2003

Aspects of Control for a Parafoil and Payload System

Nathan Slegers  
George Fox University, nslegers@georgefox.edu

Mark Costello  
Georgia Institute of Technology - Main Campus

Follow this and additional works at: http://digitalcommons.georgefox.edu/mece_fac

Part of the Mechanical Engineering Commons

Recommended Citation  
http://digitalcommons.georgefox.edu/mece_fac/3

This Article is brought to you for free and open access by the Department of Mechanical and Civil Engineering at Digital Commons @ George Fox University. It has been accepted for inclusion in Faculty Publications - Department of Mechanical and Civil Engineering by an authorized administrator of Digital Commons @ George Fox University. For more information, please contact arolfe@georgefox.edu.
Aspects of Control for a Parafoil and Payload System

Nathan Slegers* and Mark Costello†
Oregon State University, Corvallis, Oregon 97331

A parafoil controlled by parafoil brake deflection offers a lightweight and space-efficient control mechanism for autonomous placement of air-dropped payloads to specified ground coordinates. The work reported here investigates control issues for a parafoil and payload system with left and right parafoil brakes used as the control mechanism. It is shown that parafoil and payload systems can exhibit two basic modes of lateral control, namely, roll and skid steering. These two modes of lateral steering generate lateral response in opposite directions. For example, a roll steer configuration turns left when the right parafoil brake is activated, whereas a skid steer configuration turns right under the same control input. In transition between roll and skid lateral steering, the lateral response is zero, and the system becomes uncontrollable. Angle of incidence, canopy curvature of the parafoil, and magnitude of brake deflections are important design parameters for a controllable parafoil and payload system and greatly effect control response, including whether the basic lateral control mode is roll or skid steering. It is shown how the steering mode switches when fundamental design parameters are altered and as the magnitude of the brake deflection increases. The mode of directional control transitions toward roll steering as the canopy curvature decreases or the angle of incidence becomes more negative. The mode of directional control transitions away from the roll steering mode as the magnitude of the brake deflection increases, and for “large” brake deflections most parafoils will always skid steer.

Introduction

To produce rapidly deployable and ready fighting units, weapon system developers have recognized the driving need to quickly...
station large numbers of soldiers, along with their equipment in low density over a large land area. Use of this troop and equipment deployment strategy requires autonomous air delivery of many individual equipment packages to specific rendezvous points. One concept to realize this goal is to equip each individual package with a parafoil and inexpensive guidance and control module so that each package can steer itself to a prespecified rendezvous point after release from a delivery aircraft.

Detailed dynamic simulation of the flight mechanics of parachute and load systems appears to have commenced with the work of Wolf, who considered the stability of a parachute connected to a load.\textsuperscript{1} Using a 10-degree-of-freedom (DOF) representation, Wolf established that stability is reduced as riser length is increased or parachute weight is increased and that stability is improved by increasing parachute axial and normal aerodynamic force. Later, Doherr and Schilling reported on the development of a nine-DOF dynamic model.\textsuperscript{2} By comparing results from six- and nine-DOF models, they conclude a nine-DOF model adequately predicts stability characteristics. Furthermore, their work established the sensitivity of the motion of a parachute and load system to atmospheric winds. Hailiang and Zizeng used a nine-DOF model to study the motion of a parafoil and payload system.\textsuperscript{3} In contrast to Doherr and Schilling, they reported only small differences in the motion and stability between six- and nine-DOF dynamic models.\textsuperscript{2} In studying stability characteristics as a function of the pitch inertia of the payload, Hailiang and Zizeng found the decay ratio and period increase as pitch inertia is increased.\textsuperscript{3} Iosilevskii established center of gravity and lift coefficient limits for a gliding parachute.\textsuperscript{4} Brown analyzed the effects of scale and wing loading on a parafoil using a linearized model based on computer calculated aerodynamic coefficients.\textsuperscript{5} Brown found that steady-state turn response of small parafoils is more sensitive to control inputs than larger parafoils. More recent efforts by Zhu et al. as well as Gupta et al. have incorporated parafoil structural dynamics into the dynamic model of a parachute and payload system.\textsuperscript{6,7} A significant amount of literature has been amassed in the area of experimental parafoil dynamics beginning with Ware and Hassell who investigated ram-air parachutes in a wind tunnel by varying wing area and wing chord.\textsuperscript{8} More recently, extensive flight tests have been reported on NASA’s X-38 parafoil providing steady-state data and aerodynamics for large-scale parafoils.\textsuperscript{9,10} This paper considers a payload that has an attached parafoil with brakes used as the control mechanism. Using a dynamic modeling approach similar to Doherr and Schilling and Hailiang and Zizeng, stability and control characteristics of this system are examined.\textsuperscript{2,3} Particular attention is paid to steady-state control response as a function of fundamental design parameters such as parafoil canopy geometry, angle of incidence, and varying control deflection.

