BALLUTE AND PARACHUTE DECELERATORS FOR FASM/QUICKLOOK UAV

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ABSTRACT

This paper presents an overview of the decelerator subsystem designed for the gun-launched FASM/QuickLook UAV program. A ballute decelerator was required to stabilize this UAV shortly after launch, and to provide dwell time for the deployment and startup of wing, tail, and propulsion systems. In addition, a parachute was required to provide a controlled descent during the testing phase of the program. ILC Dover, Inc., in cooperation with Science Applications International Corp. (SAIC) Tactical Systems Operation, undertook a rapid, low-cost development program to supply the decelerator subsystems for FASM/QuickLook. Innovative ballute deployment and separation schemes were incorporated into a compact, simple package that attached to the aft end of the FASM/QuickLook airframe. The five month program culminated in a successful flight test on June 13, 2002 at Yuma Proving Grounds in Yuma, Arizona. Initial tests were conducted using a compressed gas gun that imparted launch accelerations of 200 – 300 G. The flight test demonstrated ballute deployment and separation, parachute deployment, and inflatable wing deployment. The technical approaches developed on this program were applied to the jointly-funded US Navy UAV program, called FASM, and the US Army program, called QuickLook, and are expected to be applied on future UAV projects. Topics covered here include: trajectory and stability analyses, design of the ballute and parachute subsystems, mechanical hardware design, ground and flight testing, and lessons learned.

PROGRAM OVERVIEW

The Office of Naval Research (ONR) awarded a technology development program to Science Applications International Corp. (SAIC) in San Diego, CA, to demonstrate a gun-launched UAV called Forward Air Support Munition (FASM). Development was jointly funded by the Army, under the QuickLook gun-launched UAV program.

The FASM/QuickLook concept is a UAV that is launched as a projectile from either a 5-in naval gun (FASM) or a 155-mm howitzer (QuickLook). During the operational sequence, the projectile airframe would be fired under a dynamic load of 300 to 2800 G, transition to an airplane by deploying inflatable wings, and then cruise and loiter for up to 3 hours at a 100-nmi range. Once deployed, it would be able to provide tactical targeting and battle damage assessment using communication-linked live imagery and GPS navigation.

The key technologies targeted for the design of the UAV were: deployable inflatable wings, miniaturized electronics, a heavy fuel engine, and a ballute/recovery parachute system. The cost goal for the UAV in high production quantities was estimated to be $ 40 K per vehicle. Figure 1 shows the final configuration of the UAV during a ground based deployment test.

Figure 1: FASM/QuickLook UAV During Ground Testing With Integrated Ballute Module – Undeployed and Deployed Configurations

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[¶] Member AIAA

BACKGROUND & REQUIREMENTS

The concept of the FASM/QuickLook program was to demonstrate the technology required for a projectile to be fired from a gun and then transition to a low-speed loitering munition. By using this approach, it is possible to use the energy from the gun propellant to launch the vehicle, extend its range, and reduce its time to target.

During the ballistic trajectory phase, the stability of the projectile was a key design concern. Analysis of the size and weight distribution of the vehicle indicated a potential for the vehicle to become unstable after launch. Initially, spin-stabilization was selected as a simple and demonstrated approach. By spinning an object, the object gains a large amount of angular momentum, thereby making it relatively immune to the influence of small external torques.[1] Unfortunately, the test phase of the program used a smooth versus a rifled gun barrel, thus the projectile could not be spin-stabilized. Also, in the operational gun system, a slip obturator would be used to reduce the spin imparted to the projectile by the rifling. As an alternative means of providing stability, it was decided that a small, rigid-finned tail section would deploy immediately after launch. However, during the development test phase, it was proposed that a reduced G-load requirement be allowed in order to mitigate risk and reduce cost. Reducing the G-load requirement during the gun launch consequently reduced the required muzzle velocity of the launch. This led to an increase in the size of the tail fins, to the point that they were too large for packaging. Further, the inflatable surfaces were not designed to be deployed at the minimum 388 ft/sec muzzle velocity. It became apparent that stability and deceleration needed to be accomplished in another manner.

