CALCULATING AERODYNAMIC COEFFICIENTS FOR A NASA APOLLO BODY USING TELEMETRY DATA FROM FREE FLIGHT RANGE TESTING

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ABSTRACT

The U.S. Army Research Laboratory (ARL) was requested by the National Aeronautics and Space Administration (NASA) Langley Research Center (LaRC) to perform a free-flight experiment with a telemetry (TM) instrumented sub-scaled Apollo shaped reentry vehicle in order to determine its aerodynamic coefficients. ARL has developed a unique flight diagnostic capability for reconstructing flight trajectory and determining aerodynamic coefficients of projectiles by using sensor data telemetered from free flight experiments. A custom launch package was designed for this experiment that included the Apollo shaped projectile, which housed a modular telemetry unit, and a rapid prototyped sabot. The experiment was able to produce estimates for aerodynamic coefficients that were considered accurate and this technique is appealing to NASA for the development of their spacecraft in the future.

INTRODUCTION

Project Constellation was launched in response to President Bush's speech at NASA Headquarters on January 14, 2004 in which he set forth an aggressive plan for future space exploration. NASA plans to develop a new fleet of vehicles with extended capabilities in order to travel back to the moon, to Mars, and beyond[1]. One of the main challenges of this bold vision is the development of a new crew exploration vehicle to house the astronauts during their missions. The CEV being developed is similar to the shape and function of the 1966 Apollo (see Figure 1); however it is three times its size and can transport up to four astronauts to the moon at a time. Achieving these ambitious goals will require NASA to focus on new technologies and methodologies.

ARL has investigated instrumented developmental munitions with custom TM systems to obtain aerodynamic coefficients for the past forty years. Recently, ARL has partnered with Arrow Tech Associates to develop a custom software program to utilize the telemetry data, along with other information available, to calculate the aerodynamic coefficients of a projectile from measured flight data[2]. This software code, Extending Telemetry Reduction to Aerodynamic Coefficients and Trajectory Reconstruction (EXTRACTR), imports the sensor data, meteorological (MET) data, radar data, and projectile physicals to process, through an iterative algorithm, a solution for the aerodynamic coefficients that would have caused the measured flight response. The code attempts to fit the measured translational and rotational sensor data to the six-degree-of-freedom (6DOF) equations of motion using both the Maximum Likelihood Method and Least Squares arriving at an acceptable solution for a given aerodynamic coefficient (usually within three or four iterations). It was the goal of this program to extend the capability of EXTRACTR to determine the aerodynamic coefficients for a projectile shaped like a NASA CEV, which will experience minimal spin. In particular, the nonlinear coefficients were of great interest to NASA.

There are many other ways of estimating aerodynamic coefficients that NASA has available to them. In the past they have used a combination of spark range and wind tunnel testing. Both have their shortcomings. Spark Range testing is taken at an indoor spark range where measurements are made from shadowgraphs placed along the range. The measured translation and orientation of the projectile is recorded and fit using a similar method as described for EXTRACTR[3,4,5]. The limitation of spark range data is that it is only taken at a few discrete points along the flight path and the body must fly relatively straight in order to avoid damaging the indoor range. Wind tunnel testing is capable of simulating a wide variety of flow regimes and flight conditions with the ability to sustain the loading environment for as long as desired. However, the interference of sting mounts in the flow regime and reduction in the degrees of freedom make it a less ideal environment for collecting pure flight response data.

Figure 1 – NASA Apollo Crew Exploration Vehicle (1966)

BODY

The experiment was conducted using an extended travel 120mm smooth-bore artillery cannon with a scaled-down Apollo CEV. This provided the quickest and most cost-efficient means to demonstrate ARL's TM technique to provide the required aerodynamics data needed by NASA. In all, 2 M829A1 slugs, 3 Apollo CEV shaped slugs, and 4 Apollo CEV TM units were shot. The M829A1 and Apollo CEV shaped slugs were fired for charge development and for verification of instrument alignment and triggers. Of the four rounds fired with telemetry, two had sabots with their symmetry axis aligned with the central axis of the gun bore (referred to as 0 degree orientation) and two had sabots with that axis pitched 15 degrees downward with respect to the axis of the bore (referred to as a 15 degree orientation) (see Figures 2 and 3).

