Introduction

Eighty-two seconds into STS 107, a sizeable piece of debris struck the left wing of the Columbia. Visual evidence and other sensor data established that the debris came from the bipod ramp area and impacted the wing on the wing leading edge. At this time Columbia was traveling at a speed of about 2300 feet/second (fps) through an altitude of about 65,900 feet. Based on a combination of image analysis and advanced computational methods, the Board determined that a foam projectile with a total weight of 1.67 lb and impact velocity of 775 fps would best represent the debris strike.

The Board received numerous comments from the public suggesting that the foam could not possibly have struck the wing at such a high velocity (about 530 mph). This posting attempts to explain how the Board determined the impact speed of the debris, and why the results are reasonable based on simple physics.

Summary

The visual evidence taken by launch cameras clearly shows the debris impact velocity was between about 500fps and 800 fps relative to Columbia. Just prior to separating from the External Tank (ET), the foam was traveling with the orbiter at about 2300 fps. The visual evidence shows that the debris impacted the wing approximately 0.161 seconds after separating from the ET. In that time, the debris slowed down from 2300 fps to about 1500 fps, so it hit the orbiter with a relative velocity of about 800 fps. In essence, the debris slowed down and the Orbiter did not, so that the Orbiter ran into the debris. The foam slowed down rapidly because it had a low ballistic number. The ballistic number of the debris was small because the foam has a low density. The same sort of physics explains why a Styrofoam cup slows down quickly if it's thrown out of a car window.

Image Analysis

The investigation image analysis team included members from JSC Image Analysis, JSC Engineering, KSC Photo Analysis, MSFC Photo Analysis, Lockheed Martin Management and Data Systems, National Imagery and Mapping Agency (NIMA), Boeing Systems Integration at Huntington Beach, and Langley Research Center. Each member of the image analysis team performed independent analyses using tools and methods of their own choosing. In addition, an investigation transport analysis team used physics based computer models to understand and support the visual evidence. This team included members from JSC Engineering, Ames Research Center, and Boeing. Representatives of the Board participated regularly in the meetings and deliberations of these teams.

The investigation image analysis team used the launch camera imagery to produce several independent measurements of the velocity of the debris along its trajectory and at the moment of impact. Two basic approaches were used:

1. Multi-camera approaches used the three-dimensional debris coordinate positions of the debris relative to the orbiter. This method provided estimates for the three components, X, Y, and Z of the velocity vector.
2. Single camera approaches assumed that, after initial movement away from the external tank, the debris motion was essentially parallel to the orbiter fuselage. Since the single camera methods required fewer assumptions and were not as sensitive to a variety of parameters (especially the uncertainty in the timing offsets between cameras), the single camera methods were viewed as a means to verify the more sophisticated multi-camera methods.

Detailed descriptions of the methods used by the individual image analyses teams to compute the debris velocity will be included in the appendices of the CAIB final report.

The impact velocity computed with the multi-camera methods ranged from 625 ft/sec to 840 ft/sec. This range is consistent with the range computed with two types of single camera methods. One single camera method, using only imagery from ET-208, yielded a velocity of 670 ft/sec (+/- 130 ft/sec). This method involved simply measuring the distance between each debris position as the debris moved down the Orbiter's fuselage and fitting a second order polynomial to the distance vs. time. The impact velocity was determined by taking the derivative of this equation at the estimated time of impact. The scale was derived using the length of the SRB. The second single camera method was applied separately to both ET-208 and to E-212 imagery, and used the debris positions in concert with a relatively simple physics-based model. This approach involved solving a 2nd order differential equation (debris position, velocity, and acceleration vs. time) and iteratively adjusting two equation parameters to minimize the difference between the derived debris positions and the measured positions. The second single-camera method yielded debris velocities ranging from 581 ft/sec to 725 ft/sec.

The wide variation in the debris velocity measurements is attributed to the following. The velocity measurements are highly dependent on the inferred debris locations from the imagery. The ET-208 resolution in particular was insufficient to provide unambiguous debris locations in all video fields. This resulted in significant differences from one analysis to another in defining the debris points, which in turn, affected the velocity calculations. A sensitivity analysis was performed on the single camera 2nd order polynomial fit solution by randomly varying the planar position coordinates of the debris within the ET-208 field of view; variation by as little as two image pixels caused the range of estimated impact velocities to vary between 540 ft/sec and 800 ft/sec.

Transport Analysis

The Board concluded that a smaller estimated impact speed range was credible based on results from transport analysis team. The transport analysis team used sophisticated computer models in variety of approaches. The transport analysis accounted for the complex air flow field over the

STS at the time of the debris shedding event, a range of feasible aerodynamic characteristics of the debris, the trajectory estimates made by the image analysis team, and the size and shape of the bipod ramp. Due to inherent uncertainties in the density, dimensions, shape, and initial velocity of the debris, the transport analysis could not uniquely define the conditions of the impact, however, the team identified a relatively narrow range of credible projectile characteristics in terms of impact velocity and ballistic number.

The ballistic number of an object expresses the relative influence of weight and drag forces on that object, and is the primary aerodynamic characteristic of an object that does not produce lift. The trajectory of an object with a large ballistic number, such as a solid steel sphere, can be computed fairly accurately without accounting for the force of drag. In contrast, the debris that struck the wing had a relatively small ballistic number, which is indicative of a large drag force relative to its weight. The small ballistic number of the debris explains why it slowed down quickly as soon as it separated from the ET. Just prior to separation, the speed of the debris was equal to the speed of the orbiter, which was about 2300 fps. Due to a large drag force (an average of about 250 lbf), the debris slowed down to about 1500 fps in about 0.161 seconds, striking the wing at a relative speed near 800 fps.

