with one plane of symmetry, tensor *A* can be further reduced to 12 unique components.[21,29,30]

During descent of a fully deployed symmetric parafoil canopy, its added mass terms are functions of air density and are defined to be the algebraic functions of cylindrical volume and parafoil geometry multiplied by empirical scaling coefficients.[24] Off-diagonal terms in (5) are introduced as corresponding values of static and inertial moments multiplied by correction coefficients. These unknown so far coefficients, which by the way depend on the state of control surfaces, are left in (5) for the further PID.

Preliminary Simulation Results

The model response on the control inputs is discussed in this section.

Figure 8 indicates the longitudinal response to a pulse input of $\delta_f = 0.5$ after the parafoil was trimmed in flight at an altitude of 3000 *m*. With flap deflection, the angle of attack increases, pitch angle increases, and flight-path angle is steeper, as is expected. A short-period type of dynamic response is also noted, which is heavily damped.

Figure 9 indicates the trajectory due to the asymmetric input of an aileron. Figure 10 shows roll-rate and yaw-rate responses due to the control input. The steady-state bank angle is about 4 º and the steady yaw rate is 2.8 º/*s*.

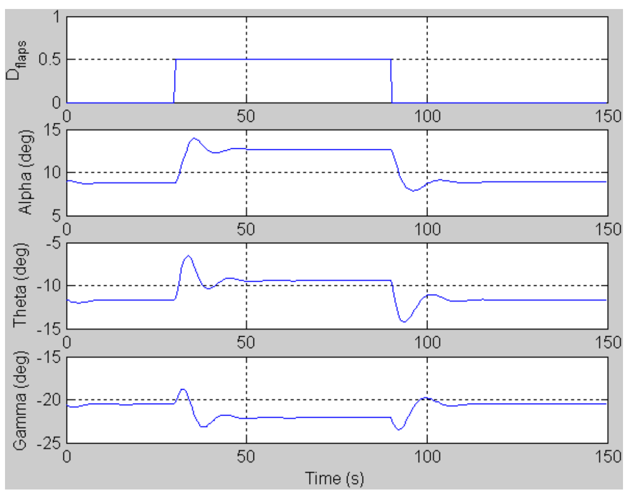

Fig. 8 Longitudinal response to flap deflection

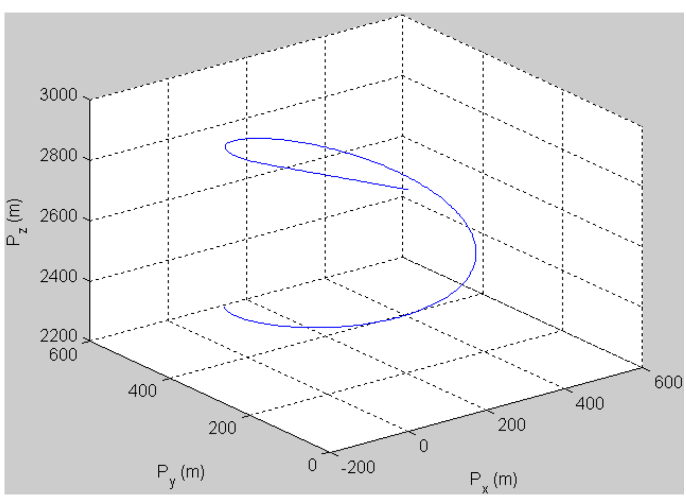

Fig. 9 Trajectory due to aileron deflection

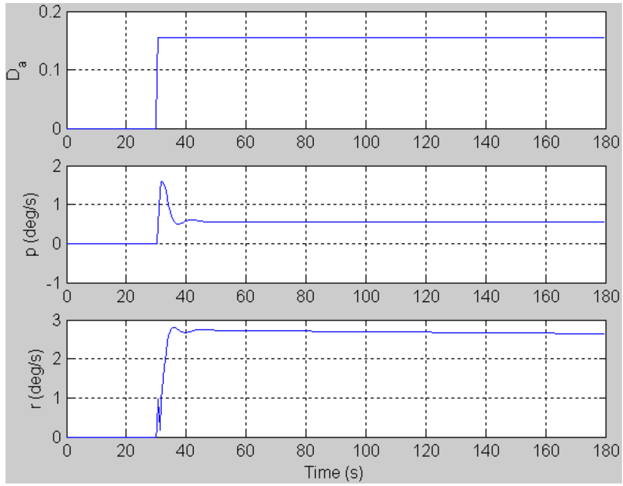

Fig. 10 Roll and yaw rate responses to aileron input

Trajectory Data Source

The following airborne suite of sensors has been used to obtain the objective information during this study:

