The Analysis and Modeling of the Deployment of NASA's X-38 Parafoil

Abstract

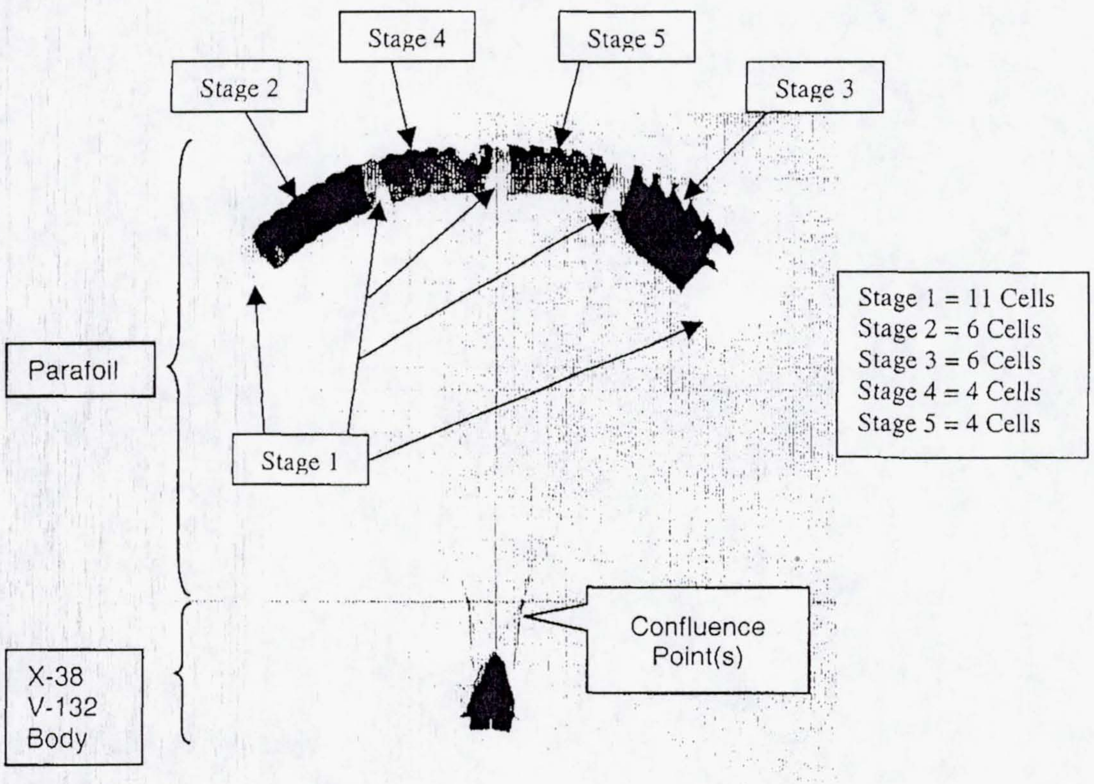
NASA is currently working on developing the X-38 Crew Return Vehicle for the International Space Station (ISS). The aerodynamics of the X-38 and its enormous 7500 ft^2 parafoil are extremely complicated and must be understood and modeled accurately before the vehicle is actually used for human space flight. A large amount of analysis has been performed on the steady state regions of the flight profile when the parafoil is already open. However, the deployment region of the flight profile has not been analyzed in much depth and is a particularly complicated dynamic flight period.

During deployment, the X-38 system has its parafoil open up to its full area in five stages over a period of 20-30 seconds. The vehicle transitions from angles of attack around 90° to 0° in about two seconds and is extremely dynamic. This paper will detail the analysis work done to generate accurate flight profile characteristics of the deployment from flight data from vehicle test drops. Additionally, a computer simulation tool for steady state flight was modified to analyze and model the parafoil deployment. Eventually, a computer model was produced that generated accurate representations of the parafoil deployment dynamics for the vehicle test drops to date.

Introduction

NASA is currently designing and building the X-38 Crew Return Vehicle which will serve as a rescue craft for up to seven people on the International Space Station (ISS). The spacecraft utilizes a wingless body and the largest parafoil ever designed (7500 ft^2) which will help the craft descend gently through the Earth's atmosphere. Due to the immense size of the parafoil, it is deployed in a staged manner, reaching its full area in five stages in a matter of 20-30 seconds. Opening the full parafoil all at once would produce incredible structural loads that would destroy the parafoil and the vehicle. NASA is currently conducting atmospheric testing using a lighter weight test vehicle, V-132, which has a smaller parafoil area (but large enough to provide a good model for the full-size parafoil) of 5468 square feet. It deploys in the same fashion the full-size parafoil will deploy. These stages can be seen in Figure 1.

Figure 1: Parafoil Stages



The X-38 V-132 test vehicle is dropped from the wing of a B-52 at high altitudes to simulate the flight profile of the X-38 reentering Earth's atmosphere. However, before the full-size vehicle is ready for manned space flight operations, the dynamics of the parafoil must be understood and modeled accurately under all conditions. The steady state regions of the flight profile (i.e. parafoil is fully deployed) have already been examined in detail. However, during deployment the analysis and modeling is much more complicated. The parafoil is changing its size, shape, area, and enclosed air mass during deployment, generating an extremely dynamic platform that experiences a large range of aerodynamic conditions. The most dynamic event occurs during the first few seconds of deployment when the first stage opens. The X-38 system transfers from an angle of attack around 90° to 0° and then back up to some trim alpha. This drastic event affects the stability of the system throughout the rest of the deployment stages. This can be seen in the test flights where some flights have ended deployment with trim angles of attack of 9°, while others have had 49°.