**Parafoil and Payload Dynamic Model**

Figure 1 shows a schematic of the dynamic system that consists of a payload body connected to a parafoil canopy. A constant velocity joint couples the parafoil and payload components at point C. The inertial frame shown in Fig. 1 is fixed to the surface of the Earth. With the exception of movable parafoil brakes, the parafoil canopy is considered to be a fixed shape once it has completely inflated. Figures 2 and 3 show a schematic of the parafoil canopy geometry. Connected to each panel are brakes that change the aerodynamic loads on the parafoil when they are deflected. The parafoil canopy is connected to joint C by a rigid massless link from the mass center of the canopy. The payload is connected to joint C by a rigid massless link from the mass center of the payload. Both the parafoil and the payload are free to rotate about joint C but are constrained by the force and moment at the joint. The combined system of the
The payload are provided in Eqs. (1–3):
\[
\begin{bmatrix}
\dot{x}_p \\
\dot{y}_p \\
\dot{z}_p
\end{bmatrix} =
\begin{bmatrix}
 u_p \\
v_p \\
w_p
\end{bmatrix}
\tag{1}
\]

The dynamic equations are formed by first separating the system at the coupling joint, then exposing the joint constraint force and moment acting on both bodies. The translational and rotational dynamics are inertially coupled because the position degrees of freedom of the system are the inertial position vector components of the coupling joint. The constraint force is a quantity of interest to monitor during the simulation so that it is retained in the dynamic equations rather than being algebraically eliminated. Equation (4) represents the translational and rotational dynamic equations of both the parafoil and payload concatenated into matrix form:
\[
\begin{bmatrix}
-m_p S^0_p \\
0 \\
-m_T b \\
0 \\
-I_p S^0_p - m_p S^p_p \\
T_p + m_\phi T_p \\
I_p + S^0_p I_p S^p_p \\
\end{bmatrix}
\begin{bmatrix}
p_b \\
q_b \\
\dot{r}_p \\
\dot{r}_p \\
\dot{x}_p \\
\dot{y}_p \\
\dot{z}_p \\
F_{\chi a} \\
F_{\chi b} \\
\end{bmatrix}
= \begin{bmatrix}
B_1 \\
B_2 \\
B_3 \\
B_4
\end{bmatrix}
\tag{4}
\]

The matrix \( T_b \) represents the transformation matrix from an inertial reference frame to the payload reference frame,
\[
T_b = \begin{bmatrix}
c_{\phi b} c_{\psi b} & c_{\phi b} s_{\psi b} & -s_{\phi b} \\
-s_{\phi b} c_{\psi b} - c_{\phi b} s_{\psi b} + c_{\phi b} c_{\psi b} & c_{\phi b} c_{\psi b} - s_{\phi b} s_{\psi b} + c_{\phi b} c_{\psi b} & -s_{\phi b} c_{\psi b} - c_{\phi b} s_{\psi b} + c_{\phi b} c_{\psi b}
\end{bmatrix}
\tag{6}
\]