The type of decelerator chosen was determined based on two factors. First, the vehicle needed to be slowed from launch velocities to speeds at which inflatable wings could be safely deployed. Second, the decelerator had to be unaffected by any spin that could be imparted to the vehicle if rifling were to be later included in the gun barrel. Based on these factors, it was determined that a ballute decelerator, rapidly deployed immediately upon exit from the gun barrel, was the preferred choice.

While a ballute satisfied the stability, deceleration, and spin requirements, it was determined that a parachute might be necessary to provide a slower descent after apogee, in order to afford additional time during which flight hardware could be deployed and started. A parachute also provided an appropriate means of recovering hardware after early test firings. The early tests were required to verify proper operation of the pneumatic gas gun, decelerator, and deployment control systems. Since it was not clear if the parachute would be required beyond the test phase, it was determined that the system should consist of separate ballute and parachute modules, such that the ballute module could be used in combination with the parachute module or as a stand alone unit.

Without the decelerator system, the test vehicle (airframe) weight was approximately 70 lbs, and was housed in a package 6.06 in (155 mm) in diameter and 71 in long. Muzzle velocity at launch was projected to be 388 ft/sec. Tests were to be conducted with the compressed gas gun oriented at a nominal 70 degree angle.

Decelerator design requirements included: ballute deployment within .25 seconds after receipt of a firing signal; a maximum snatch or deployment force of 1000 lbs; a 480 ft minimum apogee; and a velocity at apogee of 90 – 130 ft/sec. Descent rate under parachute control was targeted at 30 ft/sec.

Armed with this assessment of decelerator requirements, SAIC contacted ILC Dover, Inc. in Frederica, Delaware to develop the decelerator systems.

SYSTEM OVERVIEW

The QuickLook/FASM decelerator system consists of a ballute module and a parachute module mounted to a common base assembly. The ballute module consists of a gas generator deployed, ram-air inflated ballute, packed in a housing with an ejectable cover. This module is attached by steel cables to a base assembly which mounts to the aft end of the vehicle. Upon launch of the vehicle, a circuit detects a prolonged negative acceleration, and sends a signal to initiate the gas generator. This results in ejection of the ballute cover plate and deployment of the ballute into the airstream. The ballute is then completely inflated by dynamic pressure, using ram-air scoops located on the sides of the ballute. When the vehicle is near flight apogee, inflatable wings are deployed, the ballute module is jettisoned, and the vehicle moves on to the flight phase of its mission.

In order to allow recovery of the vehicle with minimal damage during testing, an optional parachute module was also developed. The parachute module consists of the parachute itself, a parachute deployment bag, and a housing. This module can be inserted between the vehicle and the ballute module, if desired. When the parachute module is used, the cables that attach the ballute module to the base assembly are extended, passing through the parachute module before attaching to the base assembly.

In either configuration – with or without the parachute module - the base assembly is identical, and contains pyrotechnic cable cutters which sever the ballute attachment cables in response to a signal from the vehicle. Figure 2 shows the packaged ballute and parachute module. Figure 3 shows the UAV and both decelerator modules after a test recovery.

