

Aerodynamic Reconstruction Applied to Parachute Test Vehicle Flight Data Analysis

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The aerodynamics, both static and dynamic, of a test vehicle are critical to determining the performance of the parachute cluster in a drop test and for conducting a successful test. The Capsule Parachute Assembly System (CPAS) project is conducting tests of NASA's Orion Multi-Purpose Crew Vehicle (MPCV) parachutes at the Army Yuma Proving Ground utilizing the Parachute Test Vehicle (PTV). The PTV shape is based on the MPCV, but the height has been reduced in order to fit within the C-17 aircraft for extraction. Therefore, the aerodynamics of the PTV are similar to, but not the same as, the MPCV. A small series of wind tunnel tests and computational fluid dynamics cases were run to modify the MPCV aerodynamic database for the PTV, but aerodynamic reconstruction of the flights has proven an effective source for further improvements to the database. The acceleration and rotational rates measured during free flight, before parachute inflation but during deployment, were used to confirm vehicle static aerodynamics. A multibody simulation is utilized to reconstruct the parachute portions of the flight. Aerodynamic or parachute parameters are adjusted in the simulation until the prediction reasonably matches the flight trajectory. Knowledge of the static aerodynamics is critical in the CPAS project because the parachute riser load measurements are scaled based on forebody drag. PTV dynamic damping is critical because the vehicle has no reaction control system to maintain attitude - the vehicle dynamics must be understood and modeled correctly before flight. It will be shown here that aerodynamic reconstruction has successfully contributed to the CPAS project.

I. Introduction

When testing parachutes in the wake of a blunt body, such as a capsule, it can be beneficial to analyze the aerodynamic characteristics of the forebody to understand its effects on parachute performance and the overall stability of the test configuration. In addition, flight test programs might not have a complete set of aerodynamics before starting and it could be necessary to use the flights themselves to confirm or improve the aerodynamic databases. Equipping the test vehicle with an IMU and GPS system, coupled with measurements of atmospheric winds and pressure, gives quantitative information on which to base dynamic pressure and angle of attack. Aerodynamic forces and moments calculated from measured acceleration and body rotational rates can be compared to databases and possibly improve the nominal aerodynamic predictions or uncertainties. Multibody simulations can reconstruct longer periods of flight to determine dynamic aerodynamics and parachute performance. The stability of the test article is very important and using multibody simulations allowed the Capsule Parachute Assembly System (CPAS) team to develop an updated aerodynamic stability database that affected future test architectures.

Aerodynamic reconstructions using two different tools have been used to improve the PTV aerodynamic database. During the short durations of free flight the static aerodynamics are extracted from the measure-

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ments. The free flight aerodynamics are compared to the database. The longer periods of flight under the Drogue parachutes are reconstructed using a multibody Flight Analysis and Simulation Tool (FAST). The simulation inputs are adjusted until the primary metrics (altitude, dynamic pressure, and root summation squared (RSS) of pitch and yaw rates) reasonably match throughout the segment. Parachute drag is a large driver of vehicle motion; however, the parachute drag coefficient, C_D , is not presently modeled as a function of time or PTV attitude. The average drag coefficient is adjusted to match the dynamic pressure and descent rate. The dynamic aerodynamics of the PTV have proven to be different from the original database. The C_{mq} database was adjusted as a function of angle of attack and Mach number to match the time history of flight data.

The CPAS program, which is utilizing aerodynamic reconstruction, is described in section II. Section III describes how static aerodynamics are extracted from free flight and compared with the reference database. Section IV describes how multibody simulations are used to reconstruct test flights and to make modifications to parachute performance and vehicle aerodynamics.

II. CPAS Program Description

NASA is developing the Orion MPCV to return crews from missions as distant as Lunar orbit to an ocean landing. The MPCV is a capsule similar to the Apollo capsule, but with a $\sim 30\%$ larger diameter and almost twice the mass. Although the capsule design is being led by Lockheed, the parachute system is government furnished equipment. NASA is leading the CPAS project, with the support of contractors and vendors, to design, develop, test, and qualify the parachute system. The CPAS project is approximately half way through the engineering development unit (EDU) tests of the parachute clusters configured closely to the MPCV design.^{1,2}



Figure 1. Photograph of the PTV mounted on the CPSS.