- IMU block provided the following data sampled at 100 *Hz*: Roll Rate, Pitch Rate, Yaw Rate, X Acceleration, Y Acceleration, Z Acceleration;
- Compass provided attitude data measured in the body frame and sampled at 4 *Hz*;
- GPS unit provided the following data sampled at 10 *Hz*: Latitude, Longitude, Altitude, Ground Speed, Track Angle, Velocity East, Velocity North, Velocity Up.

The WindPack dropsonde, dropped at the same time as the descending system, provided the real-time wind profile update with the frequency of 10 *Hz*. A sample of vertical profiles for both parafoil and WindPack dropsonde is shown on Figure 11.

The data collected during the only (so far) flight test was analyzed and used as a truth data for the PID.

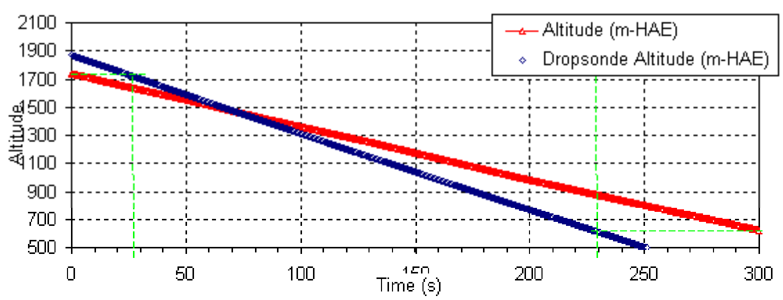

Fig. 11 Example of vertical profiles versus time

Parameter Identification Technique

For the case of the rigid wing one of the well-established system ID tools may be used to identify its aerodynamic characteristics. In the parafoil case however this approach is impossible. Moreover, the estimation of the apparent mass terms even for the case of the fixed-geometry parafoil is non-intuitive.[21,28,29] The apparent mass has the following important property: it changes with orientation of the associated motion. Therefore, appropriate choice of truth data can obviously identify the apparent mass terms that dominate specific motion. A non-standard nonlinear system PID technique including employment of the multicriteria optimization[31] to find reasonable ranges of the optimization parameters and zero-order Hooke-Jeeves method[32] to actually define the best solutions for optimization parameters was applied to tune the initial aerodynamic dependences and apparent mass terms as well. Although the PID still continues, Figures 12-14 show some preliminary results obtained so far.