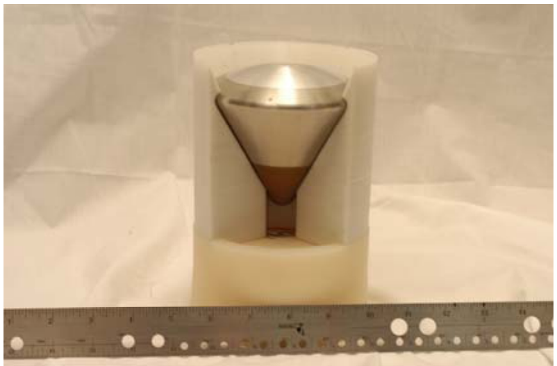

Figure 2– 0 degree Apollo CEV Sabot

Figure 3 – 15 degree Apollo CEV Sabot

The instrumented CEV rounds (see Figure 4) were made up of three parts; the body, the telemetry (TM) module, and the radome. The body was made of two materials (as seen in Figure 5 with the dual colored blunt face), the majority of the body was machined from stainless steel and a portion of the heat shield was made aluminum that was threaded into the steel and set with Lock-Tite ® in order to locate the center of gravity at the correct distance along the symmetric axis of the body (approximately 30% of the diameter from the tip of the heat shield). Stainless steel was chosen because it does not effect the magnetic measurements like other steels would. The housing for the telemetry module was also machined from stainless steel. It was necessary to have the radome machined from plastic that would allow for the telemetered data from the antenna to be transmitted through it. The TM was threaded into the body until it reached a stopping point. The radome was threaded onto a smaller diameter thread around the transmitter and antenna on the aft end of the TM housing until it made contact with the body.

Figure 4 - Instrumented CEV Round Components

The sabot design was selected with the goals of time, flexibility, and cost efficiency in mind. The sabots (4 petals total), made of polycarbonate, were rapid prototyped from a Fused Deposition Modeling (FDM) machine. This particular machine was capable of building the sabot in less than eight hours. Due to the layering process that the FDM machine uses to build a part, the sabots were capable of taking on any shape and it was possible to rotate the accepting vehicle at any angle within the sabot. A tapered nylon obturator plate sat behind the sabot. Its purpose was to hold the base of the sabot together in the tube and to create a seal during launch. The CEV launch package components are shown in Figure 5.

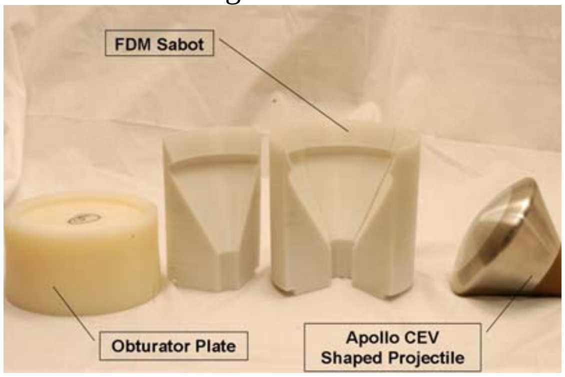

Figure 5 – Apollo CEV Launch Package

The custom telemetry module was designed with a sensor package capable of transmitting up to sixteen channels of measurement data for over one hour and twenty minutes with its rechargeable lithium polymer battery. Its measurements included rate of rotation, acceleration, and magnetic field strength in all three primary axes. The module was capable of withstanding launch accelerations up to 15,000 g's. The module had a major diameter of 50.8mm and a length of 63.5mm. Fully assembled, the module weighed approximately 0.4kg. The sixteen channel encoder featured a 118.9 ms delay that allowed for the data taken in-bore to be telemetered after muzzle exit. The analog data was transmitted after being commutated at an average sample rate 18 kHz. The sensors were aligned in the package using two custom rapid prototyped fixtures. One fixture contained spaces for the five rate sensors to be mounted, as well as a high-g accelerometer and a magnetometer around the rectangular batteries. The second aligned an ARL designed inertial measurement unit (IMU), which consisted of a dual-axis accelerometer, a tri-axis magnetometer as well as two accelerometers placed at a radius from the center (a standard practice used to give spin rate for projectile whose rotation rates exceed the capabilities of rate sensors). A detailed illustration of the telemetry module is shown in Figure 6.

