DESIGN AND TESTING OF THE HOPE-X HSFD-II LANDING SYSTEM

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This paper reports the status of the design, analysis and preliminary testing of the HOPE-X High Speed Flight Demonstrator Program (HSFD-II) Landing System. The HSFD is an experimental flight research program using 25% scale test vehicles. The test program is part of a joint Japanese NAL/NASDA research program supporting the HOPE-X unmanned re-entry space vehicle project.

Nomenclature

ABIAS - Airbag Impact Attenuation Subsystem
AGS - Airbag Gassing System
GN2 - Dry Nitrogen
HOPEX - H-II Orbiting Plane Experimental
HSFD - High Speed Flight Demonstrator

Introduction

The Phase I vehicle is powered by a turbofan engine and takes off and lands autonomously to validate terminal area navigation and telemetry/command systems. The Phase II vehicle is launched using a high altitude balloon to allow it to accelerate to transonic speeds in free-fall. The objective of this phase is to clarify the transonic aerodynamic characteristics of a winged re-entry vehicle. This paper discusses Phase II.

The HSFD-II Landing System consists of parachutes and airbags to land the test vehicle, funded and managed by the National Space Development Agency of Japan (NASDA) and the National Aerospace Laboratory (NAL) and built by Fuji Heavy Industries (FHI). This paper will discuss the integrated landing system for this vehicle (See Figure 1).

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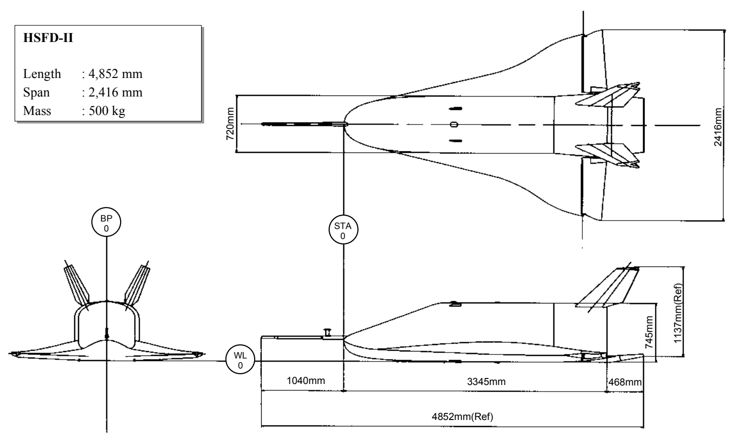

Figure 1 – HSFD-II Test Vehicle

System Description

After high altitude balloon launch at 105,000 ft, gliding supersonic flight, data acquisition, and gliding subsonic flight, recovery of the HSFD-II vehicle is initiated by the firing of a drogue gun, which deploys the pilot, drogue and single main parachute subsystem. Once stable descent is obtained under the main canopy, the vehicle repositions in preparation for landing deceleration and impact attenuation by the airbag subsystem. Airbags are deployed and monitored using a dry nitrogen gassing system. Control of airbag inflation and deflation is accomplished through the airbag sequence controller. After vehicle touchdown, the airbags prevent the composite vehicle skins from touching the ground until recovery (See Figure 2).

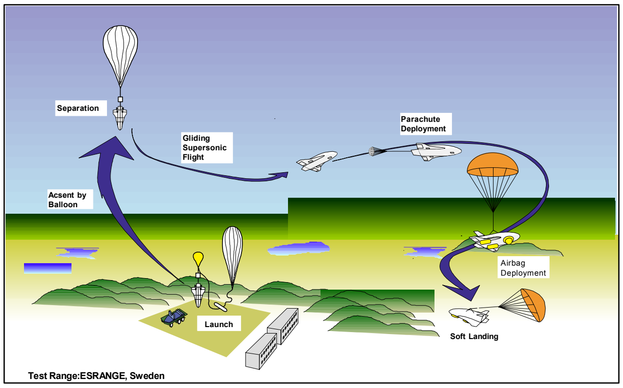

Figure 2 – HSFD-II Mission Profile

<u>Parachute Subsystem Design</u>

The parachute subsystem functions to allow both normal and limited emergency recovery of the HSFD-II vehicle. It also must be compatible with the Airbag Impact Attenuation Subsystem (ABIAS) landing terminal velocity requirement. Key customer requirements included little or no developmental parachute effort, commonality between flight termination and main recovery systems and very limited space for any deployment mechanism. As a result, the parachute subsystem is comprised of existing parachutes with designs modified for specific use on the HSFD-II vehicle. Figure 3 shows an aft view of the vehicle with the relative locations of the parachute and FTS subsystems.