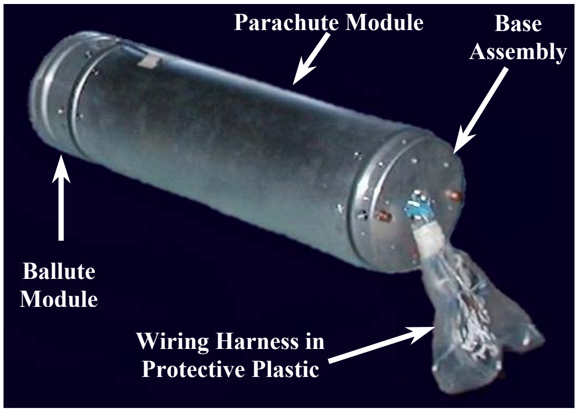

Figure 2: Packaged Ballute & Parachute Module

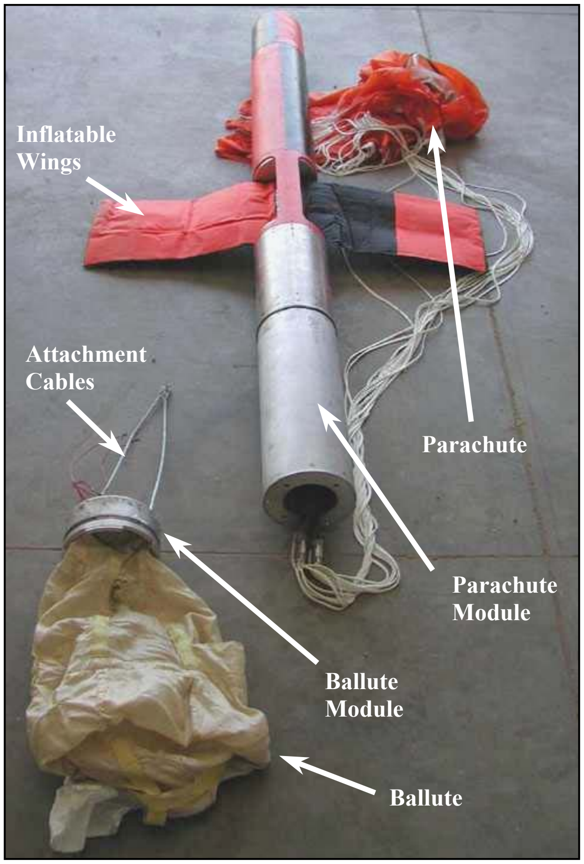

Figure 3: UAV after Launch & Recovery

BALLUTE SIZING & TRAJECTORY ANALYSIS

Ballute Sizing

A preliminary size estimate for the ballute was determined using a two-degree-of-freedom trajectory program implemented using Microsoft Excel, and developed in-house at ILC Dover. 1976 US Standard Atmospheric properties were taken from Knacke's 1992 Parachute Recovery Systems Design Manual [2] and were used in the computation of air density and Mach number as a function of altitude. A composite of several sources was used to compute drag coefficient as a function of Mach number. Program inputs included computation time step, initial altitude, initial velocity, initial flight path angle, projectile weight, and ballute diameter. To arrive at the appropriate size, the ballute diameter input was varied until the desired altitude and velocity requirements were achieved.

Trajectory Analysis

Original project requirements (later altered) called for a velocity of 90 to 130 ft/sec at a minimum flight apogee of 480 ft - conditions deemed favorable for deployment of the vehicle’s inflatable wings. An initial weight estimate of 73 lbs was used which included the basic vehicle and the decelerator modules. Firing angle was projected to be 60 degrees, and muzzle velocity was projected to be 475 ft/sec. Calculations were made assuming the vehicle was launched at sea level. Based on these inputs, a ballute size of 18 inches was chosen, resulting in a predicted flight apogee of approximately 1,137 ft MSL, with a velocity at apogee of 103 ft/sec. Apogee was predicted to occur approximately 7.3 seconds into the flight. Figure 4 shows plots of predicted velocity and flight profile.

CDR Parachute Systems, as a consultant to ILC Dover, confirmed the sizing of the ballute, and conducted a further analysis to confirm that the resultant ballute/vehicle combination would remain stable during flight. As the project progressed, critical items such as weight, firing angle, and muzzle velocity were revised. However, it was determined that the original ballute size was adequate.