The MPCV is designed to enter the atmosphere and reduce speed via aerodynamic drag to mid-subsonic speeds. Two 23 foot diameter variable porosity conical ribbon Drogue parachutes are deployed to further slow the capsule and to stabilize the vehicle attitude in the denser atmosphere at lower altitudes. Each

Drogue has two reefed stages to control inflation loads. Below a preset altitude, the guidance algorithm cuts away the Drogues at a time when the pitch and yaw rates are near minimum to reduce the possibility that the vehicle could flip as the Main parachutes deploy. The three Main parachutes are independently deployed by three mortar deployed pilot parachutes. The pilot parachute mortars are fired simultaneously with the Drogue riser cut. The Main parachutes are 116 foot ring sail parachutes - also with two reefed stages - designed so that the vehicle contacts the water at an acceptable velocity should one Main parachute fail.

The CPAS EDU tests use two different platforms to test with: a large dart designated the Parachute Compartment Development Test Vehicle (PCDTV) and the Parachute Test Vehicle (PTV). The PCDTV is a low-drag dart extracted from a C-130 aircraft for testing the parachute cluster at high velocity and dynamic pressure. The PTV, shown in figure 1, is capsule-shaped to test the wake effects on the cluster performance. It is expected that the wake will significantly reduce the performance of the Drogue parachutes. One of the primary functions of the Drogue chute is to stabilize the capsule during descent. Since the PTV is about 20 inches shorter than the MPCV the moment arm from the center of gravity to the riser fair lead is shorter. Damping due to Drogue parachutes has been shown to be a function of that moment arm squared.³ The Drogue parachutes have about half the damping on the PTV as compared to the MPCV, making the PTV much less stable than the MPCV. The PTV is mated to a modified extraction pallet - the Cradle and Platform Separation System (CPSS). Deployment is from a C-17 aircraft. Extraction has occurred at an altitude of 25,000 feet for all tests to date, but for future tests that altitude will increase to 35,000 feet. The PTV is released from the pallet a few seconds after extraction. Programmer parachutes are utilized to set the attitude and dynamic pressure at Drogue deployment. These parachutes are static line deployed by the CPSS as shown in figure 2. The Programmers connect to the PTV with a four point harness to provide more vehicle damping than a single point attachment would supply.



Figure 2. Photograph of the PTV separating from the CPSS and Programmer parachute deployment.

The aerodynamic forces on the falling capsule can be determined from the acceleration measurements on board the PTV. The PTV contains a NovAtel SPAN-SE (Synchronized Position Attitude & Navigation) - an integrated IMU and GPS system that measures and records position, velocity, acceleration, and body angular rates. A Kalman filter in the post-processing software is used to smooth the 20 Hz GPS data and to estimate position and velocity during any GPS dropouts. The attitude sensors use laser ring gyros, which are not susceptible to magnetic interference from the metallic aircraft and payload; Such interference is a common problem with other attitude sensors. The SPAN-SE IMU is not mounted at the vehicle CG so a kinematic correction is made to the data. Inertial velocity is converted to wind relative velocity using

windpack data recorded shortly after the test vehicle is dropped. The wind speed and direction are measured roughly 20 minutes after the test and a mile from the drop zone. The atmospheric temperature and pressure are measured using weather balloons approximately an hour before and after the test. Using this data, wind speed and atmospheric density are generated as a function of altitude for use in reconstructions and simulations.

III. Static Aerodynamics

PTV aerodynamic drag is critical for determining parachute performance in the CPAS program. Parachute drag force is measured by load cells at the base of the riser. The placement of the load cells at the base of the riser, very deep within the flowerpot, allows a significant amount of the riser load to be transferred to the PTV at the fair lead and within the flowerpot via friction. Therefore the load measurements are less than the true parachute riser force. To correct for this, a scale factor is applied to the load measurement. This factor is calculated by assuming that the PTV drag is known and subtracting its contribution to the acceleration as measured by the IMU. What remains is attributed to the parachute drag, which is divided by the measured riser load to obtain the scale factor.⁴ A scaling factor can be computed for each reefing stage in order to adjust the load cell measurements into agreement with the accelerometer data. The scaling factors are then linearly interpolated relative to the midpoint of each stage. The uncertainty in the vehicle drag can lead to an uncertainty in the drag of two fully open Drogue parachutes of 3%. The uncertainty is even greater for single parachutes and reefed Drogues.