The goal was to produce a model that predicts how the deployment plays out aerodynamically to allow NASA to better design the parafoil and improve inflation dynamics. To accomplish this goal, the flight characteristics of the parafoil deployment during V-132 test drops had to be analyzed. Additionally, a computer simulation tool (PDS – Parafoil Dynamics Simulator) for steady state flight was modified to analyze and model the parafoil deployment. With this modified program, sensitivity studies can then be conducted examining the impact of initial conditions, staging times, and staging areas.

The steps taken to perform the necessary analysis to achieve these goals is broken down in the following categories:

- Identify Flight Data and PDS Analysis Problems
- Analyzing Flight Data
- Modifying and Optimizing PDS
- Analyzing and Adjusting the Optimized PDS Model
- Analyzing Results from the Modified PDS Model
- Conclusions – Utilizing the new model

Before proceeding with the deployment analysis, below is a definition of variables used throughout the paper.

Definition of Terms and Variables:

Confluence Point = Point where parafoil lines come together
C_L = Coefficient of lift
C_D = Coefficient of drag
C_M = Coefficient of moment about ¼ chord
Cm_{conf} = Coefficient of moment about confluence point.
W = Weight
M = Mass
q = Dynamic pressure
S = Total Area of parafoil
S' = Area term for parafoil area which is modeled as increasing linearly during each stage of deployment
γ = Flight path angle
β = Beta (angle between velocity vector and parafoil)
α = Angle of attack
θ= Pitch
ϕ= Roll
Vz = Vertical velocity
Vh = Horizontal velocity
Vr = Total Velocity
a_x = Horizontal acceleration (Body X axis)
a_z = Vertical acceleration (Body Z Axis)
P3D3 – X-38 Vehicle 132 Drop #3
P3D4 – X-38 Vehicle 132 Drop #4
P3D5 – X-38 Vehicle 132 Drop #5

Identifying Flight Data and PDS Analysis Problems

PDS, or Parafoil Dynamics Simulator, is a FORTRAN parafoil simulation tool. PDS is an eight degrees of freedom (DOF) simulator that has 6 DOF's for the parafoil and 2 DOF's for the vehicle. The vehicle is free to rotate in the yaw and pitch planes with respect to, and independently of the parafoil in PDS. It is used to produce an aerodynamic model of a parafoil and its vehicle as two rigid bodies connected at a confluence point. Using data tables from existing Aero-databases of parafoil dynamics, this simulation generates a complete aerodynamic model for the parafoil including C_L, C_D, C_m, γ, α, θ, ϕ, Vz, and Vh.

However, PDS has some limitations to be considered when using it to analyze parafoil deployment dynamics. First off, PDS was originally designed to model steady state regions of the flight with a fully deployed parafoil. The aerodynamic data tables for C_L, C_D, and C_M that PDS used were originally based off of analysis of low angle of attack flight from palette test drops. However, the deployment period of the flight is not steady state as it experiences accelerations as the parafoil deploys, and the vehicle flies at high angles of attack. The lack of a steady state condition on the deployment also complicates the generation of the C_L and C_D from flight data. The steady state equations only account for accelerations from gravity are not valid during deployment. Deployment of the parafoil induces additional accelerations that need to be considered during deployment.

Other problems include that PDS's model can be compared to only three V-132 test drops. This limits the available flight data to analyze and compare with PDS models. Even amongst these flights, there are different configurations and initial conditions, which make producing one model to describe every flight difficult. For example, NASA engineers noticed for the first V-132 test drop, P3D3, that the parafoil did not inflate smoothly as it deployed. The parafoil was crunched and deformed during deployment and inflation. To combat this effect, NASA installed floor inlets on the bottom of the parafoil for flight P3D5 to allow for easier inflation of the parafoil. Although the crunch effects are still evident on each test drop, the floor inlets somewhat help to reduce deformation effects for P3D5. These deformation effects affect the ability to compare flight data to PDS, as PDS does not in anyway model these deformation effects. The deformations are definitely important as they affect in immeasurable ways the size, shape, area, and mass of the parafoil and therefore affect how the system flies. This is a limitation of PDS that must be noted.

Wind corrected velocities also pose a problem for comparing PDS and flight data. The X-38 uses FADS, or Flush Air Data System, to record wind velocities, which are used in generating the true horizontal velocities of the vehicle in flight data. However, when the vehicle is at high angles of attack, as it is during first stage, the FADS inlets are not facing the wind velocity and are unable to make accurate measurements of the wind velocities and direction. Therefore, flight data's wind corrected horizontal velocities are uncertain during high angles of attack flight.

