Demonstration of Procedure for Designing Impact-Bag Attenuation Systems with Predictable Performance

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A six-degree-of-freedom mathematical model and computer program were used to predict the performance of a rectangular-shaped impact-bag attenuation system that was designed and fabricated for drop-testing an MQM-34D remotely piloted vehicle (RPV). The impact bag was a lightweight structure without internal supports and having reliable, repeatable bag-pressure relief orifices. Elastometric materials suitable for the total temperature environment were used. Bag pressures and RPV loads were predicted for both vertical and horizontal velocity components. The drop tests showed close agreement between the predicted and actual results. The impact bags protected the RPV from significant damage. The computer technique resulted in the vent-pressure/vent-area design that minimized RPV rebound following impact.

Introduction

THIS paper describes a program in which a six-degree-of-freedom (DOF) math model and computer program were used to predict the performance of a rectangular-shaped, impact-bag attenuation system designed and fabricated for drop testing an MQM-34D remotely piloted vehicle (RPV).

For more than 20 years, Goodyear has been conducting research and development on impact-bag attenuation systems for aircraft and cargo recovery systems. Figure 1 shows an early design suitable for missile or RPV applications.[1] Figure 2 shows a barrel-type impact attenuation system developed for the deceleration of cargo platforms having load capacities of 5000 to 20,000 lb.

Figure 3 shows a typical torus-shaped impact attenuator designed to land spacecraft on the moon or planets. This nonventing torus was designed to impact either on the plane of the torus or on the edge. Drop tests showed that the impact forces were somewhat less, whereas deflections were somewhat greater than those predicted by theoretical calculations. Performance prediction is recognized as a cost-effective method of minimizing the number of drop tests needed to qualify an impact-bag attenuation design. However, making performance predictions for early impact-bag designs was difficult for several reasons:

First, early pressure relief systems were characterized by inconsistent behavior. These have been replaced by more reliable systems.

Second, early impact bags used body-of-revolution designs, since this shape was normal for bags after inflation and during impact. Rectangular-shaped bags offer a more efficient method of obtaining improved stroke characteristics. In order to obtain rectangular shapes, many bags were tried which used internal straps and/or threads; but these proved to be bulky and costly. This problem has been overcome by an improved method of fabricating large rectangular bags by laying them up on simplified tooling.

Third, early performance predictions were carried out by hand calculations or by simple machine calculators. The advancement of computer technology in recent years has greatly enhanced the analytical methods used in performance predictions.

Received Oct. 24, 1975; presented as Paper 75-1378 at the AIAA 5th Aerodynamic Deceleration Systems Conference, Albuquerque, N. Mex., Nov. 17-19, 1975; revision received Oct. 1, 1976.

Index categories: Aircraft Deceleration Systems; Aircraft Landing Dynamics.

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Progress in these three areas contributed significantly to the success of a recent Goodyear program, which resulted in the demonstration of a procedure for designing an impact-bag attenuation system with predictable performance. This program qualified a five-bag system for the crew module of the B-1 aircraft.[2] Figure 4 summarizes the definition of the system, and Fig. 5 shows the actual installation of the inflated system on a test module. Approximately 25 development and 42 qualification shipsets of impact-bag systems were fabricated during the B-1 program. The math model and computer program developed for the B-1 program formed the basis for those used in the program described in the remainder of this paper.

Math Model and Computer Program

Several mathematical models were developed for analyzing the performance of the B-1 impact-bag attenuation bag system. A 6-DOF mathematical model (three translation and three rotation) was developed to handle both rigid and nonshifting bags, as well as bags that could shift position due to lateral friction forces. The shifting-bag model showed good agreement with the system drop-tests results up to the point of structural impact. However, it proved difficult to simulate test fixture structural characteristics and ground interaction.

The computer program for the 6-DOF mathematical model was established for up to five bags located at different positions with respect to the module CG and base. The important variables of the computer program included initial bag pressure, bag vent pressure, bag vent area, velocity magnitude and direction, and bag footprint data. Inputs of vehicle characteristics, such as weight, moment of inertia, and CG location, also were entered. Tradeoff studies then were made to determine the following factors with respect to time: velocities at CG, bag pressure, g load at CG, pitch and roll characteristics of angle, velocity and acceleration, and tail and wing-tip velocities at structural impact.