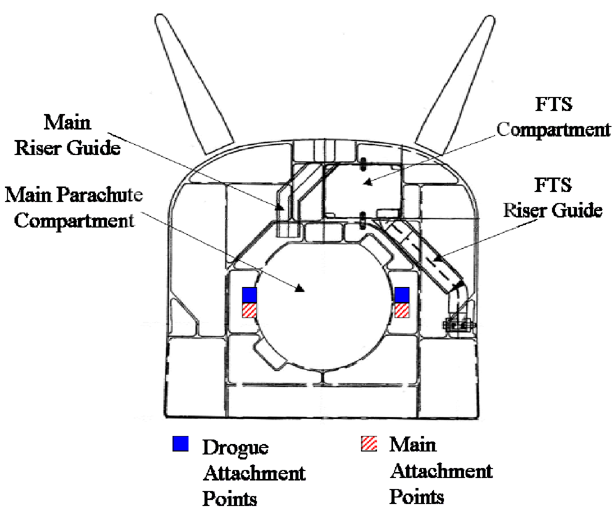

Figure 3 – Parachute Subsystem Location

A drogue gun was chosen over a mortar, due to space limitations, thus making parachute deployment / wake interaction a more challenging task.

The parachute subsystem consists of a 250 fps 1 lb. slug drogue gun, a Nylon 1.8-ft. pilot ribbon parachute, a Nylon/Kevlar 7.3-ft. conical ribbon chute and a Nylon/Kevlar 62.5 ft slotted Polyconical main chute. Figure 4 shows the main canopy details.

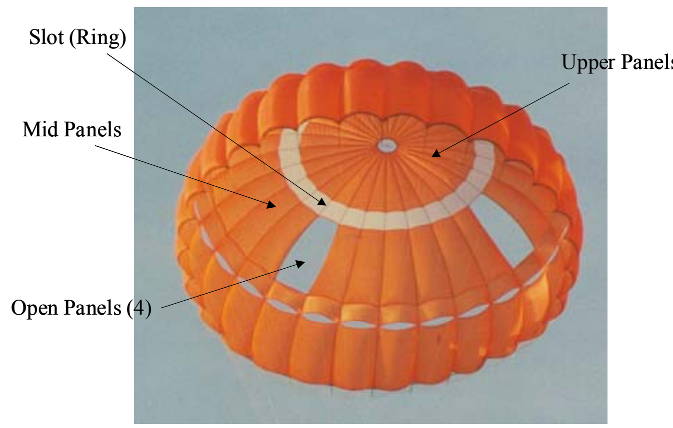

Figure 4 – HSFD 62.5 ft. Main Canopy

<u>Airbag Impact Attenuation Subsystem Design</u>

Airbag compartment layout was predetermined based on the location of the landing gear compartment in the Phase I vehicle. This presented a unique challenge, as the aft airbag compartments are closer together than ideal, to provide proper broadside landing performance. This factor drove the configuration of the ABIAS to that shown in Figure 5.

The forward airbag set is comprised of a spherical impact bag connected via a one-way valve to a toroidal anti-bottoming bag. The aft impact bags are also spherical, however the anti-bottoming bags are of an outrigger type design to help in wing tip and bodyflap protection. All of the impact airbags include two deflation orifices that are triggered to open at a specific landing gee level to prevent vehicle rollover and limit gee levels during the landing cycle. The impact bags include two orifices to aid in prevention of vent blockage during landing.

Once on the ground, the anti-bottoming airbags must sustain pressure to allow enough time for ground crews to safely recover the stages from the landing zone.

The bags are constructed using the Radio Frequency Welding Technique, better known as RF-Welding. The process fuses materials together by applying radio frequency energy to the areas to be joined. It is simpler and less time consuming than chemical bonding. Although the desired inflated bag shape is spherical, the actual fabric is assembled as a Dodecahedron. This shape was chosen as it simplifies the RF welding process by using straight line welding.