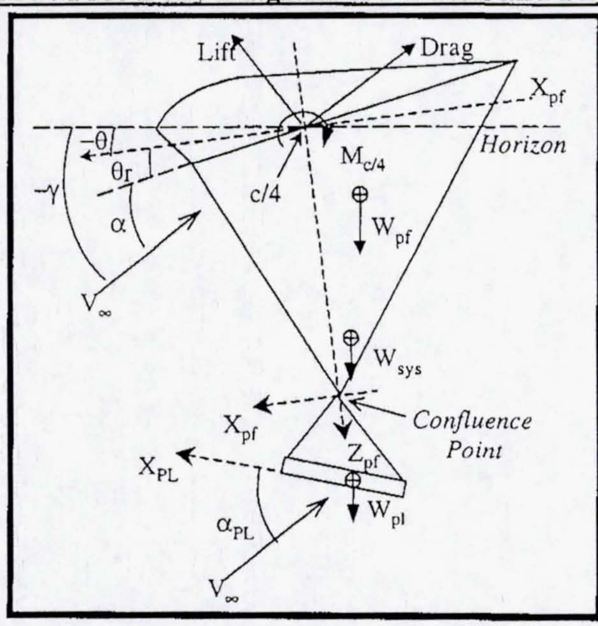
Additionally, PDS idealizes the vehicle and the parafoil as a system where the lines connecting the two bodies are always in tension and PDS does not allow for independent vehicle roll. In reality, the X-38 and its parafoil are not a rigid body system, and they have the freedom to move independently of each other in basically every direction. The result of this freedom is that during test flights, particularly during deployment, the vehicle may have a different attitude than the parafoil. This causes problems when trying to compare flight data with simulation results as PDS produces the aerodynamics of the parafoil and actual test drops only yield vehicle data. For all test drops to date, data recording systems have only been mounted on the vehicle, not on the parafoil. To compare PDS to flight data to see the validity of PDS's model, the vehicle dynamics from flight data must be represented as the parafoil dynamics. When the vehicle's attitude is different than the parafoil's attitude in test drops, it is inaccurate to directly transfer the vehicle dynamic data to the parafoil. Analysis of flight test video has revealed that there are times during the flight when the two bodies are not acting together and adjustments have to be made to flight data to allow comparison with the model from PDS. This is accomplished by using transformation matrices to improve the accuracy of the attitude from flight data.

In summary, the unsteady nature of deployment, the different vehicle configurations, the unknown errors in wind velocity corrections, and the independence of the parafoil and vehicle must be considered, and if possible corrected, when modeling the deployment of the parafoil.

Analyzing Flight Data

For the flight data analysis, the analysis problems just outlined had to be considered and corrected. Figure 2 shows a free body diagram of a parafoil and payload system such as the X-38.

Figure 2: Free Body Diagram of Parafoil and Payload



The steady state equations serve as a starting point for determining the true flight coefficients of lift and drag.

$$C_L = [(W)\ COS\ (\gamma)]/(qS) \qquad C_D = [(W)\ SIN\ (\gamma)]/(qS)$$

As previously mentioned, the system during deployment is not in steady state as its area is changing, there are outside accelerations from deploying the parafoil, and the system has not yet reached terminal velocity. Therefore, the accelerations in the lift and drag direction must be considered and the parafoil area must be increased in integral fashion to accurately find C_L and C_D. Since there are other forces than gravity producing accelerations on the system, it is no longer valid to represent the forces solely as weight (W). A more accurate description is that the forces acting on the parafoil are equal to mass times acceleration. This acceleration is then broken down into components along the drag axis and along the lift axis. To do this, first the flight path angle (γ) and the total velocity had to be found using components of the velocity. The equations for CL and CD are derived from F = Ma and are as follows:

$$\gamma = Tan^{-1}\ (Vz/Vh) \qquad Vr = (Vz^2 + Vh^2)^{1/2}$$

$$d\gamma/dt = \Delta\gamma/\Delta t \qquad dVr/dt = \Delta Vr/\Delta t$$

$$C_L = M\ [(d\gamma/dt)(Vr) + g\ (\cos\ (\gamma)]/qS'$$

$$C_D = M\ [-(dVr/dt) - g\ (\sin\ (\gamma)]/qS'$$

Additionally, the angle of attack (alpha, α) of the parafoil had to be generated from vehicle data. Vehicle Alpha is found by using the free body diagram of Figure 2.

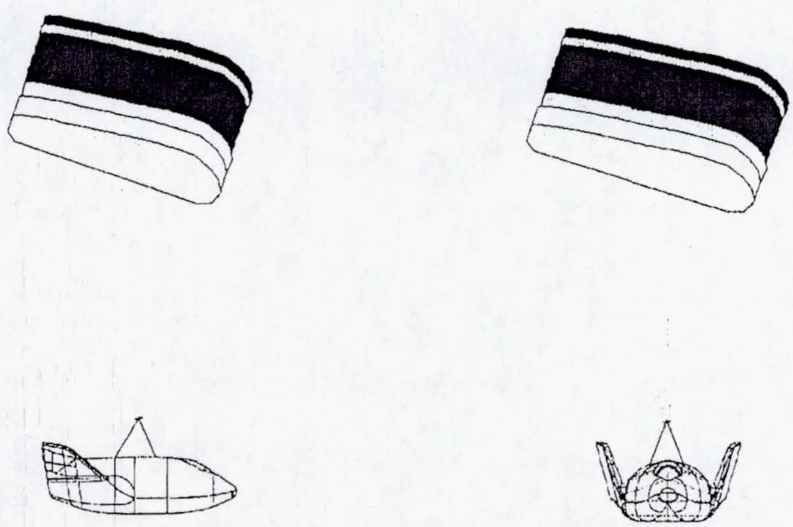
$$\alpha(\text{vehicle}) = -\gamma + \theta\ (\text{pitch})$$

This results in the vehicle alpha. To generate the parafoil alpha, the rigging (9.6°) and hanging (5°) angles of the parafoil are subtracted from the vehicle alpha.