whereas, \( T_p \) represents the transformation matrix from an inertial reference frame to the parafoil reference frame,
\[
T_p = \begin{bmatrix}
c_{\psi p} c_{\phi p} & c_{\psi p} s_{\phi p} & -s_{\phi p} \\
-s_{\psi p} c_{\phi p} - c_{\psi p} s_{\phi p} + c_{\psi p} c_{\phi p} & c_{\psi p} c_{\phi p} - s_{\psi p} s_{\phi p} + c_{\psi p} c_{\phi p} & -s_{\psi p} c_{\phi p} - c_{\psi p} s_{\phi p} + c_{\psi p} c_{\phi p}
\end{bmatrix}
\tag{7}
\]

The common shorthand notation for trigonometric functions is employed, where \( \sin(\alpha) \equiv s_\alpha, \cos(\alpha) \equiv c_\alpha, \text{ and } \tan(\alpha) \equiv t_\alpha \). The matrices \( I_\phi \) and \( I_p \) represent the mass moment of inertia matrices of the payload and the parafoil body with respect to their respective mass centers, and the matrices \( I_F \) and \( I_M \) represent the apparent mass force coefficient matrix and apparent mass moment coefficient matrix respectively:
\[
I_F = \begin{bmatrix} A & 0 & 0 \\
0 & B & 0 \\
0 & 0 & C
\end{bmatrix}
\tag{8}
\]
\[
I_M = \begin{bmatrix}
I_a & 0 & 0 \\
0 & I_B & 0 \\
0 & 0 & I_c
\end{bmatrix}
\tag{9}
\]

Equations (11–14) provide the right-hand side vector of Eq. (4).
\[
B_1 = W_p + F_{\chi a} - m_p S^0_p S^p_e \begin{bmatrix} x_{ib} \\
y_{ib} \\
z_{ib}
\end{bmatrix}
\tag{10}
\]
\[
B_2 = W_p + F_{\chi a} - I_p \dot{T}_p \begin{bmatrix}
\dot{x} \\
\dot{y} \\
\dot{z}
\end{bmatrix} - S^0_p I_p S^p_e \begin{bmatrix} u_A \\
v_A \\
w_A
\end{bmatrix}
- m_p S^0_p S^p_e \begin{bmatrix} x_{ib} \\
y_{ib} \\
z_{ib}
\end{bmatrix}
\tag{11}
\]
\[
B_3 = M_e - S^0_e I_b \begin{bmatrix} p_b \\
q_b \\
r_b
\end{bmatrix}
\tag{12}
\]
\[
B_4 = M_a - T_p T_e^T M_p - S^0_p (I_p + I_s) \begin{bmatrix} p_p \\
q_p \\
r_p
\end{bmatrix}
\tag{13}
\]

where
\[
S^0_e = \begin{bmatrix} 0 & -r_b & q_b \\
r_b & 0 & -p_b \\
-q_b & p_b & 0
\end{bmatrix}
\tag{14}
\]
\[
S^p_e = \begin{bmatrix} 0 & -r_p & q_p \\
r_p & 0 & -p_p \\
-q_p & p_p & 0
\end{bmatrix}
\tag{15}
\]

The weight force vectors on both the parafoil and payload in their respective body axes are given in Eqs. (16) and (17).
\[
W_b = m_b g \begin{pmatrix}
-s_{0_b} \\
s_{0_b} c_{p_b} \\
c_{0_b} c_{p_b}
\end{pmatrix}
\]
(16)
\[
W_p = m_p g \begin{pmatrix}
-s_{0_p} \\
s_{0_p} c_{p_p} \\
c_{0_p} c_{p_p}
\end{pmatrix}
\]
(17)

Equation (18) gives aerodynamic force on the payload from drag, which acts at the center of pressure of the payload assumed to be located at the payload’s center.