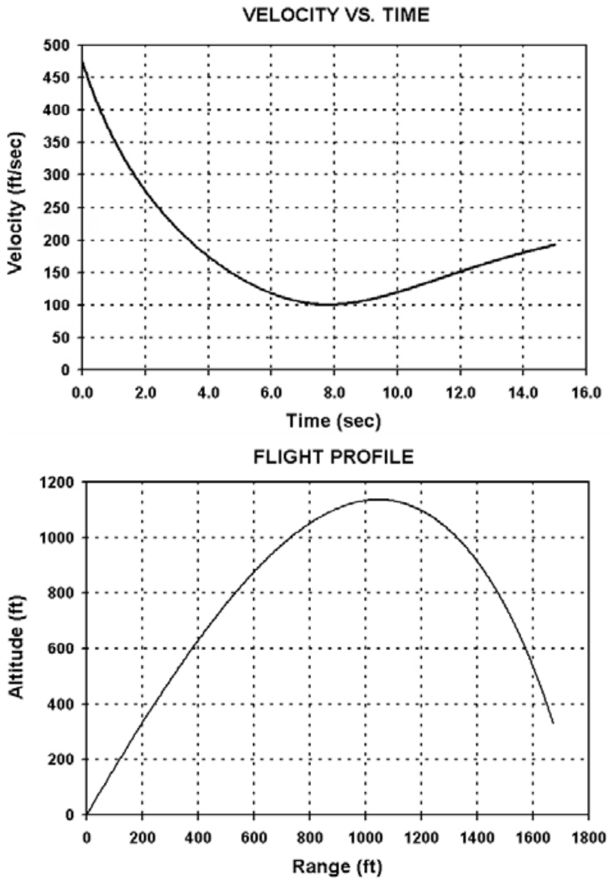

Figure 4: Predicted Velocity and Flight Profile Plots

BALLUTE DESIGN

Ballute Size & Shape

Limited time and funding dictated that the ballute design be based on previous ILC Dover designs. A decision was made to emulate a ballute recently developed by ILC Dover for the Small Munitions Dispenser (SMD) project under contract to Boeing Phantom Works in St. Louis, MO. [3] The heritage of the SMD ballute design can be traced to the Mk82 retarder system developed by Goodyear.[4,5] Weight and trajectory requirements dictated a ballute that was considerably smaller than that used for the SMD project. Aerodynamic loads were similarly reduced, allowing the use of lighter construction materials and techniques. Figure 5 shows the nominal shape of the Goodyear style of ballute. The ILC Dover design makes use of an elliptical shape in the rear, with a minor axis equal to √2/2 times the major axis.

Ballute Materials

In order to keep the project cost low, a material was selected that was already in-house at ILC Dover. This material was a silicone rubber coated Vectran fabric. The silicone rubber was applied to one face of a 50 x 50 count, 200 denier Vectran HS fabric to render it gas impermeable. The coated fabric weight was 4.3 oz/yd^2 and the tensile strength in warp and fill directions was 400 lb minimum. Analysis of the maximum stresses expected in the fabric and seams indicated that the material was appropriate for the application.

Kevlar reinforcement webbings were used at the ram-air scoops and at the rear of the ballute to support deployment & inflation loads.

Ballute Construction

The body and burble fence were of an 8 gore construction. Four ram-air scoops were created by

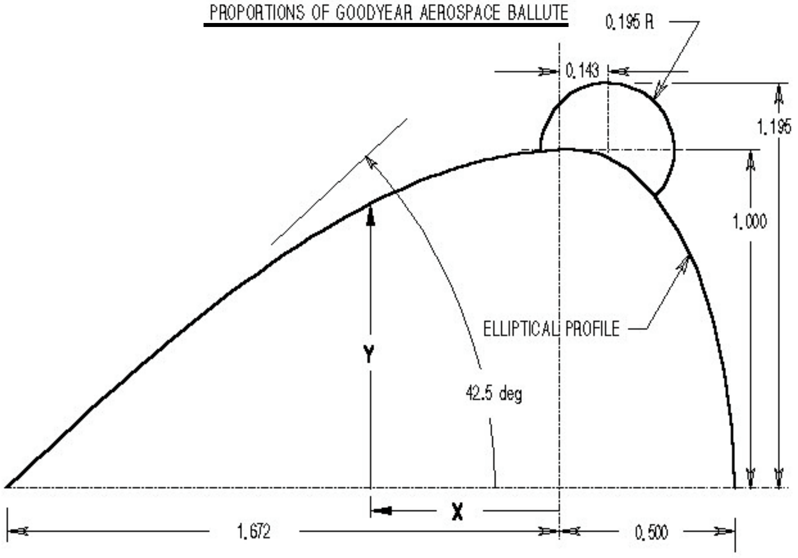

Figure 5: Ballute Geometry

overlapping foreshortened body gores with a flap of material attached at 3 sides and open to airflow at the fourth. Gore seams were fell type. The burble fence was attached to the ballute using a lap seam.