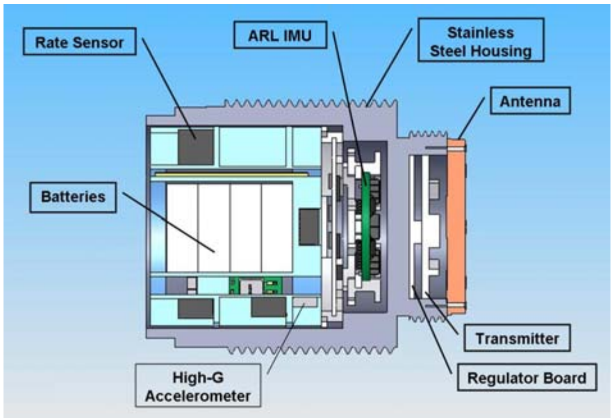

Figure 6 – Apollo CEV Telemetry Module Cutaway View

Each CEV TM module was calibrated prior to the flight test. Each sensor was calibrated by imparting a known excitation to the sensor and measuring the output. This output was then adjusted with a scale factor and bias to adjust the output to match the known input in the desired units. Accelerometers were calibrated by rotating the module through a few revolutions at a slow speed and reviewing the response of the sensor to the acceleration of gravity (See Figure 7). Angular rate sensors were calibrated using a single axis rate table (See Figure 8). The unit is rotated at several known rates in a stepping manner and sensor response is recorded so that the correct scale factor and bias can be applied to the sensor. Data taken during this step was used to calibrate the axial offset (AO) accelerometers on the IMU. Finally, magnetometers were calibrated using a Helmholtz Coil (See Figure 9). The coil generates a preset array of magnetic fields of different magnitude and orientation which will characterize the response of the magnetometers in the telemetry module. Following sensor calibration, physical measurements were taken. The mass, center of gravity, and mass moments of inertia were measured using instrumentation at the Transonic Experimental Facility.