Based on preliminary stress calculations and the fabrication process, the best-suited material for the airbags was determined to be polyurethane coated Nylon previously used on large-scale radar decoys for the United Kingdom and United States Navies.

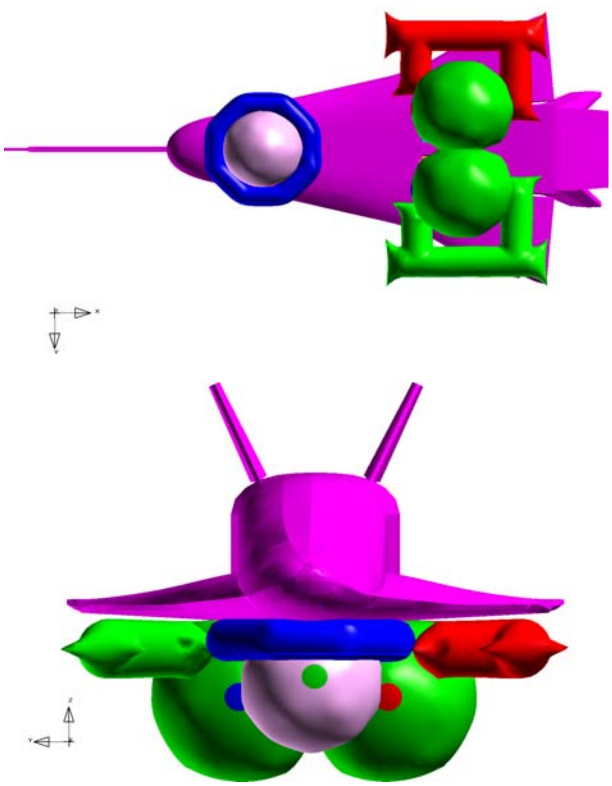

Figure 5 – HSFD-II Airbag Configuration

Airbag Gassing System Design

The Airbag Gassing System (AGS) controls the GN_2 that inflates the airbags used in the impact attenuation and landing of the HSFD-II vehicle. Due to limited space on the vehicle, there is one centralized AGS that is utilized for inflation of all airbags. Supply lines lead from the AGS to all three airbag compartments.

The AGS is composed of a series of valves, pressure switches and tubing mounted to a pallet. The pallet is located horizontally above a pair of high-pressure bottles within a customer-defined envelope located just aft of the forward airbag compartment. Components of the AGS include two dry nitrogen filament wound bottles with stored gas at 3,000 psi, three electric normally closed solenoid valves, three pressure switches and one pyro valve. The reusable pyro valve provides the dual functionality of a fill valve and isolation valve prior to firing, which protects the fill system from reverse flow while filling the supply bottles, until signaled to fire and open the bottles. The valves are connected by a series of Swaglok fittings using ¼ inch SS tubing.

Relief valves are situated within the supply lines to prevent over inflation of the airbags during descent due to gas warming. Inflation time must be under 30 seconds with monitoring and refill capability throughout the landing descent. Figure 6 shows the AGS system.

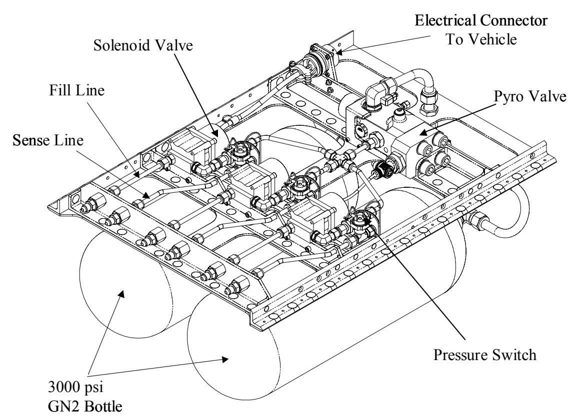

Figure 6 – AGS System

Analysis and Simulation Tasks

Several tools were used to help in the design and analysis phases of this program. These tools were crucial in guiding Irvin to the best design for HSFD-II vehicle recovery since a limited amount of testing was afforded.