The ballute was attached to the packing canister using a "dead man" – in this case, a 304 stainless steel ring formed from .25" diameter round stock., and sitched into a loop of fabric at the base of the ballute. The dead man was captured in a pocket in the packing canister. The general arrangement of the ballute is shown in figure 6.

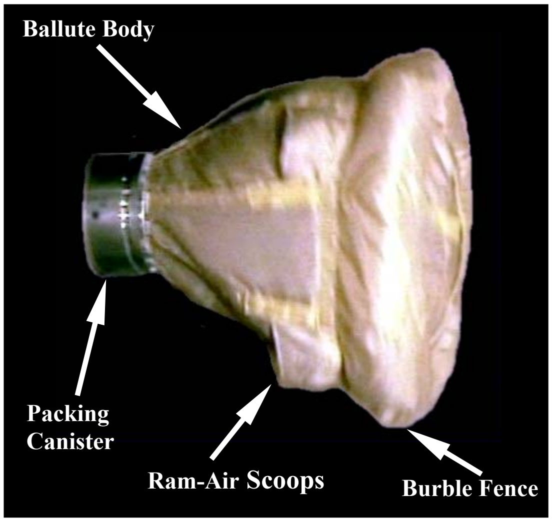

Figure 6: Ballute (Inflated)

Ballute Deployment

Rapid deployment of the ballute was dictated by a need to provide stability immediately upon exit from the gun barrel. Based upon previous experience, a gas generator was selected as the deployment initiator. A cost effective solution was achieved using a gas generator developed for this application by Talley Defense Systems. Talley's inflation system was designed to provide sufficient gas to both eject the tightly packed ballute from its canister and to partially inflate the ballute.

PARACHUTE DESIGN

The parachute module consisted of the parachute itself, a parachute deployment bag, and a housing. Parachute design and fabrication were subcontracted to Pioneer Aerospace Corporation (PAC) in South Windsor, Connecticut.

PAC first considered a 13 ft triconical canopy. Although this would have met descent rate requirements, packing volume and minimal available extraction forces would prove to be a challenge. Computer simulations were performed and the design was downsized. A 9.5 ft triconical 12 gore parachute was selected for testing. This selection balanced the desired descent rate with a relatively small packing volume, minimal extraction force, and minimal opening load specifications. A significant design challenge was using the minimal drag force produced by the ballute to deploy the parachute near flight apogee. The drag force from the ballute available to deploy the parachute was estimated to be < 12 lbs.

A deployment bag was designed to securely contain the canopy, allow for the orderly deployment of the line sets, and also to allow extraction from the packing canister with minimal force. A Spectra cloth using flute type line stows was selected. The deployment bag was connected to the forward end of the ballute module. When cable cutters separated the ballute module, it extracted the parachute as it dropped away. Bench