Flight data attitude, particularly parafoil pitch, must also be corrected where possible. As detailed in the Analysis Problems section, the vehicle can move independently of the parafoil, which generates problems in finding the parafoil attitude. This problem of independent motion of the vehicle is a problem that that applies mostly to the deployment stages of the flight, not steady state flight with a fully deployed parafoil. Therefore, it had not been previously analyzed until the deployment of the parafoil was analyzed. One particularly interesting problem is when the vehicle yaws independently of the parafoil. Figure 3 shows an example for orientations of a relative yaw of 0° and a relative yaw of 90°.

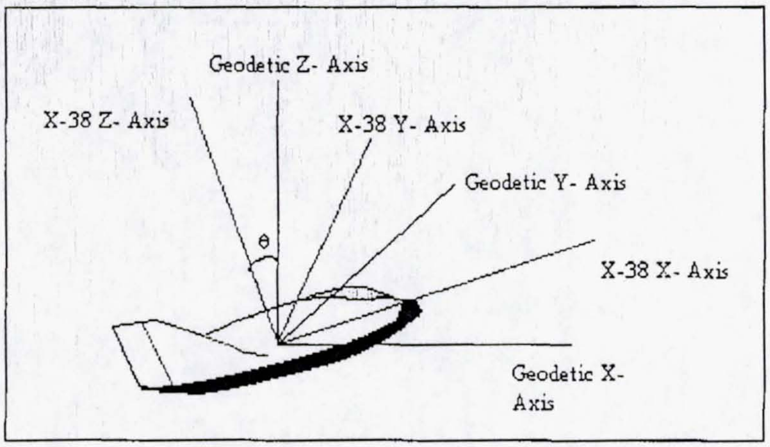
Figure 3: Vehicle Position Relative to Parafoil:

X-38 with relative yaw = 0° **X-38 with a relative yaw = 90°**



When there is a relative yaw of 90°, in transferring vehicle attitude to the parafoil, a vehicle pitch would be represented as a parafoil roll and a vehicle roll as a parafoil pitch. This inaccuracy can be corrected by using transformation matrices to find the true parafoil attitude. However, there is one major assumption to make to allow the following calculations to be accurate. Beta, the angle between the incoming velocity vector and the x- axis of the parafoil, must be assumed to be zero. Looking at flight data and simulation models, this is a fairly reasonable assumption as beta fluctuates in a small region from zero to five degrees. If this assumption is not made, the attitude of the parafoil is unknown, particularly the X- and Y- axes, and the Geodetic coordinate system can not be used. Using this assumption, the problem is solved by finding the X-38 Body Z-axis in the Geodetic Coordinate Frame. The angle between the X-38 Body Z- axis and Geodetic Z-axis will produce the true parafoil pitch.

Figure 4: Geodetic and X-38 Body Axes used to find true parafoil pitch



This angle is found using the vehicle's pitch, roll, and yaw as Euler angles and using the appropriate transformations. The transformation matrix and the necessary operations are shown in the following calculations.

$$Z_{body} = (x, y, z)_{geo}$$

$$Z_{body} =$$

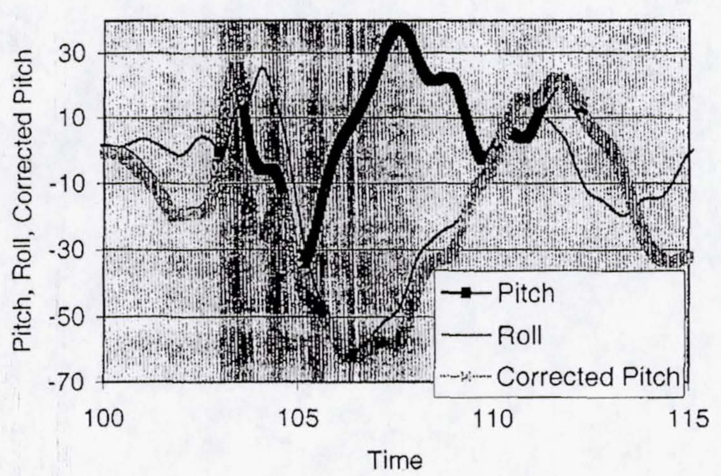
$$[0 \quad 0 \quad 1]_{Zb.} \begin{bmatrix} \cos.\varphi\cos.\theta & \cos.\varphi\sin.\theta\ \sin.\phi - \sin.\varphi\cos.\phi & \cos.\varphi\sin.\theta\ \sin.\phi + \sin.\varphi\sin.\phi \\ \sin.\varphi\cos.\theta & \sin.\phi\sin.\theta\ \sin.\varphi + \cos.\varphi\cos.\phi & \cos.\phi\sin.\theta\ \sin.\varphi - \sin.\phi\cos.\varphi \\ -\sin.\theta & \sin.\phi\cos.\theta & \cos.\phi\cos.\theta \end{bmatrix}$$

$$\theta_{new} = (90 - \tan^{-1}(z/(x^2 + y^2)^{1/2}))$$

After running through these calculations, it was recognized that this operation would always produce a positive angle. The flight video clearly indicates both positive and negative pitch angles for the system. To determine sign changes, the dot product of the Body Z-Axis and the Horizontal Velocity vector was found. When this value changes signs, so does the sign of the new parafoil pitch.

The results of making these corrections were very striking and greatly increased the accuracy in which the flight profile was represented. Figure 5 shows the large difference these calculations make in determining true parafoil pitch from vehicle data for V-132 flight P3D5.