Parachute analysis performance was fine-tuned using DCLDYN, an Irvin in-house tool. The program is a 3 DOF simulation of a vehicle's motion and trajectory during deceleration by the aerodynamic drag of an attached parachute system. The majority of the parachute qualification is confirmed by similarity based on previous program usage.

Preliminary airbag sizing analysis was accomplished using BAGDYN, an Irvin in-house tool. This program provides a rigid body simulation of a vehicle landing on airbags. The airbags are simulated as dashpot dampers and pneumatic springs with proper modeling of the vent mass flow equations, and the option for either analytical or experimental inputs for airbag volume and footprint during deflection. The input deck also allows selected theoretical airbag geometries. These are most useful during the concept definition and pre-test planning phases.

Figure 7 represents an example of a vehicle/airbag system model during impact, and a summary of the equations that BAGDYN employs during the simulations.

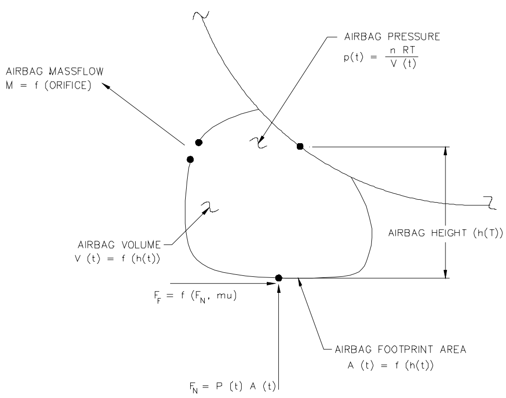

Figure 7 – Vehicle/Airbag System Model

In addition, detailed analysis was performed using LS DYNA. This explicit Finite Element Analysis technique allows large amplitude, time based analysis for impact simulations. This tool was primarily used to analyze airbag fabric stresses, soil compliance, attachment loads, and structural interface loads. Both BAGDYN and LSDYNS played key roles in the optimization of test matrices.

Figure 8 shows one component of the airbag finite element model in a pre-inflated and post-inflated state. The Dodecahedron shape can be clearly seen.

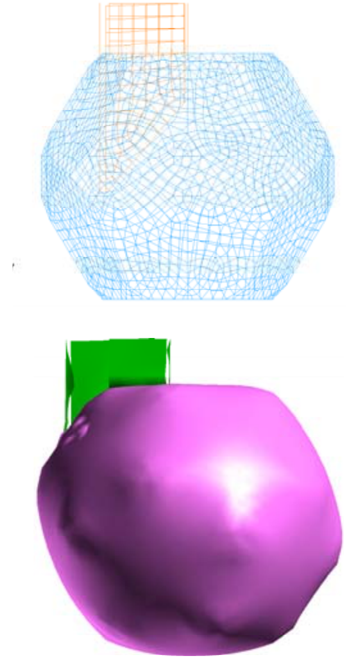

Figure 8 –LSDYNA Model of Impact Airbag

Parachute Test Results

Due to the integrated nature of the parachute subsystem with the ABIAS, it was important to have a main parachute that provided the best possible stability. Recent main parachute testing resulted in the oscillation data shown in Figure 9.

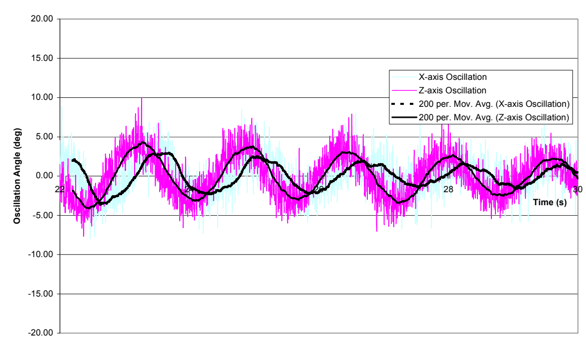

Figure 9 – Main Parachute Oscillation Test Data

Plotted is the X and Z-axis versus time. For this test, X and Z were the planar directions perpendicular to the velocity vector; the Y-axis is aligned with the descent velocity vector. The plot shown tracks the oscillation after the main parachute inflation has occurred and the parachute is descending. These data were derived from onboard accelerations and while the basic measurement has a random noise component, filtering of this data produces a usable signal, as shown in Figure 10.