\[
F_A^b = -\frac{1}{2} \rho A_b V_b c_D \begin{pmatrix}
u_b \\
v_b \\
w_b
\end{pmatrix} \tag{18}
\]

The payload frame components of the payload’s mass center velocity that appear in Eq. (18) are computed using Eq. (19).

\[
\begin{pmatrix}
u_b \\
v_b \\
w_b
\end{pmatrix} = T_b \begin{pmatrix}
x \\
y \\
z
\end{pmatrix} + S_b \begin{pmatrix}
x \\
y \\
z
\end{pmatrix}
\]
\[
\begin{pmatrix}
u_b \\
v_b \\
w_b
\end{pmatrix} = T_b \begin{pmatrix}
x \\
y \\
z
\end{pmatrix} + S_b \begin{pmatrix}
x \\
y \\
z
\end{pmatrix}
\]
(19)

The shape of the parafoil canopy is modeled by joining panels of the same cross section side by side at angles with respect to a horizontal plane. The i-th panel of the parafoil canopy experiences lift and drag forces that are modeled using Eqs. (20) and (21), where \(u_i, v_i, w_i\) are the velocity components of the center of pressure of the i-th canopy panel in the i-th canopy panel frame:11

\[
L_i = \frac{1}{2} \rho A_i \sqrt{u_i^2 + w_i^2} C_{L_i} \begin{pmatrix}
u_i \\
v_i \\
w_i
\end{pmatrix}
\]
(20)

\[
D_i = \frac{1}{2} \rho A_i V_i c_D \begin{pmatrix}
u_i \\
v_i \\
w_i
\end{pmatrix}
\]
(21)

Equation (20) provides the total aerodynamic force on the parafoil canopy.

\[
F_A = \sum_{i=1}^{n} T_i (L_i + D_i)
\]
(22)

The resistance to twisting of the coupling joint is modeled as a rotational spring and damper given by Eq. (25):

\[
M_r = \begin{pmatrix} \mu \left( \psi_p - \psi_b \right) + C_r \left( \psi_p - \psi_b \right) \end{pmatrix}
\]
(25)

From the same modified sequence of rotations, \(\psi_p\) and \(\psi_b\) are given in Eqs. (28) and (29):

\[
\psi_p = -c_{\psi_p} s_{\psi_p} s_{\psi_b} c_{\psi_b} + c_{\psi_p} s_{\psi_b} s_{\psi_p}
\]
(28)

\[
\psi_b = -c_{\psi_b} s_{\psi_b} s_{\psi_p} c_{\psi_p} + c_{\psi_b} s_{\psi_p} s_{\psi_b}
\]
(29)

where

\[
t_{\psi_p} = c_{\psi_p} s_{\psi_p} c_{\psi_b} + s_{\psi_p} s_{\psi_b} c_{\psi_p}
\]
(30)

\[
t_{\psi_b} = c_{\psi_b} s_{\psi_b} c_{\psi_p} + s_{\psi_b} s_{\psi_p} c_{\psi_b}
\]
(31)

Given the state vector of the system, the 12 linear equations in Eq. (4) are solved to obtain derivatives of the state vector along with the coupling joint constraint force components required for numerical simulation.