At all times during a drop test a parachute is either open or in the process of being deployed. Engineering judgment is used to determine the times during chute deployment when the non-aerodynamic forces on the PTV are small enough to ignore. For those short durations the measured drag, as determined from the IMU accelerations, are compared to the PTV database. The original PTV aerodynamic database was adjusted after the first test, designated CDT-3-3, based on newly available wind tunnel results and the flight measurements. The flight confirmed that the PTV drag was higher than originally predicted and that the new wind tunnel test results should be included in the database. Unfortunately, during the drop tests the PTV drag varied across the entire uncertainty band of the database, and we were unable to reduce the uncertainties. The subsequent PTV test, CDT-3-5, also had enough variability that we have not reduced the uncertainties.

Figure 3(a) shows the drag coefficient as a function of total angle of attack for a number of flight test periods and database values. The solid gray line represents the original database nominal drag. The dashed lines represent the uncertainties, which were large due to differences between wind tunnel and computational fluid dynamics data. The solid red line represents the database updated with new wind tunnel data. It can be seen that the nominal drag is greater from total angle of attack of 140 to 180 degrees. These new results were used to adjust the nominal drag higher and to reduce the uncertainties. There are three periods of PTV flight where the drag due to parachutes is relatively small: The CPSS to Programmer flight (C2P), the Programmer to Drogue flight (P2D), and the Drogue to Main (D2M) flight. As can be seen in figure 2, the Programmer chute is static line deployed as the PTV leaves the CPSS and will apply some force on the PTV during deployment. The PTV leads the CPSS through the air, therefore the aerodynamic interaction is minimal between the two objects after the PTV clears the CPSS. The second free-flight period is between Programmer and Drogue flight. The Drogue is mortar deployed simultaneously with the cutting of the Programmer riser. The mortar could cause a pressure spike on the back surface of the PTV. Also, the deployment of the parachute and suspension lines from its bag introduces forces on the vehicle. Finally, the PTV has the longest free flight time between the Drogues and Mains (D2M). The Pilots are mortared out, inflate, and then pull out the Main deployment bags. This time should be the best for determining drag, but as can be seen in the figure, data from the two flights show the drag at the opposite limits of the uncertainty.

Although the variation of drag could be due to natural unsteadiness of the flow, the dynamic pressure uncertainty, changes in surface roughness, and heat shield gaps all could contribute. Improving the understanding of any sources of measurement uncertainty is an ongoing task. Inertial velocity measurements are combined with wind and pressure measurements to determine airspeed. Since the wind and pressure measurements are recorded at different times and locations, there is a fairly large uncertainty in the actual atmosphere that the test vehicle flies through. The uncertainty in drag force is approximately 5% primarily due to uncertainty in dynamic pressure. Capsule drag can be greatly affected by surface roughness, gaps in