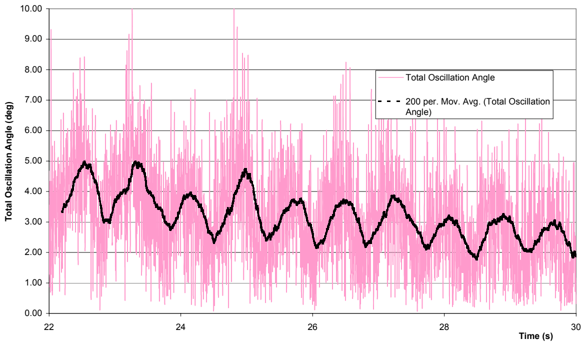

Figure 10 – Main Parachute Total Oscillation Angle

Figure 10 shows the result of taking the vector sum of the X and Z components. This results in a parachute oscillation angle of from 3 to 5 degrees as the parachute descends. The 5 degrees of oscillation occurs nearest the opening inflation and latter dampens to only 3 degrees. The stability of this parachute results in reducing the dispersion envelope that the airbag system needs to accommodate.

Airbag Drop Testing

Airbag drop tests were conducted to provide a correlation database to validate airbag simulations and demonstrate successful landings. However, drop testing alone cannot correctly predict landing characteristics, as parachute riser force is not available. This force is a significant term in the overall impact acceleration. Therefore, final success of the vehicle landing, particularly in terms of peak acceleration is demonstrated through simulation.

Another feature of airbag drop testing is to establish confidence in the airbag vent control aspects of the airbag sequencer. A brass board version of the actual sequencer was used during drop testing. This demonstrated the control technique and validated any time delays associated with the controller.

Figure 11 shows the drop test set up that was used to validate airbag simulations. The drop test vehicle shown is a full-scale recreation of the bottom section of the HSFD-II flight test vehicle including airbag compartments, nose boom and aft body flap. It simulates the vehicle mass and Cg location with moments of inertia approximated.

Controlling the height of the model above ground controls model vertical velocity. Running the model down the provided drop test rails generates horizontal velocity. The model is stabilized at the desired horizontal velocity well before the end of the drop test rails. Forward and aft model carriers reach the end of the rails at the same instance. Test data output included the following:

- 3-Axis Cg Acceleration
- Pressure for all Airbags
- Model Rotational Rate – Pitch & Roll
- Vent Release Monitoring (Witness Wire)
- High Shutter Speed Video

Data was recorded at 1000 Hz bandwidth, and delivered digitally, which enabled detailed correlation comparison to the simulations.

Figure 11 – Airbag Drop Test Set Up

Test Results vs. Simulation

The ability to match test data with computer simulation was very much a function of making sure the FEA model closely represented the actual airbags and test vehicle. Flap interfaces, airbag to airbag interaction, venting characteristics, model moment of inertia, airbag fabric properties, blockage effects are just a few of the things that had to be carefully monitored and checked. As the model matured, comparison between simulation and test became very good.

An example of LSDYNA output data can be seen in Figures 12 through 14. Figure 12 shows the test versus simulation comparison of the forward impact airbag pressure as a function of time. The bag is originally filled to 2 psia. As the vehicle begins landing, the airbag pressure increases to approximately 6 psia. The trigger gee level is met at which time the orifice is then triggered to vent. Although not an exact match, the correlation is very good.