Figure 5: Pitch, Roll, and Corrected Pitch vs Time - P3D5



The dark squares plot is the recorded vehicle pitch and the light line is the vehicle roll. The plot with "x's" is the angle generated by the calculations just described and represents the true parafoil pitch. In comparison to the vehicle pitch and roll plots, this new pitch sometimes mirrors the vehicle pitch, sometimes mirrors the vehicle roll, and is also a combination of the two at times. This confirms that the vehicle experiences a large relative yaw during deployment, and shows how large an impact a relative yaw can have on the accuracy of representing vehicle data as parafoil data.

Modifying and Optimizing PDS

In addition to the above calculations and corrections to flight data, the actual PDS code had to be modified to allow it to more accurately model parafoil deployment. The first step was to eliminate the old aero-database data tables that had been defined for low alpha, steady state flight regimes. These look-up data tables contained values for C_L, C_D, and C_M versus angle of attack and were coded in directly into PDS as data points. As mentioned previously, the X-38 parafoil flies in both high and low angles of attack during deployment, and therefore this set of data points was invalid for deployment analysis. To replace these data tables, step functions and linear interpolations between each step were coded into PDS to describe the plots of C_L, C_D, and C_M versus angle of attack. This allows for the easy adjustment of the aerodynamics of the parafoil in PDS by simply changing the values of the step functions instead of changing every data point in a table.

Using the step functions, a MATLAB optimizing routine was adapted for PDS that had the ability to change the values of each step and rerun the simulation. The MATLAB function changed a total of 35 coefficients for C_L, C_D, and C_M using random numbers within user-defined limits. After running this simulation with the new steps, the optimizer would calculate a cost or error function, which was based on the magnitude of difference between the simulation results and flight data. Certain critical factors were given more weight than others such as pitch, Vz, and Vh. The larger a cost function, the worse model that set of steps produced and vice versa. Each cost function is compared to the cost function from the pervious run to determine how to best change the coefficients for the next run. The optimizer runs through this routine until it reaches a point that there is insignificant change in the cost function.

With PDS modified and the optimizer installed, the environmental data from the V-132 test drops such as density and wind velocities were inputted into PDS to produce aerodynamic computer models. These models could be compared to the actual aerodynamic data from the V-132 test drops. For V-132 flight P3D5, PDS produced a surprisingly accurate model with the vehicle trimming at the correct angle of attack of approximately 8.5 degrees. Flight P3D3 posed an interesting problem. This flight trimmed at a much higher angle of attack (~50°) than all the other flights, and to ensure an accurate model, PDS had to trim at this high angle. Again, the optimizer produced an accurate model, this time with a high trim angle of attack. For flight P3D4, video and flight data analysis has shown that the errors in wind velocity correction are particularly large and that there was a large amount of independent movement between the vehicle and parafoil that cannot be easily corrected. Due to these inaccuracies in flight data, it is difficult to confidently back out the parafoil aerodynamic data from the vehicle test drop data. Therefore, at this time, it was not used in generating one model that can describe all flight profiles.

Based on the two optimized flights P3D5 and P3D3, a model had to be formed that could be used to describe all flights. Plotting the aerodynamic curves of C_L, C_D, and C_M versus α from both flights, a trendline was formed that averaged any differences between the two models. Using that trendline as the new Aero-database, P3D3 and P3D5 were run, producing good results with the correct trim angles for both flights.

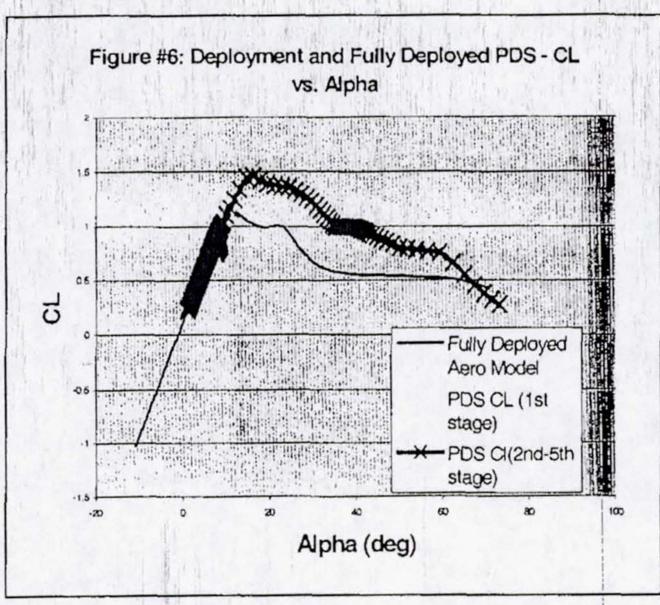
Analyzing and Adjusting the Optimized PDS Model