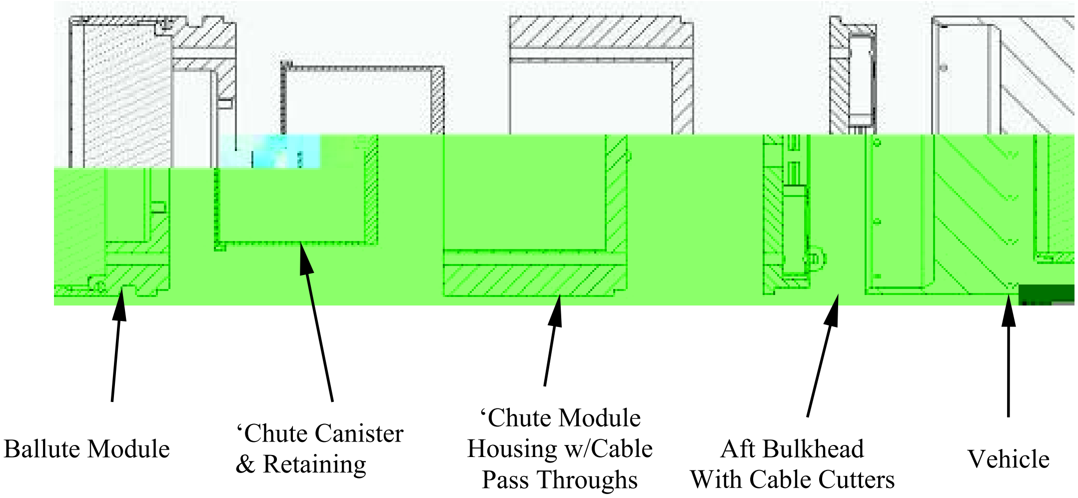

Figure 7: Parachute Module Design Concept

testing proved that this design could contain the parachute and still allow extraction with less than 7 lbs of force. Figure 7 illustrates the parachute module design approach.

DEPLOYMENT & STAGING

Gas Generator & Diffuser

One requirement for the FASM/QuickLook vehicle was that the ballute deploy immediately upon leaving the gun barrel. A gas generator was chosen to achieve this goal. A gas generator produces a large volume of gas in a fraction of a second, creating a pressure surge that can eject a packed ballute out of a canister. Gas generators have been successfully used at ILC Dover in previous decelerator deployment applications

Analysis showed that ram-air would be sufficient to maintain the shape and stability of the ballute after deployment. The gas generator was therefore only required to deploy and partially inflate the ballute to get the ram-air scoops into the airstream.

A Talley S-100S series non-azide inflator was selected for FASM/QuickLook. The S-100S series inflator is a multi-purpose pyrotechnic device that can be easily tailored to meet a variety of desired output characteristics. In addition, the overall geometry and size of the device was amenable to the limited package size.

When the inflation gas exits the gas generator, it is at an extremely high temperature. This gas can easily burn through the ballute and render it ineffective if not cooled before it comes in contact with the packed ballute. Cooling is accomplished by means of a diffuser. The diffuser supplied with the gas generator could not be used because of space constraints, requiring a custom diffuser to be designed.

The diffuser that was designed consisted of a stainless steel cap with a series of holes in its cylindrical surface to dissipate the gases into the ballute canister. Heavy gage steel wool was packed inside this cap and the open end was butted against the gas generator exhaust nozzle. The diffuser housing and steel wool served to absorb some of the heat and diffuse the gas from a concentrated stream.

It was found that the gases, even after passing through the diffuser, were still capable of burning a hole in the ballute fabric. To further deflect the gases and avoid localized contact with the packed ballute material, a nomex blast patch was placed over the diffuser opening. This patch helped shield the packed ballute and spread the hot gases uniformly inside the canister. Figure 8 shows the gas generator and diffuser arrangement within the ballute module base assembly.

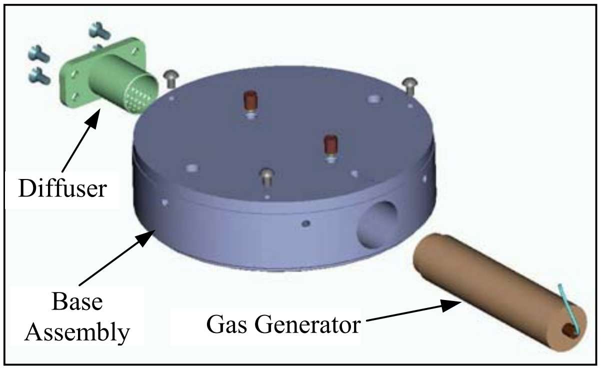

Figure 8: Gas Generator & Diffuser

Ballute Canister Cover Plate Attachment

In past projects, sheet metal cover plates had been used to retain a ballute in a packing canister. These cover plates were designed to easily deform when inflation pressure acted on the inner surface, allowing the ballute to deploy. This approach could not be used on FASM/QuickLook because of the higher loads encountered in a gun launch system.

The design approach chosen used a low shear strength aluminum wire as the retaining feature for the cover plate. The wire sits inside a circumferential groove formed in the cover plate and the canister top. When the gas generator is fired, the inflation pressure pushes the cover plate out with enough force to shear the aluminum wire at eight locations, releasing the packed ballute. Figure 9 illustrates the cover plate attachment method.