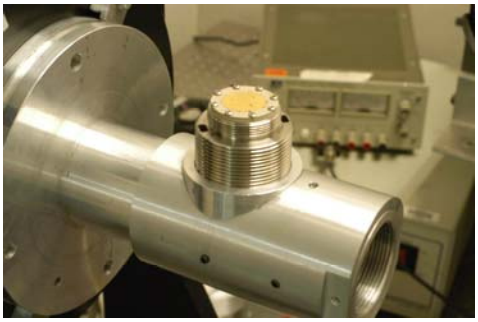

Figure 7 – Accelerometer Calibration Setup

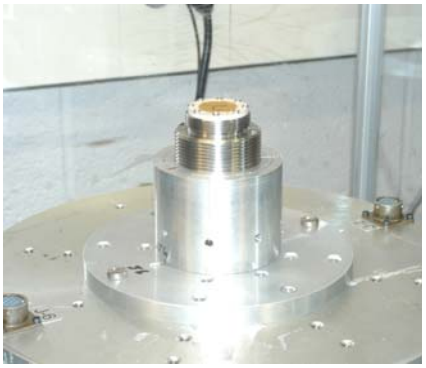

Figure 8 – Rate Sensor Calibration Setup

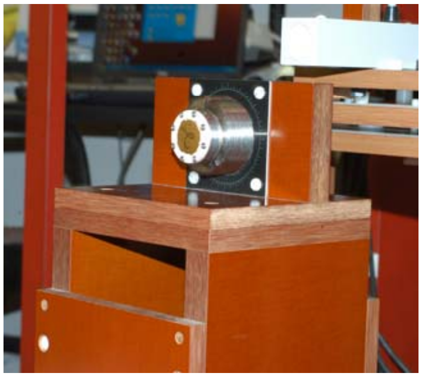

Figure 9– Magnetometer Calibration Setup

The experiment was performed at the Transonic Experimental Facility (TEF) located at APG, MD on April 26-27, 2006. A double travel 120mm smooth-bore cannon, shown in Figure 10, was used to launch the rounds. An extended travel barrel (approximately 8.8 meters in length) can increase the muzzle velocity approximately 20 percent without increasing the launch accelerations and loading to the launch package when compared to a single length barrel. It was important to maximize the muzzle velocity of the NASA Apollo CEV so that data could be obtained through the highest Mach numbers. The quadrant elevation of the gun was set to 45°. Piezoelectric pressure probes provided pressure measurements at the breech and at a point halfway down the gun. Peak pressure was also measured by copper crusher gages. A Weibel tracking radar with a tracking antenna provided measurements of the Apollo's velocity and position as it traveled down range. A stationary radar was aimed at the muzzle to give a more focused measurement of muzzle exit velocity. A MET measurement system was placed near the firing site to provide local conditions and weather balloons were launched three times each day to monitor conditions higher in the atmosphere.

Figure 10 – Double Travel 120mm Cannon

A high speed (flight follower) video camera, capable of panning along the flight path, tracked the projectile from the muzzle through its first 100 ms of flight. This video provided visual verification of sabot integrity, structural integrity of the projectile, and an indication of the quality of the sabot separation. The importance of this flight follower video was demonstrated in this experiment and will be discussed in the results section later. The flight follower setup is shown in Figure 11. It is positioned along the line of fire, approximately 78 meters down range from the muzzle.

Figure 11 – Flight Follower Camera

A TM van (Shown in Figure 12), operated by Aberdeen Test Center (ATC), was equipped with telemetry data acquisition instrumentation. Three receiving antennas were placed around the firing site with different orientations in order to increase the quality of the data received and ensure no data would be lost (see Figure 13). All CEV TM data times were stamped with IRIG-B time and time-zero referenced to an infrared (IR) sensor that was pointed at the gun to detect muzzle blast.

Figure 12 – Telemetry Van Interior

Figure 13– Dish Antenna

This paper will focus on the data received from the third instrumented Apollo CEV shot (CEV4), which was launched in a 15 degree sabot. The CEV4 data was considered the best set because it did not experience any impact from pieces of the sabot or obturator after separation during its flight, thus reducing the risk of tainted aerodynamics data. The CEV flight body recontact issue during flight was verified visually for each CEV from the flight follower video. This recontact issue was resolved in a follow-on sabot redesign program. After combining data from all three antennas, a master data set was compiled in which no frames of data were lost. The calibration measured prior to flight was applied to each channel of sensor data. The body-fixed principal axes of the CEV (I,J,K) and the Earth-fixed (X,Y,Z) were defined (see Figure 14).

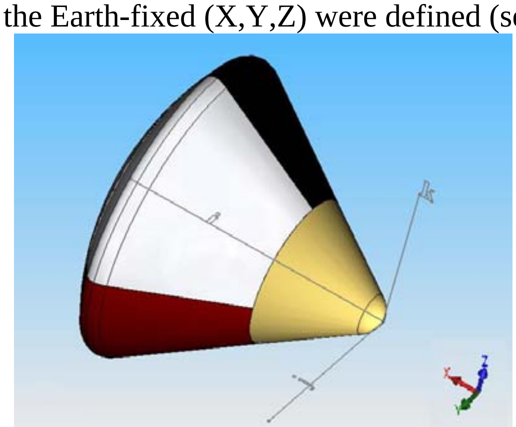

Figure 14 – Coordinate System for Apollo CEV

Set-back acceleration loads at launch exceeded the range of both the axial and radial sensors (9,000G's and 300 G's, respectively). Accelerometers placed at a radial offset from the symmetric axis of the body can be used to calculate the spin rate. This technique is not as accurate when the spin rate is not much larger than the yawing rates. The effects of the yawing rate on the accelerometers can be removed if it is well known. Angular rate sensor data was planned for that purpose; however rate sensors for both the J and K axes were clipped during the flight. The clipping was caused by unexpected motions during flight that caused the rate sensors to be out of range. Without removing the full effects of the yawing motion, the accelerometer data calculated a spin rate about 3.5 Hz for the first second of flight.