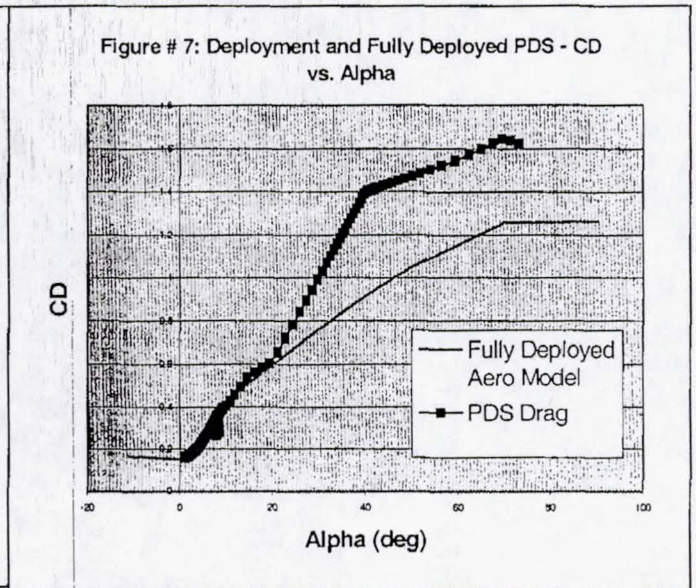
Although the new PDS was generating the correct flight profiles for the trim alpha, comparison of the first stage for almost all of the other aerodynamic characteristics showed a great deal of error. This was expected as the first stage was the most dynamic period and two steps were taken to help eliminate this error. The error sources are the same as mentioned earlier under analysis problems. The first correction made was to account for the affects the relative vehicle yaw had on the actual vehicle (not the parafoil) drag. PDS incorporates vehicle drag, which NASA has calculated through other tests and analysis, to help generate parafoil drag. Since the vehicle presents a different and larger cross section to the free stream velocity when it is yawed with respect to the parafoil, the vehicle drag is higher. Therefore, increased vehicle drag was inputted into PDS during deployment.

The second correction was made after analysis of flight video for P3D3 and P3D5. In both cases, the parafoil undergoes a sizable deformation during first two stages as it is inflating. During the first stage, the deformation is a result of the parafoil not inflating quickly enough to form its airfoil shape. This lowers the lift of the parafoil. In the second stage, the problem is that the parafoil structure deforms as the lift increases, therefore increasing drag. This result is seen in the video as a momentary stall of the parafoil during the deformation at high C_L. PDS cannot model these events with its original code. However, during second stage, a drag increase was hard coded into the program to simulate these effects. Additionally, the lift of the parafoil for the first stage was hard coded in as a lower value than the lift during the rest of the deployment. This helps model the unformed parafoil shape in first stage. Using these modifications, PDS produced highly accurate models of the X-38 system.

Analysis of Results from the Modified PDS Model

The following figures compare the new aerodynamic deployment model to the aerodynamic model for the steady state, fully deployed parafoil.





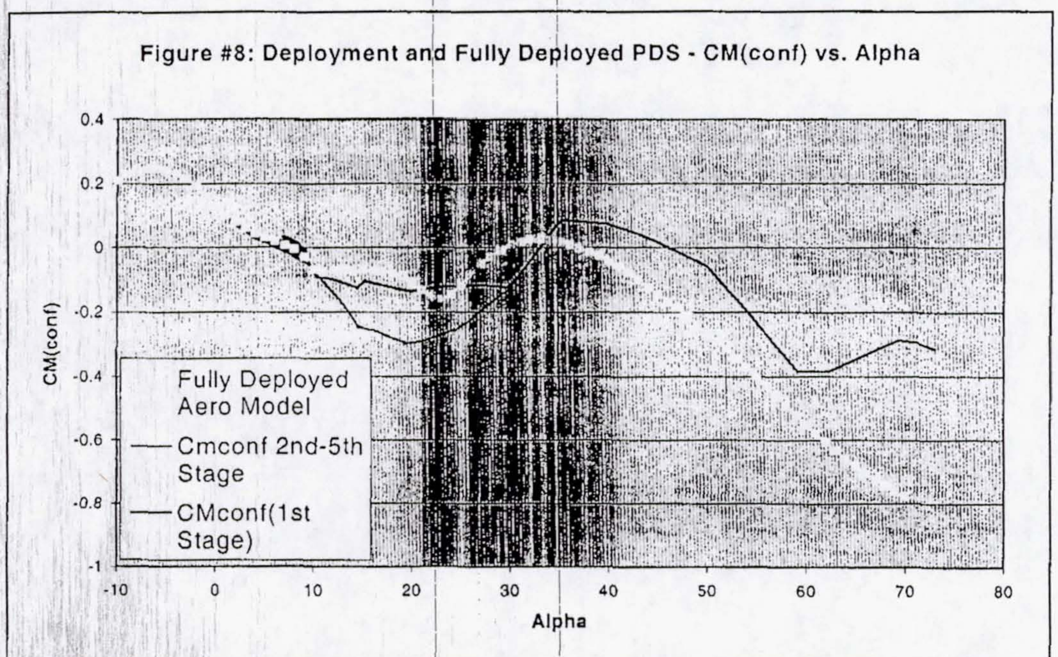


Figure 6, C_L vs. α, compares the lift of the new deployment model to the old steady state model. It also shows the two different lift curves that result from the first stage deformations. During first stage, the parafoil has a lower lift than during the second through final stages of deployment. Figure 7, C_D vs. α, compares the drag of the new deployment model to the old steady state model. The drag is significantly higher in the deployment model at higher alphas as the parafoil has not achieved its fully inflated shape and there are deformations increasing drag. However, notice in both models that at lower alphas, the new drag and lift curves are very similar to the steady state models. This is a result of the fact that once the system settles at the lower alphas, generally by the third stage, the dynamics of deployment are not nearly as violent as the first few stages.