The computer program 6-DOF equations, assumptions, and limitations were reviewed thoroughly, extended, and analyzed during the B-1 program. The data exist in internal memoranda. Although no updated published information is available, the basic assumptions can be gleaned from the proposal prepared for the B-1 program.[3]

Design Constraints

A typical schematic for an impact-bag system is shown in Fig. 6. A single-bag system was devised for installation and test on a representative RPV with the following performance requirements: 1) vehicle weight = 1600 lb; 2) vertical descent

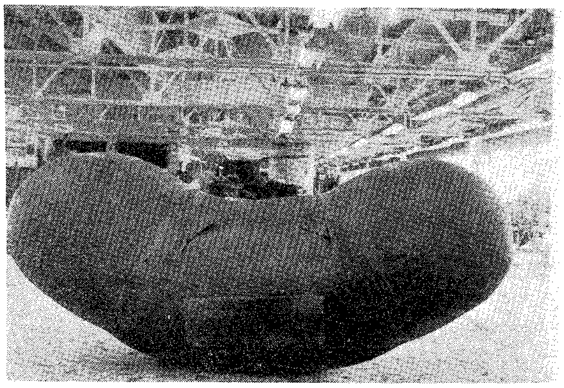


Fig. 1 Inflatable impact bag for Mace missile.

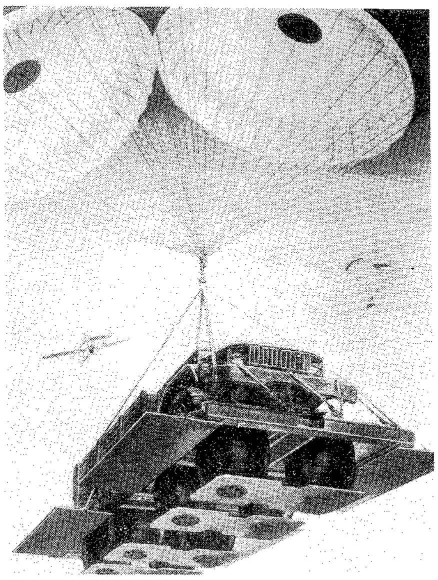


Fig. 2 Barrel-type impact-attenuation system for cargo platform payload.

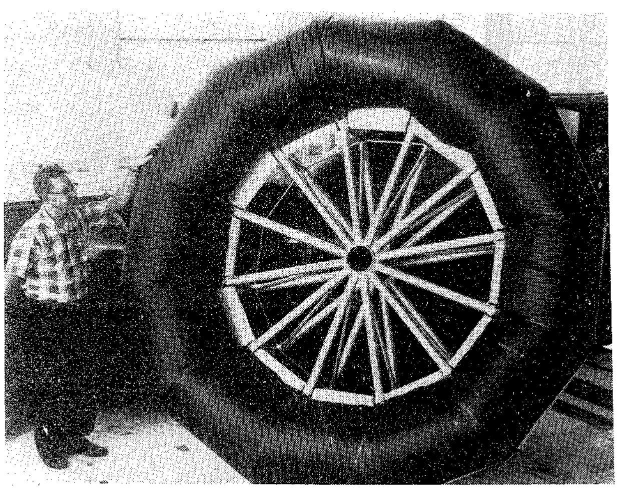
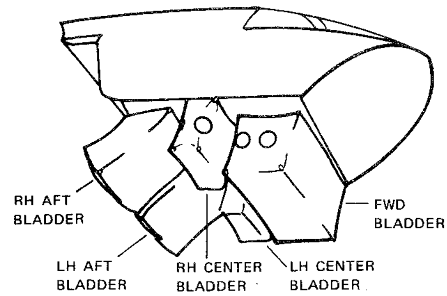


Fig. 3 Torus-shaped impact attenuator for lunar/planetary landing.

velocity = 19 fps; 3) horizontal velocity (any direction) = 17 fps; 4) maximum CG deceleration (G_Z) = −8; 5) vertical limit load factor = 9.0 max = ($1 - G_Z$); 6) maximum allowable vertical velocity at vehicle impact = 5 fps; 7) maximum allowable pitch velocity at structural impact = 2 rad/sec; 8) maximum allowable roll velocity at structural impact = 4.7 rad/sec; and 9) maximum allowable bag pressure = 10 psig.

The bag was to be located around and near the aft end of the engine nacelle of a model MQM-34D RPV. A B-1 forward



BLADDER SUBSYSTEM:

FIVE BLADDERS PER SYSTEM
NATSYN COATED NYLON FABRIC
2.2 PSIG NORMAL OPERATING PRESSURE

BLADDER	VOLUME (EACH) (FT^3)	SIZE (EACH) (IN.)	STROKE (EACH) (IN.)	TOTAL WEIGHT (LB)
FWD (1)	87	80 X 50 X 49	48	30.7
CTR (2)	20	40 X 31 X 37	36	19.8
AFT (2)	39	49 X 38 X 46	45	34.1
			TOTAL WEIGHT	84.6

INFLATION SUBSYSTEM:

THREE GAS BOTTLES WITH CITS SWITCH IN EACH BOTTLE:
ONE AT 597 IN.^{3}
TWO AT 382 IN.^{3}
GN_2 AT 5000 PSIG AT 70°F
FIVE ASPIRATORS
THREE EXPLOSIVE VALVES
THREE PRESSURE REGULATORS
TWENTY-ONE LINE ASSEMBLIES AND ASSOCIATED FITTINGS
WEIGHT = 88.5 LB

TOTAL SYSTEM WEIGHT = 173.1 LB

Fig. 4 Definition of B-1 impact-bag attenuation system.