Angular rate sensors have proven through other ARL munitions test programs to be prone to a loss of data for a short period of time after launch because of the way the sensors operate. It is believed that the vibratory mass system inside the sensor packaging enters a resonance regime caused by the vibrations of gun-launch. Based on previous test flight data up to 15,000G's, the angular rate sensor data for the first 100-200 ms of flight will not be considered accurate. The measurement range on some of the rate sensors were also shown to be too low for frequencies encountered during the projectiles flight. Although the angular rate exceeded the range of the sensors during a part of the flight, a fit of the data yields good comparison to other sensors data and results using EXTRACTOR. Analysis of the rate sensors with higher ranges, that did not clip until later in the flight, support a 4 Hz spin rate of the body during the first second of flight.

The magnetometer data collected was excellent. After corrections for scale factor and bias, the data was checked for readings in the gun tube which confirmed the strength of the earth's magnetic field at that point. Processing of the magnetometer data shows large yawing motion but it does not suggest that the body was tumbling. Mag J was processed for magnetic roll rate, agreeing with the angular rate sensor data that the projectile experienced a spin of nearly 4 Hz during the first second of flight.

Information gained by this early processing was used to check against the reconstruction performed by EXTRACTR. All parameters are input to EXTRACTR including a description of physical characteristics (mass, length, center of gravity, and moments of inertia), initial aerodynamic prediction (often using PRODAS), MET data, radar data, initial conditions (gun location, quadrant elevation, azimuth), and sensor definition (scale factor, misalignment, cross-axis sensitivity, and location).

EXTRACTR fits measured motion history to 6 DOF equations of motion while iteratively varying aerodynamic coefficients, using a maximum likelihood method, until a match of the motion history is achieved. This fit is accomplished with a window of data at a time due to Mach number dependencies. In this manner, a best fit of coefficients is achieved over a large range of Mach numbers.

EXTRACTR analysis is initiated by inputting a model of the projectile that matches its exterior geometry and physical properties (mass, length, center of gravity, and mass moments of inertia). At this point an initial aerodynamic model can be generated using Projectile Design Analysis System (PRODAS). The user is then prompted to input the test's initial conditions including the quadrant elevation, azimuth, initial pitch and yaw angles, initial pitch and yaw rates and MET data, the position of the radar with respect to the gun, the local Earth magnetic field, and the position of the sensors with respect to the center of gravity as well as any misalignment or cross-axis sensitivity. Finally, the TM sensor and radar data is inputted with the option for the user to eliminate any frames that are deemed to be invalid.

Once all the data has been input, EXTRACTR proceeds to estimate the aerodynamic coefficients. The data is integrated using estimated values of the aerodynamic coefficients and initial conditions from the initial aerodynamic model. Those same equations are then partially differentiated for each coefficient forming a set of parametric equations, which are then numerically integrated to obtain values for the partial derivatives with respect to each coefficient. A differential corrections equation is then set from a Taylor expansion of the dependent variables of the equations of motion. The sensor data is then compared to the computed values in a weighted least squares sense and corrections are computed for the coefficients and initial conditions. The coefficients are adjusted by these corrections and the process begins again with these new values of the coefficients. The method will iterate until convergence is achieved. It has been shown through experience that convergence should occur by the third or fourth iteration.

EXTRACTR software analysis of the experimental data from CEV4 was done to; (1) extract the aerodynamic force and moment coefficients, and (2) reconstruct the flight trajectories for the flight segment of interest. The flight segment of interest was from launch down to Mach 0.6, but prior to rotating through 90 degrees. In other words, the CEV's seemed to tumble after about 1 to 1.5 seconds of flight. CEV4 showed some motion damping very early in the flight, before exhibiting undamped motion for the remainder of the flight. After the data was analyzed to extract relevant aerodynamics including; axial force, normal force, pitching moment, and pitch damping moment, the flight trajectory was reconstructed. The fits to the magnetometer, accelerometer, and angular rate data are considered very good. Figure 18 shows the total angle of attack and Mach Number for CEV4 plotted against time. The trajectory reconstruction yielded the following comparisons of experimental data to EXTRACTR calculated values shown respectively below in Figures 15-19; the radar velocity, the magnetic pointing angle, acceleration in k direction, and angular rate.