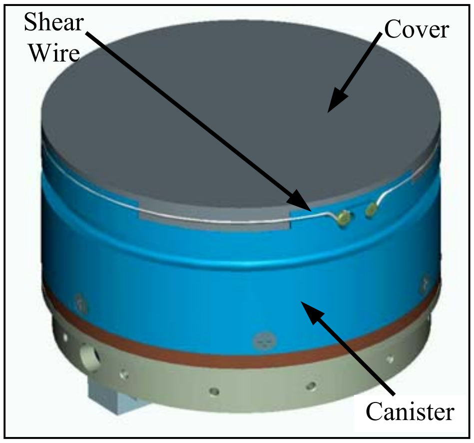

Figure 9: Ballute Module Cover Plate Attachment

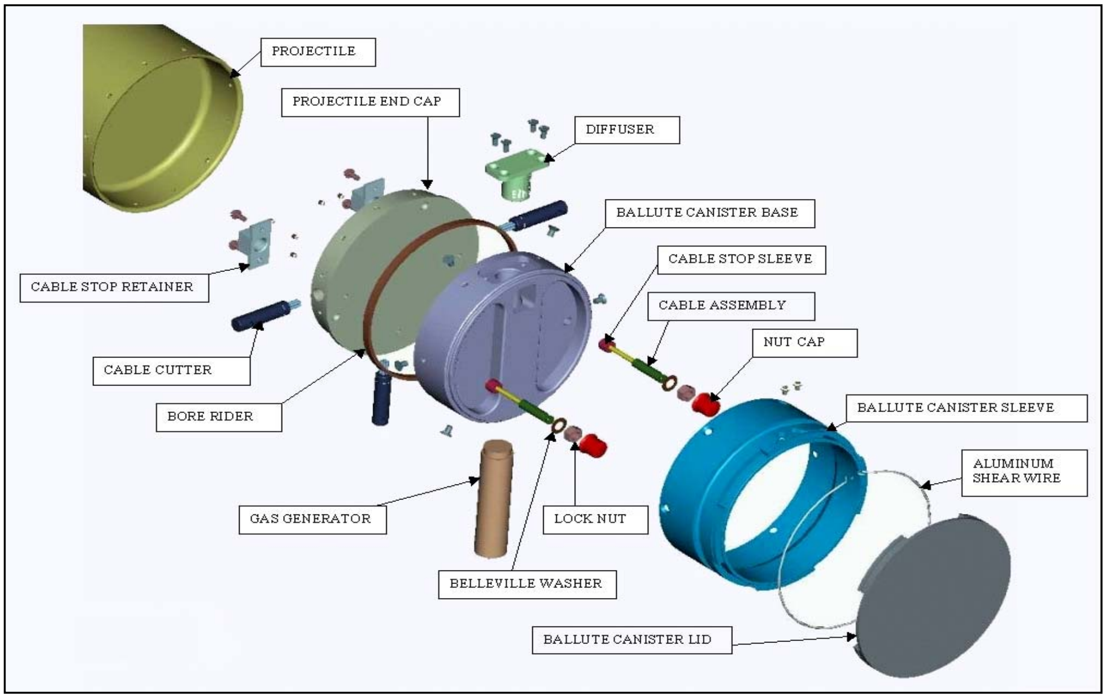

Figure 10: Ballute Assembly Exploded View

Staging Approach

A set of 5/32" diameter steel aircraft cables held the ballute module to the base assembly. To separate the ballute module from the projectile at apogee, these two cables, along with the electrical wires to the gas generator, are cut. This is achieved by using three Pacific Scientific (Quantic Industries) type 5800 series guillotine cable cutters, one for each cable and a third for the electrical wires. Figure 10 shows an exploded view of the ballute assembly including the cable cutters.