Figure 8 plots C_{Mconf} vs. α, and is particularly important in describing the behavior of the X-38 system. Basically the equation behind C_{Mconf} is derived from transferring the axis of rotation from the quarter chord where C_M is found to the confluence point of the parafoil lines. It is dependent on the values for C_D and C_L. The result is extremely useful in determining Trim Angle of Attack. When the C_{Mconf} is equal to zero, there is no moment acting on the system around the confluence point, and therefore the system has no forcing action to change its orientation and angle of attack. This plot shows that the C_{Mconf} goes to zero three times over the range of angles of attack that the X-38 flies through. Each of time C_{Mconf} goes to zero is a trim alpha, but some trim points are more stable than others are.

The initial conditions and the timing of the staging are vital to determining which trim point the parafoil will stick at. The ideal angle of attack for the parafoil is around 9°

and flight P3D5 flies at this angle. However, P3D3 flies at a trim of ~50°. The difference between these flights is that because of initial conditions and the timing of the staging of the parafoil for P3D3, the vehicle had enough momentum to swing back up past the 9° trim point and get stuck at the high trim point. P3D5 was more stable and did not have enough momentum to achieve this.

Using this new aerodynamic database for C_L, C_D, and C_M, the optimized results, and the first and second stage modifications, P3D5 and P3D3 were run. The following figures show the accuracy of the PDS model compared to flight data for P3D5. Earlier version of PDS had little convergence with flight data but these results produce fairly accurate trends following flight data. They compare flight data with the finished deployment PDS model after being optimized and modified with the corrections for the first two stages incorporated. Particular items of interest include the correct, low trim angle of attack seen in Figure 9 and the accuracy that the Vertical Velocity and Lift are modeled in Figures 10 and 11. Figure 12 also produces a good match for drag and the inserted second stage drag spike is evident from 108-112 seconds.

Figure 13 is particularly important as it shows the magnitude of the changes to better model the 1st and 2nd stage deformations made to PDS. It plots Horizontal Velocity versus time and shows a stark improvement in the PDS model after the lower first stage lift and increased second stage drag were incorporated. Also plotted on the Figure are the Corrected and No Wind Correction Horizontal Velocities. Due to the analysis problem detailed earlier, wind corrections can be unreliable at higher angles of attack as experienced in first and second stage. Therefore, the true flight data horizontal velocity profile is somewhat uncertain at high angles of attack. That is why both plots are shown.