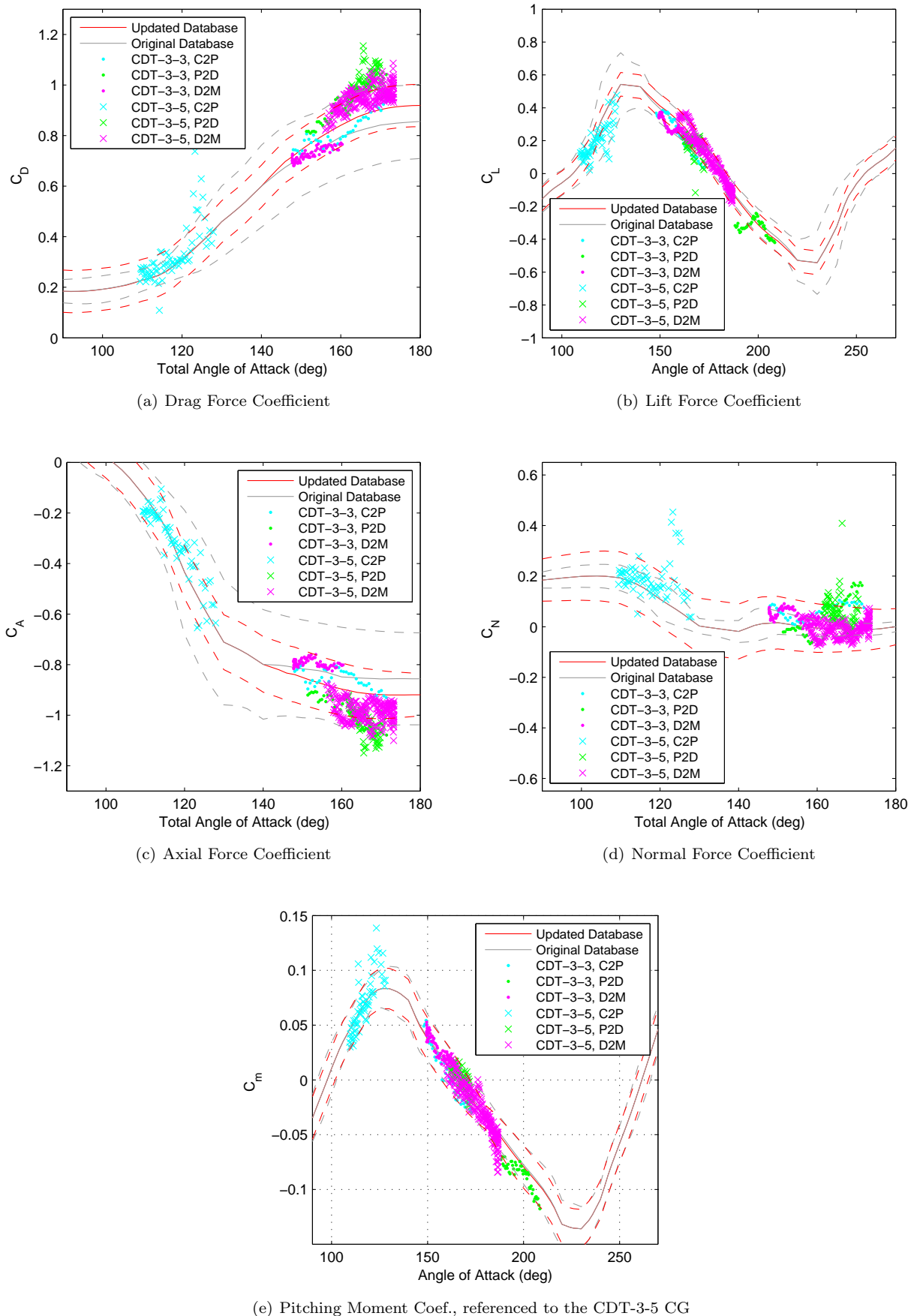


Figure 3. Comparison of database and measured PTV aerodynamic coefficients.

the surface, or ridges on the surface. The PTV heatshield is designed to have the same outer mold line as the MPCV and is assembled from 13 separate pieces with gaps of up to 3/8" between the panels. On the first flight, those gaps were not covered. On subsequent flights, the gaps were covered with tape.

For completeness, aerodynamic coefficients were extracted for all six body axis forces and moments during the portions of free-flight. Figure 3 also shows the normal, axial, and lift force coefficients and the pitching moment coefficient. The aerodynamic extraction of the free flight data confirmed the updated static aerodynamic database, but has been unable to reduce the uncertainties. The uncertainties in drag coefficient affect parachute performance calculations. One potential solution in work is to move the load measurement out of and above the flowerpot.

IV. Aerodynamic Reconstruction

Aerodynamic reconstruction can be accomplished with single-body or multibody dynamics simulators. We use FAST, a 6 degree of freedom (6-DOF) multibody simulator developed by the Flight Mechanics and Trajectory Design branch at NASA-Johnson Space Center. FAST was built to be an easily reconfigured simulation tool for the rapid delivery of atmospheric trajectory design products for conceptual vehicle studies and post-flight analysis products for prototype vehicle test flights. FAST simulates the 6-DOF motion due to aerodynamics and gravity for both the PTV and the parachutes as a coupled system. Measured conditions at chute deployment are used as initial conditions in the simulation and the resulting motion is compared with flight data.