### Results

The system of equations given in Eq. (4) is solved using LU decomposition and the equations of motion just described are numerically integrated using a fourth-order Runge–Kutta algorithm to generate the trajectory of the system from its point of release. Simulations under different conditions are performed so that the performance of the controllable parafoil and payload system can be evaluated. The payload is a cube measuring 1.0 ft (0.3 m) on a side and has a weight of 10 lbf (44 N) with uniform density. The parafoil consists of five panels as shown in Fig. 2, each having dimensions of \(1.25 \times 2.5\) ft (0.38 × 0.76 m) and having a combined weight of 0.05 lbf (0.22 N). The mass center of each panel from its base is 1.3 ft (0.4 m). The parafoil panel area remains small from the release of the parafoil until 0.6 s when the panel areas increase until 2.9 s when the final areas are reached. The length of the rigid links from the coupling joint to the payload mass center and the coupling joint to the parafoil mass center are \(r_{ref} = 3.0 K_b\) ft (0.91 K_b m) and \(r_{ref} = 0.5 L_b - 4.0 K_b\) ft (−0.15 − 1.22 m), respectively. The rotational stiffness and damping at joint C were chosen to be 0.35 lb·ft/rad (0.47 N·m/rad) and 0.025 lb·ft/rad² (0.034 N·m²/rad²), which were sufficient to maintain the parafoil and payload within 10 deg of yaw angle. The panel aerodynamic coefficients used in the simulations are shown in Fig. 4. The generated coefficients are representative of the general parafoil simulated and have the same trends as data collected for parafoils over a broad range of dimensions.1,11 The six apparent mass coefficients are based on the following formulas of Lissaman and Brown,12 where, \(r, c,\) and \(b\) are the thickness, chord, and span of the parafoil. The appropriate air density must multiply the coefficients in Eqs. (32–37).

\[
A = k_A \pi (r^2 b/4)
\]
(32)
Table 1  Parafoil dimensions

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>(t)</td>
<td>0.33 ft</td>
</tr>
<tr>
<td>(c)</td>
<td>2.5 ft</td>
</tr>
<tr>
<td>(b)</td>
<td>6.0 ft</td>
</tr>
<tr>
<td>(a^*)</td>
<td>0.17</td>
</tr>
<tr>
<td>(A^*)</td>
<td>2.4</td>
</tr>
</tbody>
</table>

Table 2  Apparent mass and correction coefficients

<table>
<thead>
<tr>
<th>Correction coefficients</th>
<th>Apparent mass coefficients</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters</td>
<td>Values</td>
</tr>
<tr>
<td>(k_A)</td>
<td>0.913</td>
</tr>
<tr>
<td>(k_B)</td>
<td>0.339</td>
</tr>
<tr>
<td>(k_C)</td>
<td>0.771</td>
</tr>
<tr>
<td>(k_{A^*})</td>
<td>0.630</td>
</tr>
<tr>
<td>(k_{B^*})</td>
<td>0.872</td>
</tr>
<tr>
<td>(k_{C^*})</td>
<td>1.044</td>
</tr>
</tbody>
</table>

The apparent mass coefficients in Eqs. (32–37) have three-dimensional correction factors that are also given by Lissaman and Brown that depend on the aspect ratio \(A^*\) and the arc-to-span ratio \(a^*\). For the properties of the parafoil listed in Table 1, Eqs. (32–37) and the three-dimensional correction factors are evaluated and listed in Table 2.