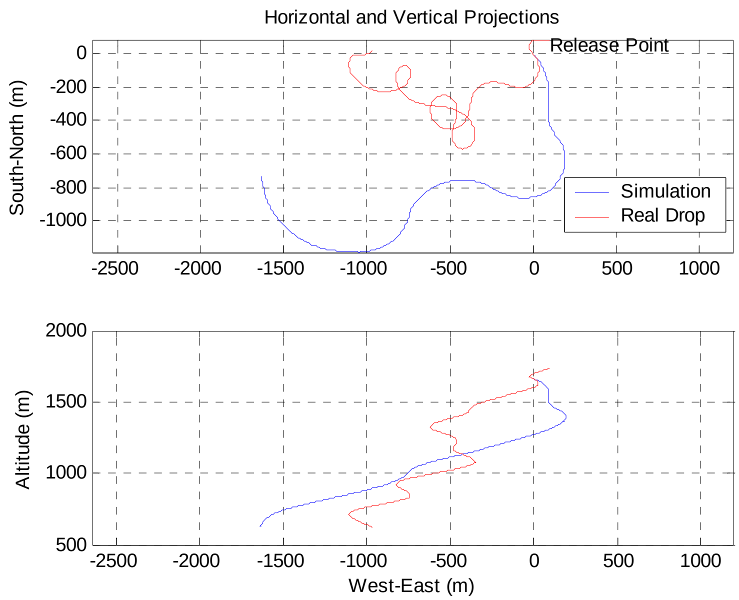

Fig. 12 Comparison of the flight test data with the original (not-tuned) model

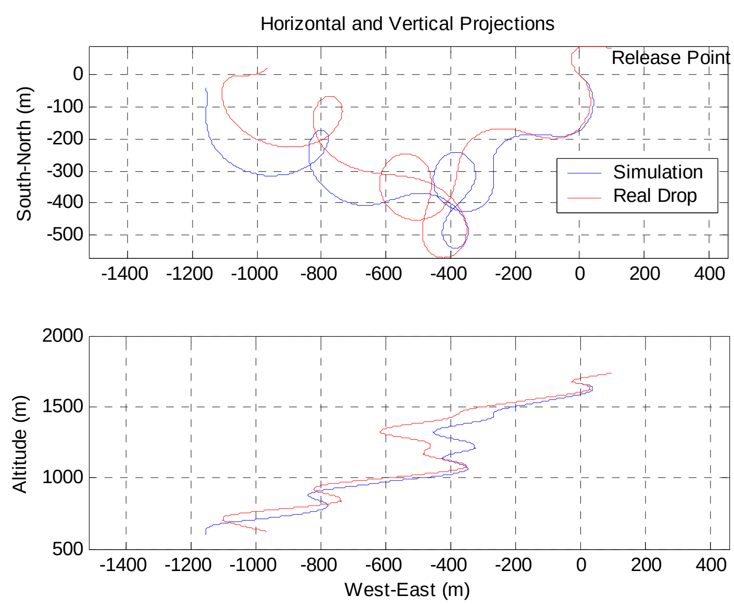

Fig. 13 Comparison of the flight test data with the tuned model

While the original model matches the integral behavior of the system in terms of glide ratio (2.5) and vertical velocity (3.7 *m/s*) fairly well some correction was needed to match the turn rate 6 °*/s* demonstrated during the flight tests.

Figure 12 demonstrates the discrepancy of the original model in the lateral channel. Figure 13 shows how the changing of the only coefficient $C_{n\delta a}^{nom}$ from 0.019 to 0.032 improves the model. Further improvement involving more coefficients is also possible (Figure 14). However in this case the developed PID technique involves finding and using only Pareto-optimal[31] solutions, which do not make other criteria (vertical channel matching, eigen frequencies, etc.) worse.

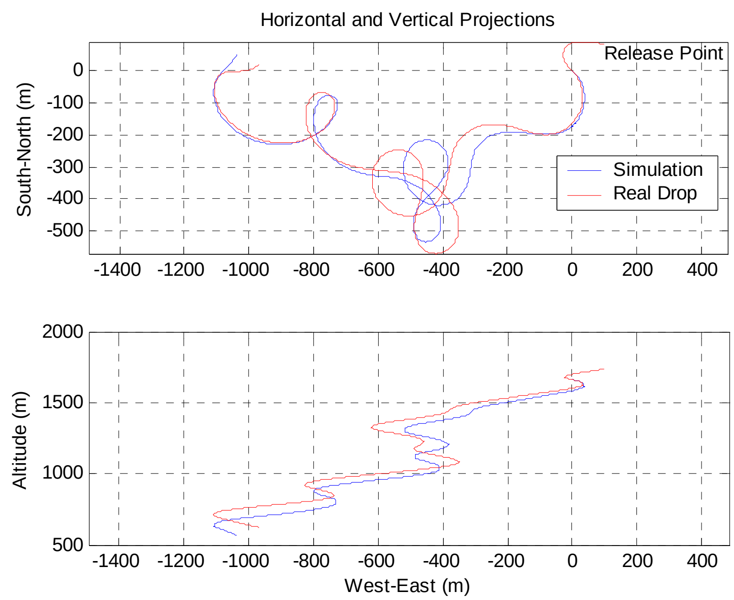

Fig. 14 Example of the further tuning

Conclusions

The complete 6DoF model of the parafoil system has been developed and realized within the MathWorks MATLAB/Simiulink environment. The model demonstrates an adequate response for the control inputs and matches the result of the flight tests well. A nonlinear system identification technique is currently being applied to tune the model and correct the apparent mass terms. The authors intend to present more PID results upon the completion of the tests.

Acknowledgments

The work was performed under research grants from the US Army Soldier Systems Center and the US Army Yuma Proving Ground under the technical guidance of Richard Benney and Scott Dellicker, respectively. The authors are grateful for their continued support.

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