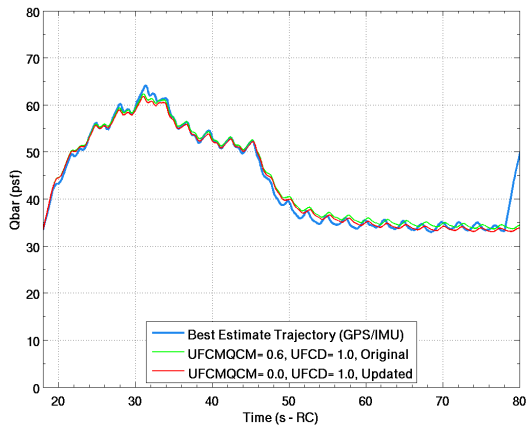
The PTV aerodynamic dynamic stability, called dynamic damping or C_{mq} from here forward, was originally assumed to be equal to that of the MPCV. The first PTV flight experienced pitch motion with rates near the maximum predicted by the Monte Carlo assessment. The PTV flying with two Drogues is shown in figure 4. Aerodynamic reconstructions were accomplished to determine the cause of the relatively large pitch motion. The simulation models the parachute performance and vehicle motion, and these are compared to the flight data. The chute performance parameters and the PTV mass properties and aerodynamic properties are adjusted - within reason - to best match the flight data.

The first parameter that is matched is dynamic pressure as shown in figure 5(a). Small differences in dynamic pressure (~ 1 psf) results in large differences in total drag force on both the PTV and the parachutes. To match dynamic pressure, the total drag of the system must be close to the true value. A very good method for checking that the average dynamic pressure, and hence average drag, is correct is to compare the altitude history. Parachute drag is varied to try to keep the actual and reconstructed altitude difference, as shown in figure 5(b) to less than 75 feet for the Drogue phase of flight. The true parachute drag has large oscillations that are a function of both capsule orientation (wake effects) and Drogue performance, as shown in figure 5(c). By matching the altitude history, those oscillations are averaged out.

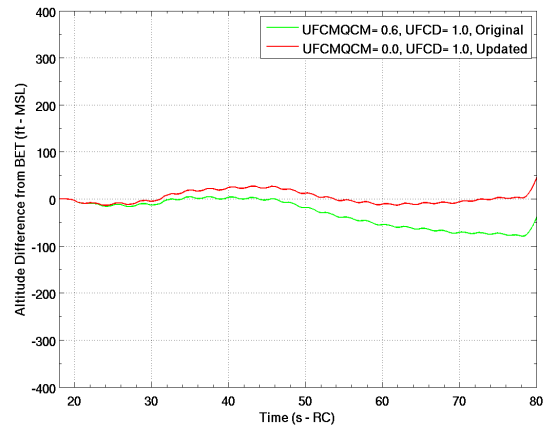
When simulated drag gives acceptable altitude differences and dynamic pressures, the pitch and yaw motion of the vehicle should be simulated well if the aerodynamic dynamic damping database represents the flight vehicle. There are many ways to adjust aerodynamic parameters: scale up the entire database, bias the entire database, use the uncertainties to adjust the utilized value, modify the database point by point, or any combination thereof. The current implementation of the aerodynamic database allows for the former three options to be implemented fairly easily for any aerodynamic value. Values of C_{mq} uncertainty factors are used as a basis for modifying damping. The C_{mq} value is scaled between the nominal (UFCMQCM = 0) and the maximum uncertainty (UFCMQCM = 1.0) for all values of Mach number and angle of attack when accomplishing each reconstruction. When developing a new database based on flight data, C_{mq} is adjusted



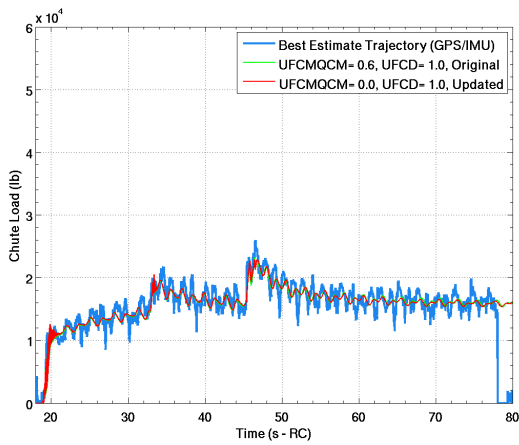
Figure 4. PTV under two Drogues.