For the baseline simulation the parafoil and payload system is released from an altitude of 5000 ft with a level speed of 50 ft/s. The panel angles \(\alpha_1\), \(\alpha_3\), as shown in Fig. 2, are 35 and 15 deg, respectively; \(\alpha_5\) is 0 deg; and the angle of incidence is \(-8.5\) deg. Baseline simulation results are shown in Figs. 5–10. Figure 5 plots pitch angle vs time of the payload and parafoil, which shows a large negative pitch of the parafoil and payload as a result of the large aerodynamic forces on the payload and the small aerodynamic forces on the parafoil before it fully opens. The opening of the parafoil at 0.6 s begins an increase in aerodynamic forces on the parafoil, and the pitch angles of both the payload and parafoil begin to increase before settling to \(-7.0\) deg for the payload and \(-29.5\) deg for the parafoil. The body pitch rates of the payload and parafoil shown in Fig. 6 oscillate at a frequency of 2 Hz during the opening of the parafoil at 0.6 s and decay to near 0 by 12.0 s. The vertical velocity, forward velocity, aerodynamic angle of attack, and constraint forces shown in Figs. 7–9 also show similar oscillatory characteristics during the opening of the parafoil and reach steady states by 12.0 s. The altitude of the payload mass center vs time shown in Fig. 10 begins to decrease rapidly during the opening of the parafoil but reaches a steady glide rate after the pitch angle of the payload and parafoil have reached their steady-state values.
For a controllable parafoil a subject of interest is the control authority of both large and small brake deflections. The control response to a brake deflection is dependent on the orientation of the panel angles. A set of nine different cases of panel orientation is used in the following trade studies and is defined in Table 3. Figure 11 shows the response of the baseline parafoil with a $-3.0$-deg angle of incidence and a constant small right side brake of 10 deg applied after a 10-s settling period. Cases C, D, and E have negative turn rates for the small right side brake, whereas cases F and G have positive turn rates. The control authority of small braking reverses as the orientation of the panel angles become more curved. The baseline parafoil with a $-3.0$-deg angle of incidence demonstrates two modes of control. The mode of control for the less curved cases A–E is roll steering. The flatter parafoil uses increased lift, which dominates drag from the 10-deg brake to roll the parafoil and subsequently yaw. The mode of control for the more curved cases F–I is skid steering. Increased drag dominates lift, and increased drag on the right side of the parafoil generates yawing of the parafoil. Figure 12 shows the turn rates vs time for the five parafoil cases shown in Fig. 11. The negative sign on the turn rate signifies the
turn is counterclockwise if looking down on the parafoil. It can be seen that the turn rates settle to a near constant value by 22 s for all five panel cases. A critical panel orientation occurs between cases E and F where the parafoil switches from roll steering to skid steering and a small brake would fail to generate yawing. Turn rates are shown in Fig. 13 vs panel case for three angles of incidence: −3.0, −7.0, and −13.0 deg. The critical panel orientation changes as the angle of incidence is decreased. The critical panel orientation for a −3.0-deg angle of incidence is between cases E and F, for −7.0 deg the critical angle is between F and G, and for −13.0 deg the critical angle is between G and H. Reducing the angle of incidence or reducing the curvature of the parafoil canopy moves the mode of steering toward roll steer and decreases the control authority of a nominally skid steering parafoil and increases the control authority of a nominally roll steer parafoil. Iacomini and Cerimele observed this trend in NASA’s X-38, which is a skid steering parafoil, noting that making the angle of incidence more severe “decreased turn rates for a given turn setting.”

To investigate the sensitivity of the control response caused by the lift to drag ratio of the parafoil, the drag curves shown in Fig. 4 were held constant while the lift curves were varied ±15%. The control response is dependent on the lift-to-drag ratio of the panels, and the turn rates are shown in Fig. 14 vs steady-state lift-to-drag ratio for three angles of incidence: −3.0, −7.0, and −13.0 deg. Similar to varying panel curvature, a critical lift-to-drag ratio occurs where the parafoil switches from roll steering to skid steering and a small break fails to generate yawing. The critical lift-to-drag ratio changes as the angle of incidence is decreased. The critical lift-to-drag ratio for a −3.0-deg angle of incidence is 2.04 deg; for −7.0 deg and −13.0 deg no critical lift-to-drag ratio is reached, and a skid steering mode does not occur.

Conclusions

Using a nine-degree-of-freedom flight dynamic model, it has been shown that parafoil and payload systems exhibit two basic modes of directional control: skid steering and roll steering for small brake deflections. For a particular configuration the mode of directional control depends on the angle of incidence and the panel orientation. The parafoil’s mode of directional control is skid steering for canopies of “high” curvature and “smaller” negative angles of incidence. The mode of directional control transitions toward roll steering as the canopy curvature decreases or the angle of incidence becomes more negative. The mode of directional control also transitions away from the roll steering mode as the magnitude of the brake deflection increases, and for “large” brake deflections most parafoils will always skid steer. Control reversal is usually undesirable, and because parafoils have a tendency to skid steer for large brake deflections care needs to be taken to know and avoid the range of small braking that can induce roll steering. With careful design a parafoil and payload system can be properly modified so that roll steering can be eliminated all together.

References