TESTING

Ground Testing

Several ballute test articles were fabricated for ground testing. Ground testing included a proof test to verify construction integrity; deployment tests to verify gas generator function and cover plate retention; deployment tests in the path of a blower to verify ram-air inflation; and a combination test that demostrated deployment, ram-air inflation, and staging functions. The latter test also verified proper function of the SAIC-supplied event controller.

Parachute Testing

Drop testing of the parachute system was performed in February 2002. A 60 lb test vehicle was instrumented with accelerometers and barometric recording devices. The envelope of the parachute canister was duplicated, and the opening velocity profile was achieved by using a timed cutter on the pilot chute. The test vehicle was dropped from an altitude of 1,300 ft MSL. The vehicle free fell for approximately 7 seconds to reach the required deployment speed of 125 ft/sec. Once the cutter fired, the parachute was extracted, and opening loads, deployment speeds, and canopy descent rates were measured.

Results from the two tests performed showed that the design met project requirements. Opening loads were under 20 G and descent rate was less than 31 ft/sec. Figure 11 is a photograph taken at the drop test.

Figure 11: Parachute Drop Testing

Flight Testing

In June 2002 at the Yuma Proving Grounds in Yuma, Arizona, flight tests were completed to evaluate some of the UAV's subsystems. This test phase was aimed at risk reduction for the final vehicle configuration. The flight test demonstrated ballute deployment and separation, projectile stability, inflatable wing deployment, and parachute deployment and operation.

Installed in the vehicle was a flight computer which controlled ballute deployment and separation timing, as well as wing deployment.

The flight test used a smooth-bore nitrogen gas gun to provide launch accelerations of 200 – 300 G. This gun was chosen to reduce testing costs and provide freedom to vary launch G's. Upon discharge, the 93 lb projectile was accelerated to approximately 200 G's with a muzzle velocity of 388 ft/sec. At 0.25 seconds from muzzle exit, the ballute deployed to stabilize and decelerate the projectile. Near the trajectory apogee of 987 ft and 6 seconds into the flight, the inflatable wings deployed at a velocity of approximately 113 ft/sec. The vehicle then descended to 850 ft, and at 10 seconds into the flight the ballute canister was jettisoned, deploying the parachute. Figures 12 through 16 illustrate the test sequence.

Figure 12: Projectile Launch from Gas Gun

Figure 13: Ballute Deployed

Figure 14: Ballute Inflated and Wings Deployed

Figure 15: Ballute Jettison & Parachute Extraction

Figure 16: Parachute Descent

LESSONS LEARNED

As a result of flight testing, one item of hardware was identified for redesign. During the gun launch, the ballute cover plate was found to have deformed as a result of gun firing pressure. Initially the ballute cover plate design was based on the assumption that the compression packed ballute would fully support the cover plate. In fact, the packed ballute did compress further and the cover plate plastically deformed under the gun firing pressure. Figure 17 shows the cover plate after the gun pressure deformed it into a concave shape.

Figure 17: Ballute and Cover Plate after Recovery

Post test inspection also revealed that the gas generator had burned a hole through the ballute fabric. When the cover was deformed in the gun barrel, it wedged into the canister, requiring more inflation pressure to be ejected than originally planned. This allowed hot gas to contact the ballute fabric for a longer period of time than intended.

Both issues were solved by adding an intermediate pusher plate, which distributed the pressure to the rigid outer housing of the ballute canister. An alternate solution would have been to redesign the cover plate to include a concave profile and make the lid out of a stronger and/or thicker material.

Overall the flight tests were highly successful. The ballute performed as expected by providing stability for the projectile and deceleration for wing deployment. Once the ballute was jettisoned, it provided the necessary extraction force for the parachute system. The parachute lowered the vehicle to a benign landing, resulting in a successful recovery.

ACKNOWLEDGEMENTS

The authors thank Mark Skidmore and John Bednarz of Talley Defense for responsive support in the development and delivery of gas generators, and George Barnard of CDR Parachute Systems for assistance in trajectory stability analysis.

The authors would like to recognize and thank the FASM Program Manager, Peter A. Morrison, Program Manager, Weapons Technology , Office of Naval Research, and the Quicklook Program Manager, Robert Werko, US Army TACOM-ARDEC.

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