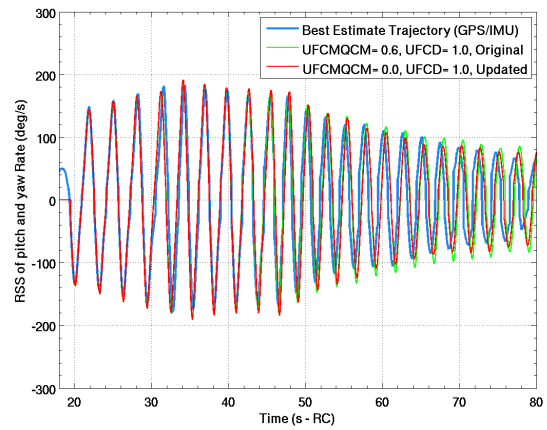
(a) Dynamic Pressure



(b) Altitude Difference



(c) Total Parachute Load



(d) RSS of Pitch and Yaw

Figure 5. Reconstruction of CDT-3-3 with original and new aerodynamic databases compared to the flight trajectory.

point by point in the database. Of course, as the PTV pitch motion changes the PTV drag changes and large changes require iterating on chute drag. The metric used for quality reconstruction of body motion is the RSS of pitch and yaw rate. Both amplitude and frequency are matched as closely as possible by adjusting UFCMQCM and mass moments of inertia.