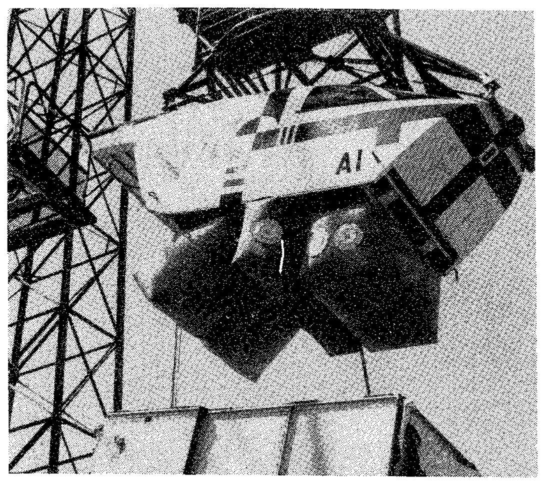


Fig. 5 Impact-bag attenuators on B-1 crew module test unit.

impact bag was modified with a saddle contour to fit around the bottom of the engine nacelle. The bag was a single-compartment bag with a rectangular box-like shape, as depicted in Fig. 7. Four orifice assemblies were used to vent the bag during the impact stroke and thus control the maximum bag pressure. Since this was strictly a test installation to demonstrate the impact bag principle, no attempt was made to optimize the installation or to develop new techniques. Schedule and cost dictated the use of a modified B-1 qualifiable bag.

Many investigations have been conducted to determine a reliable, predictable, and repeatable bag pressure relief system compatible with deployable structures. It was determined that the orifice system shown in Fig. 8 proved the most effective for the B-1 application. Soft aluminum shear pins were found to be the most effective in controlling the maximum bag pressure. For a vent relief pressure of 4 psig and using a 7.5-

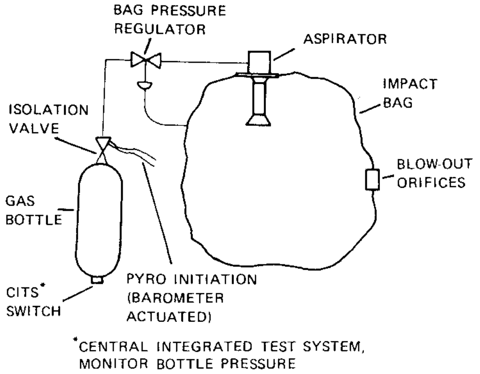


Fig. 6 Inflation system schematic of typical aircraft impact-bag system.

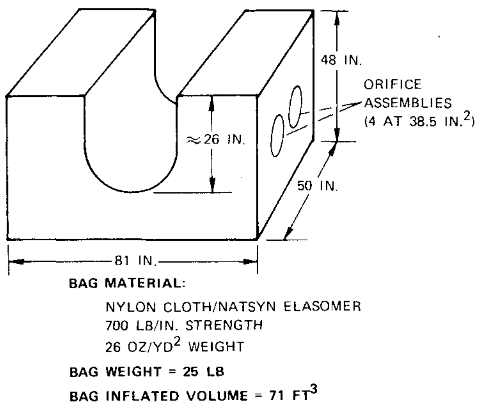


Fig. 7 Maximum inflated dimensions of impact bag for MQM-34D RPV.

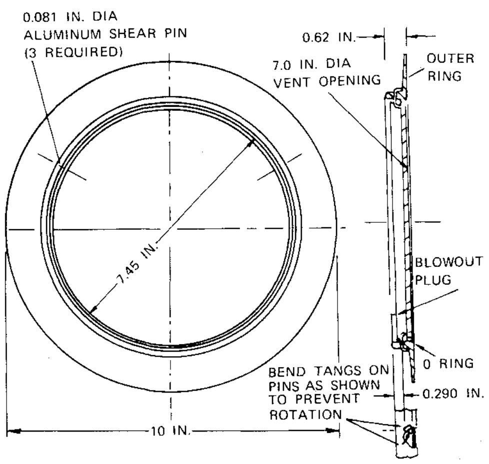


Fig. 8 Bag orifice system for impact-bag applications.

in. diam orifice plate (area = 43.0 in.^{2}), it was determined that either three pins of 0.081-in. diam or five pins of 0.064-in. diam would be suitable for venting the bag pressure. Both of these pin sizes were used for the B-1 program. Since no modifications to the orifice plates were necessary with the three-pin system, the 0.081-in. pins were chosen for the MQM-34D RPV.