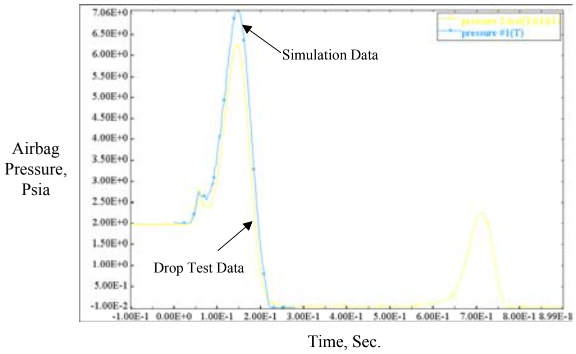

Figure 12 –Forward Airbag Pressure Test vs. Simulation Comparison

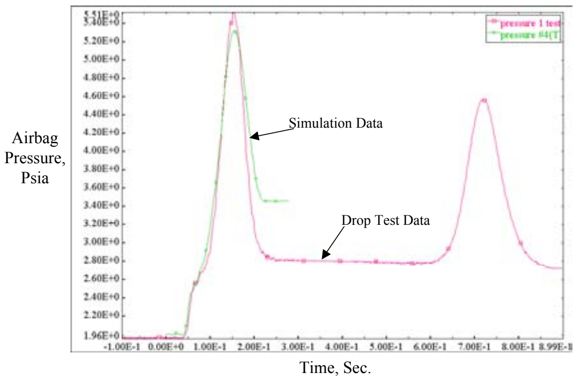

Figure 13 –Forward Airbag Pressure Test vs. Simulation Comparison

The forward anti-bottoming airbag shows excellent correlation as the peak airbag pressures are 5.51 psia (test) and 5.40 psia (simulation). It can be seen that the simulation does not match the test data at the bottom of the peak pressure spike. This occurred because the bag to bag venting between the impact and anti-bottoming bag was not quite correct. It should also be noted in all of the plots the simulation run times were not as long as the test data acquisition time.

A critical customer requirement was the vehicle Cg acceleration level. This comparison is shown in Figure 14. The peak levels for both test and simulation show excellent agreement at approximately 6.5 gees.

Additional post processing of the LSDYNA output was completed to show fabric stress areas and levels.

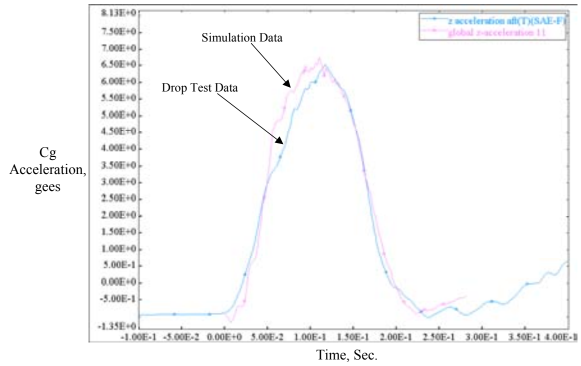

Figure 14 – Vehicle Cg Acceleration Test vs. Simulation Comparison

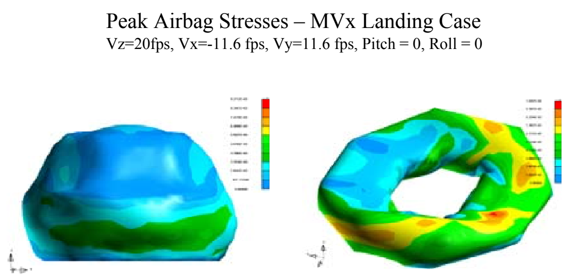

Figure 15 – Forward Airbag Contour Plots

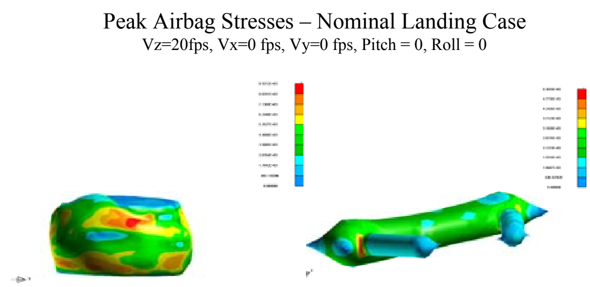

Figure 16 – Aft Airbag Contour Plots

Figure 15 shows a contour plot of the peak airbag stresses for the forward impact and anti-bottoming airbags. The landing condition is a vertical velocity of 20 fps along with a broadside velocity of 11.6 fps.

Figure 16 shows a contour plot of the peak airbag stresses for the aft impact and anti-bottoming airbags. This is the nominal landing condition of a 20 fps vertical velocity and no broadside velocity.

Looking at the simulation results in this manner validated that the proper fabric was selected to withstand the landing stresses seen by the airbags in all landing conditions.

Summary

The landing system for the HOPE-X HSFD-II test vehicle provided some unique challenges with regards to space allocation of the various systems and available airbag location. However, with the combined use of previous test experience, new test data and the simulation tools mentioned, a viable landing system was developed.

The use of computer simulations to evaluate multiple airbag configurations saved hundreds of test hours and dollars.

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