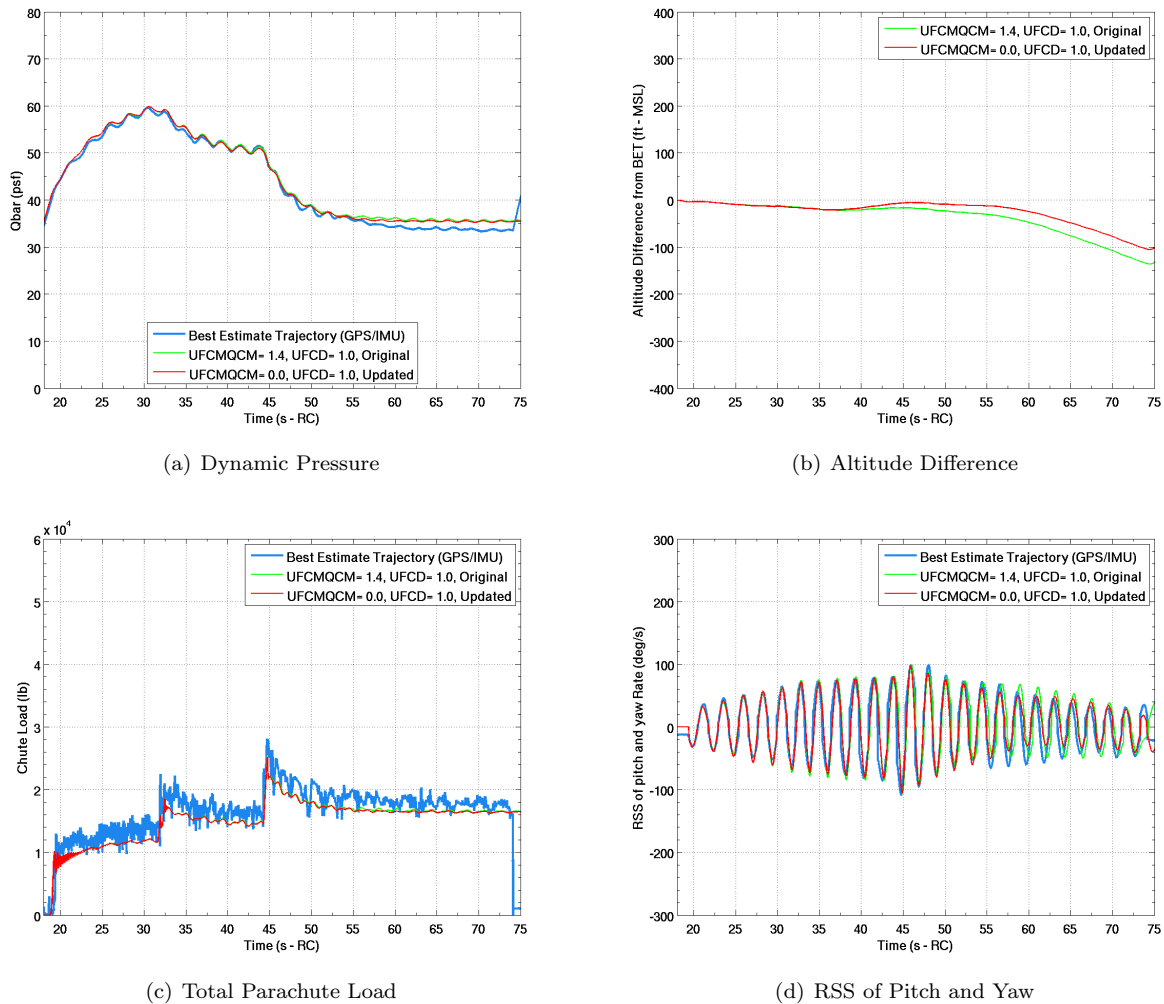


Figure 6. Reconstruction of CDT-3-5 with original and new aerodynamic databases compared to the flight trajectory.

As has been mentioned, the first PTV flight had more motion in pitch than expected. The reconstruction process found the best match resulted from using a UFCMQCM of 0.6, as shown in figure 5(d). I_{yy} also had to be increased by 3% of the calculated value to match the frequency of pitch motion. The second PTV flight had again more motion than expected during the second reefed stage of the Drogues. After many attempts at reconstructing the second flight it was found that a very large UFCMQCM of 1.2 to 1.4 was required to match the RSS of pitch and yaw rates; For clarity only UFCMQCM = 1.4 is shown in figure 6. Here, every other cycle of the RSS is negated to better show the vehicle motion. A key to matching the pitch and yaw rates was adjusting the mass moments of inertia in two dimensions so that the periods of simulated motion matched flight. The best matches were found with I_{yy} decreased by 3.5% and I_{zz} increased by 3% from the calculated values. The inertia is calculated use the ProE CAD package and has an uncertainty of $\pm 10\%$, so the relatively small adjustments are reasonable. The two flights had different hang angles under the Drogues, so different ranges of angle of attack were experienced in each flight. Because the PTV shape is different than that of the MPCV, which the dynamic damping database was originally developed for, the C_{mq} is significantly different at certain angles of attack. The second PTV flight happened to oscillate through a region with dynamic damping greater than the uncertainties in the database. The discovery of the issue delayed the CDT-3-7 flight test in order to develop an updated PTV aerodynamic database and to

create an optimized algorithm that cuts the Drogue parachutes at a better combination of angle of attack and pitch and yaw rates for a safe Main deployment. An example of the updated C_{mq} database is shown in figure 7.

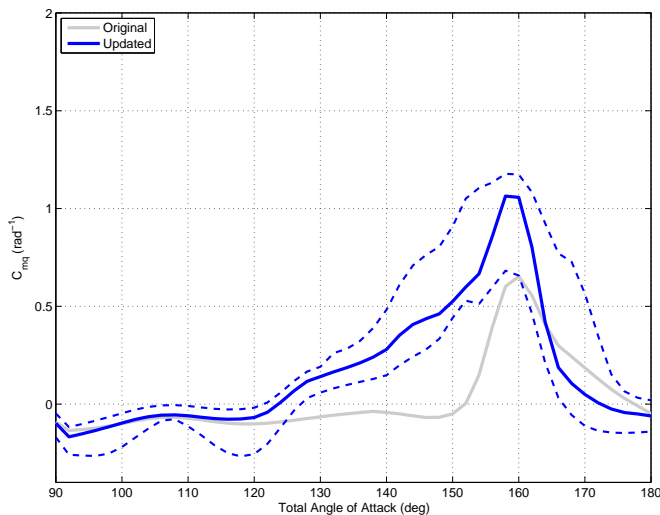


Figure 7. Example of modification to updated C_{mq} database.

V. Conclusion

The NASA/Jacobs CPAS team is continually adding to the knowledge of parachute performance in a vehicle wake and the coupled dynamics of a capsule by testing with the PTV. Analyzing the aerodynamics of the PTV has proven to be an integral part of the overall test program and has been used to improve the quality and reliability of the tests. Understanding vehicle drag is important when characterizing chute performance since the load measurements were made below the fairlead and do not accurately reflect the actual parachute load. Development of a more representative dynamic damping database anchored to flight test data has allowed testing to proceed with reasonable and better understood risk.

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