Basic Physics Analysis

The reasonability of the foam impact velocity estimates made during the investigation can be verified using fundamental physics.

The motion of the debris obeys Newton's laws of motions. Newton's second law states that the net force on an object is equal to the time rate of change of its momentum. For a constant mass system, Newton's second law is given by the familiar equation.

$$\sum \vec{F} = m\vec{a}$$

where m is the mass of the object, a is the acceleration, and sigma F is the net force on the object.

Assuming that the Shuttle was moving vertically, and that the foam motion was vertical only. The vertical component of Newton's second law is

$$\sum F_Z = ma_Z .$$

where the z direction is taken to be positive upwards.

During the debris flight, there were two forces acting on the debris in the z direction: the aerodynamic drag force and its weight. The aerodynamic drag force, F_D, acts in the opposite direction of the objects motion. Since the object is moving upward with the Shuttle at the time of separation, F_D acts downward in the negative z direction.

Therefore, Newton's second law for the debris object becomes

$$-F_D - W = ma_Z .$$

The force due to gravity is the product of the object's mass, m, and the acceleration due to Earth's gravity, g:

$$W = mg .$$

The aerodynamic drag force, F_D, is given by the following equation

$$F_D = \frac{1}{2} \rho_{AIR} C_D A V^2$$

where:

V	is the velocity of the air that flows around the object,
ρ_{AIR}	is the density of the air that flows around the object,
C_D	is the drag coefficient of the object based on a reference area,
A	is a reference area, typically the average area of the object projected onto the direction of motion

Substituting these expressions for the drag and force due to gravity in Newton's second law, and solving for the acceleration, we find that

$$a_Z = -\frac{1}{2m} \rho_{AIR} C_D A V^2 - g. \qquad (1)$$

Since the debris was shed while the Shuttle was traveling at supersonic speeds, the density of the air that flowed over the debris is complicated by the presence of shock waves emanating from the orbiter nose, the SRBs, and the debris itself. However, as an approximation, we can use the atmospheric density of air at about 66,000 feet above sea level, or

$$\rho_{AIR} \cong 0.092 \frac{Kg}{m^3}$$

The drag coefficient and reference area are functions of the shape of the debris, which is unknown. However, based on experimental results for a variety of shape at supersonic speeds, we can approximate that the drag coefficient is equal to one and the reference area is the average surface area.

$$C_D A = (1)\left(\frac{Lw + Lt + wt}{3} \right)$$

Using the dimensions of the foam shot during the impact test: a length of 0.574m, width of 0.292m, and thickness of 0.142m, we get

$$C_D A = 0.097 \, \text{m}^2$$

The weight of the foam used during the impact test was 1.68 lb, which corresponds to a mass of 0.76 kg.

The velocity of the air that flow around the object, V , changes with time. However, at the instant that the object separates from the ET, the initial velocity is equal to the speed of the Shuttle,

$$V_i = 2300 \text{ fps} = 701 \text{m/s}$$

Substituting these values, we can see that the first term in equation (1) at the time of separation is

$$\frac{1}{2m} \rho_{AIR} C_D A V_i^2 = \frac{1}{2(0.76 Kg)}\left(0.092 \frac{Kg}{m^3} \right)\left(0.097 m^2 \right)\left(701 \frac{m}{2} \right)^2 = 2870 \frac{m}{s^2}.$$

We can see that the first term in equation (1) is much larger than the acceleration due to gravity. Therefore, as a simplifying assumption, we can neglect the second term so that equation (1) becomes

$$a_Z \cong -\frac{1}{2m}\rho_{AIR}C_D A V^2. \tag{1'}$$

We know that acceleration is the time rate of change of velocity, therefore this equation can be re-written as

$$\frac{dV}{dt} \cong -\frac{1}{2m}\rho_{AIR}C_D A V^2.$$

This is now a separable differential equation. It follows that

$$\int_{V_i}^{V_f}\frac{dV}{V^2} \cong -\int_0^{t_f}\frac{1}{2m}\rho_{AIR}C_D A\,dt.$$

Solving these integrals, we find that

$$-\left(\frac{1}{V_f}-\frac{1}{V_i}\right) \cong -\frac{1}{2m}\rho_{AIR}C_D A t_f$$

Solving for the final velocity, we have

$$V_f \cong \frac{1}{\left[\dfrac{1}{2m}\rho_{AIR}C_D t_f + \dfrac{1}{V_i}\right]}$$

Using the impact time determined from the launch cameras, $t_f = 0.161$ s, we find finally that

$$V_f = 423 \text{ m/s} = 1376 \text{ fps}$$

Notice that this velocity is positive, indicating that the object was still moving upward at this time. However, this is not the impact velocity relative to the orbiter wing. At the time of the debris event, the Shuttle had an acceleration of about twice gravity, which is negligible for this approximate calculation. Therefore, the impact speed relative to the orbiter wing is given approximately by

$$V_{IMPACT} = V_f - V_i$$
$$V_{IMPACT} = 924 \text{ fps}$$

This result demonstrates that a basic physics analysis, which neglects the complexities associated with the supersonic flow field and uses several approximations, produces an estimate of the debris impact velocity that is within 20% of the value used during the foam impact test.