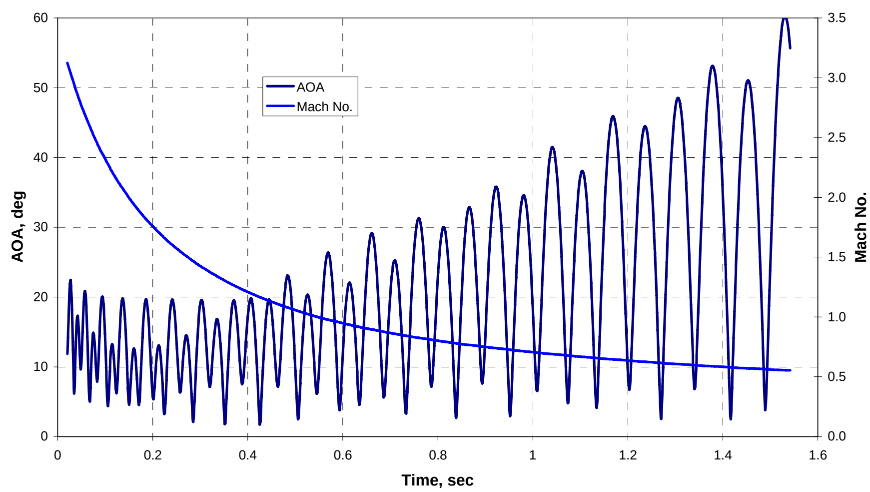

Figure 15 – Total Angle of Attack for CEV4

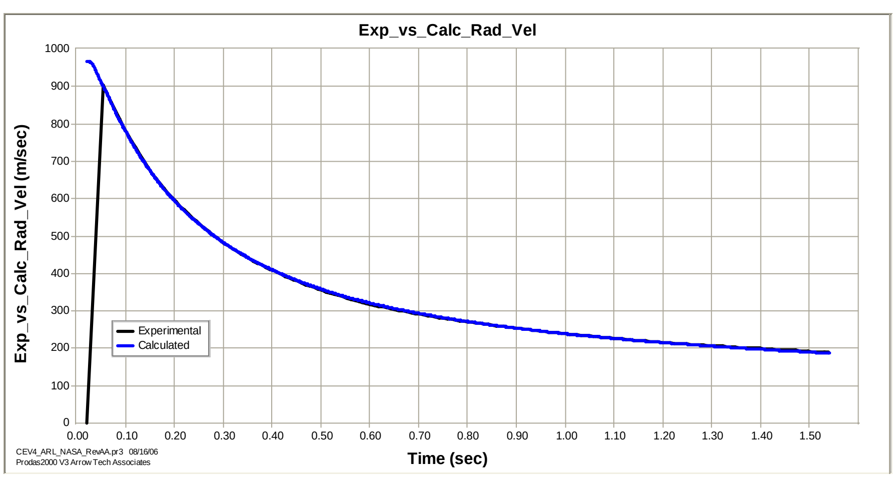

Figure 16 – Radar Velocity for CEV4

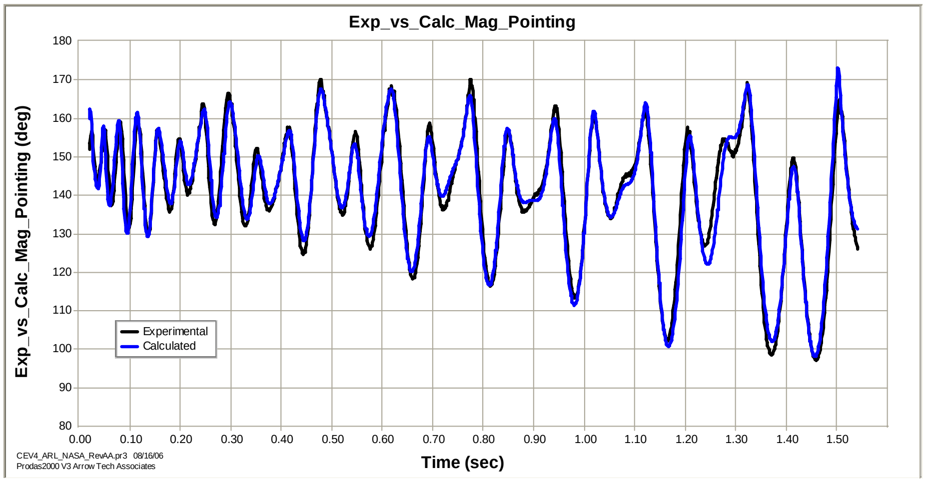

Figure 17 – Magnetometer Angle for CEV4

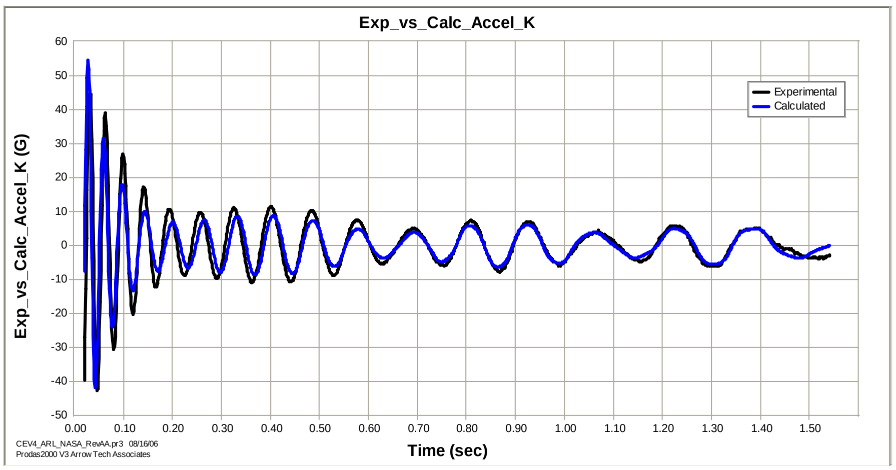

Figure 18 – Accelerometer k for CEV4

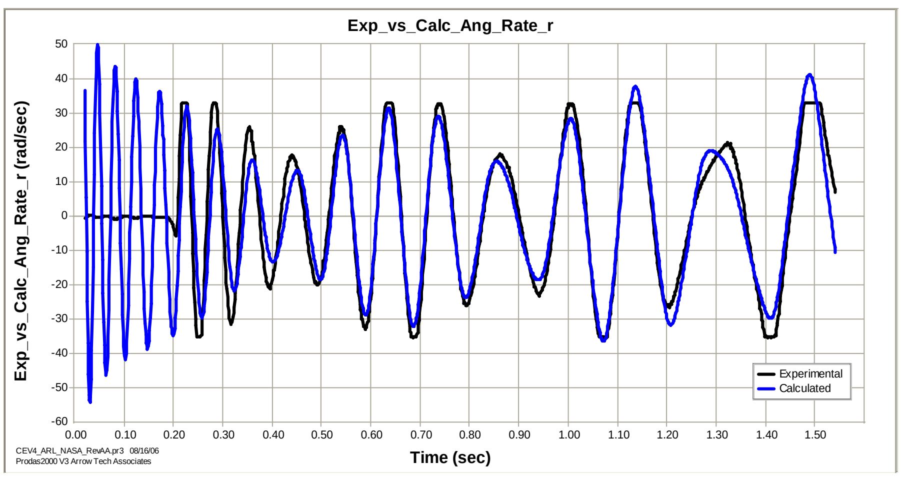

Figure 19 – Angular Rate r for CEV4

CONCLUSIONS

This experiment was the first in a series to evaluate the usefulness of on-board inertial measurements to characterize the aerodynamic characteristics of a NASA re-entry vehicle. In addition, model validation, test procedures, sensor suite performance, and data reduction procedures as part of the implementation of EXTRACTR as the integrated analysis system for dynamic flight data. Using EXTRACTR, the aerodynamics and stability characteristics were extracted from the experimental measurements. Reconstruction of the flight dynamics and trajectories showed close agreement with the experimental data measurements. The aerodynamic results varied more from round to round than expected. This large variation is attributed to external interferences with the rounds, mostly from sabot interference. The large angle motion dominated the pitch damping effect and drove the axial force variations at large angles. Overall the EXTRACTR analysis closely matched the measured flight dynamics and provided a valuable case study to improve the procedure and analytical capabilities of EXTRACTR for the future.

Future plans for this venture include finalizing the aerodynamic coefficient extraction from this experiment and utilizing the lessons learned to perform a free flight telemetry experiment with NASA's new CEV. It is also likely that ARL will design and instrument several other subscale models of other spacecraft being developed for Project Constellation, most notably the Launch Abort System (LAS)

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