Figure 9: Alpha vs. Time - P3D5

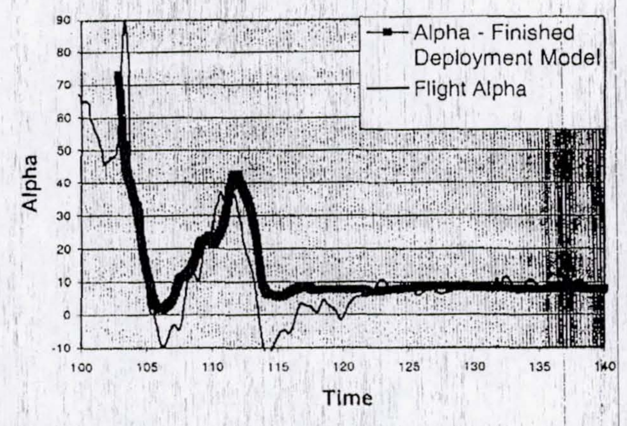


Figure 10: Vz vs. Time - P3D5

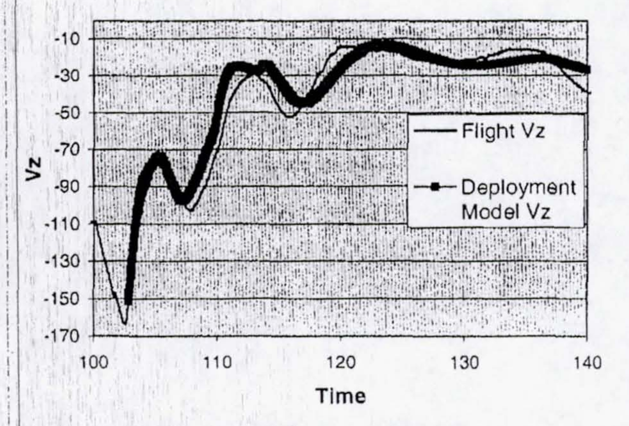


Figure 11: CL Comparison -P3D5

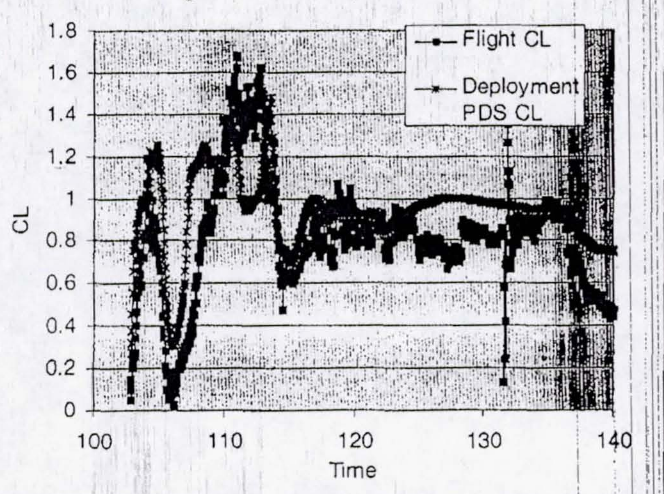


Figure 12: CD comparison -P3D5

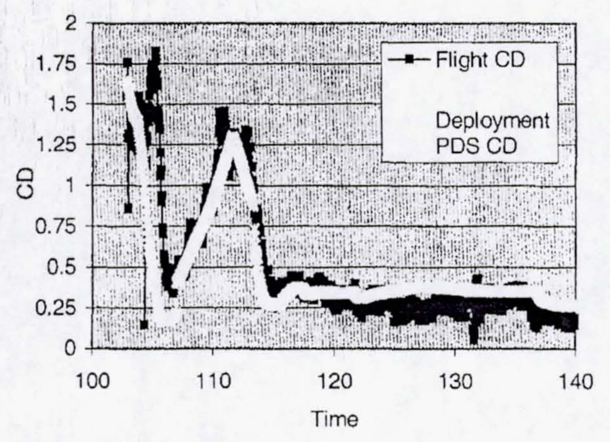


Figure 13: Vh vs. Time - P3D5

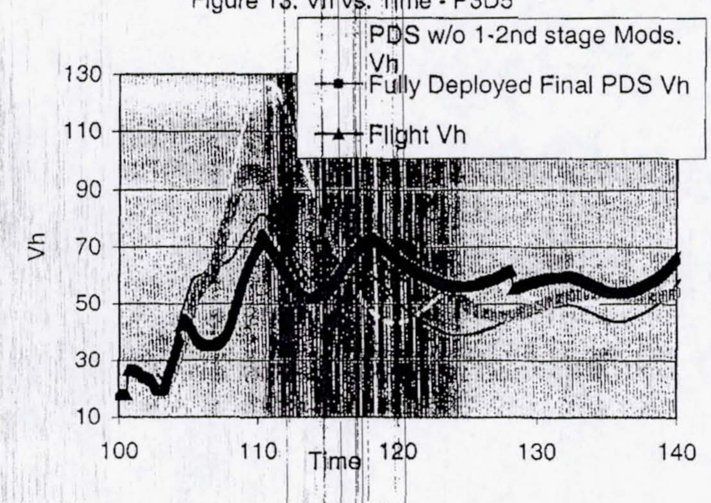
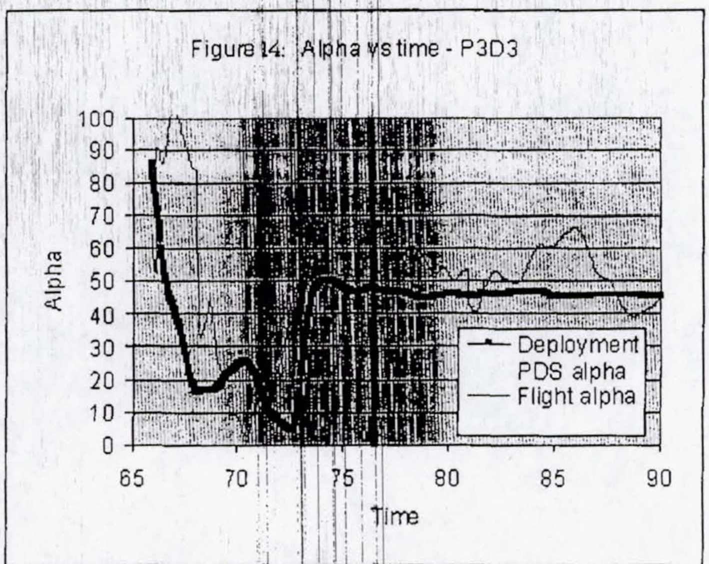


Figure 14 below is from flight P3D3 and is included to show that the new PDS model is able to produce flight profiles where the vehicle trims at a high angle of attack. This shows the versatility and accuracy of the new deployment PDS tool. Other aerodynamic plots for P3D3 and the new PDS model matched well with flight data as it did for P3D5.



Conclusions - Utilizing the New Model

With this new computer model, it is possible to perform sensitivity studies. The initial conditions at deployment play a large role on the dynamics of the flight. The effects of changing initial pitch, roll, yaw, and horizontal velocity can be examined with this modeling tool. For example, the initial pitch can be varied to determine the acceptable ranges of initial pitch angles for the vehicle to trim at a low angle of attack. Other sensitivity studies can be performed with the staging events of the parafoil. Using the new PDS, changes in the staging times and the duration of each stage can help indicate what staging periods produce the most stable flight. Additionally, stages can be combined in the modeling tool and have larger areas of the parafoil opened up at a time.

For example, combining stages 1 and 2 so 17 parafoil cells open during stage 1 instead of 11 cells. This has the possibility of making the flight more stable; however, the greater loads produced by these larger areas must be examined to ensure the safety of the vehicle.

Additional work needs to be performed to apply the computer model to flight P3D4 and any future test flights. However, the flight data analysis of the deployment provides a good foundation for generating accurate parafoil deployment data for future drop tests. Additionally, PDS has been modified to handle parafoil deployment considering the dynamics seen in test flight, particularly the first and second stage dynamics. The result is seen in the comparisons between flight data and PDS for P3D5 and P3D3, where the model produces a highly accurate description of the flight profile of the X-38 system. It is capable of predicting a low angle of attack for P3D5 and a high angle of attack for P3D3. The model also matches the trends of flight data for C_D, C_L, Pitch, Vertical Velocity, and Horizontal Velocity. The result of this work is a model that can be used to predict flight profiles for future flights under a variety of conditions allowing NASA to define a stable and safe flight envelope for the X-38 system.

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