The bag footprint was determined by geometric iteration for roll and pitch angles up to the 30-deg condition of the vehicle. Figure 9 shows how the bag cross-sectional area changes for various strokes or deflections during impact for the zero pitch, zero roll condition. The center of pressure (CP) for the footprint essentially remains in the same position for this case, whereas, for other roll conditions, the CP changes with deflection. Figure 10 shows the footprint for the 30-deg

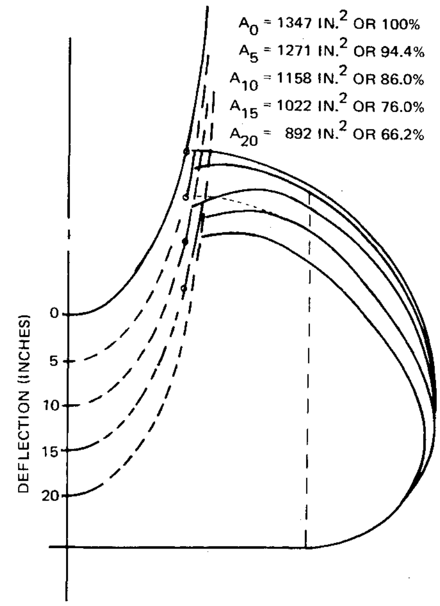


Fig. 9 Footprint analysis of impact bag for 0-deg roll, 0-deg pitch condition.

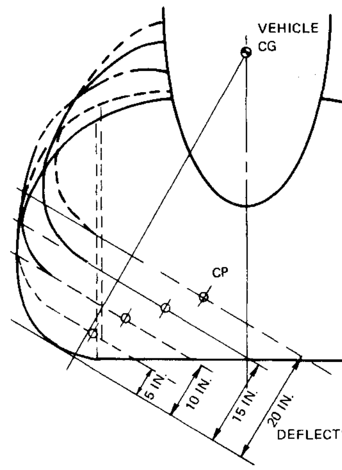


Fig. 10 Footprint analysis of impact bag for 30-deg roll, 0-deg pitch condition.

roll, 0-deg pitch condition, and has the CP location changes with respect to the vehicle CG. As the deflections increase, the bag wraps itself around the vehicle nacelle, and the bag volume decreases while the bag pressure increases. Figure 11 shows the decrease in bag volume for the range of roll angles and deflections considered for the computer program. Figure 12 shows the footprint analysis for the ±30-deg pitch conditions, and also shows the anticipated CP and CG distance relationships.

These data (footprint area, bag volume change, CP position, CG position) were incorporated into the computer program. Several computer runs were made in which the bag vent area and vent pressure were varied. Results indicated that a vent area of at least 115 in.^{2} was required for an initial bag pressure of 1.0 psig and a vent pressure of 4.0 psig; otherwise, the g loads would exceed 8. Two bag locations were investigated. It was found that bag location at the aft end of the nacelle gave significantly lower pitch angles, but showed little change in G_Z, bag pressure, and displacement characteristics.

Material Considerations

The basic materials used in bladder or impact bag fabrication are coated fabrics. The fabrics consist of a nylon woven cloth coated with a rubber elastomer. The fabrication

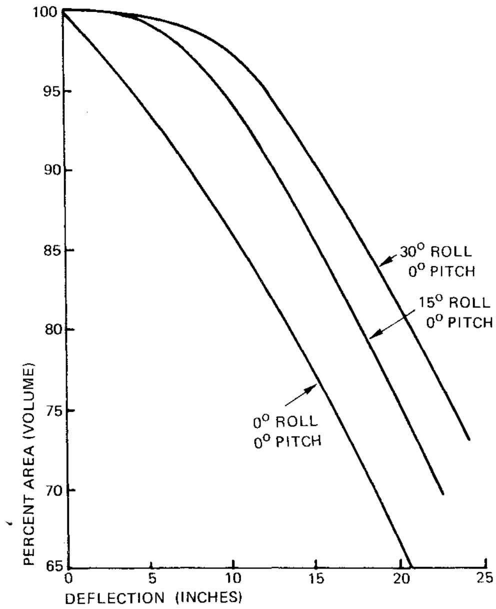


Fig. 11 Impact-bag cross-sectional (volume) variation for different roll angles and deflection (stroke) conditions.

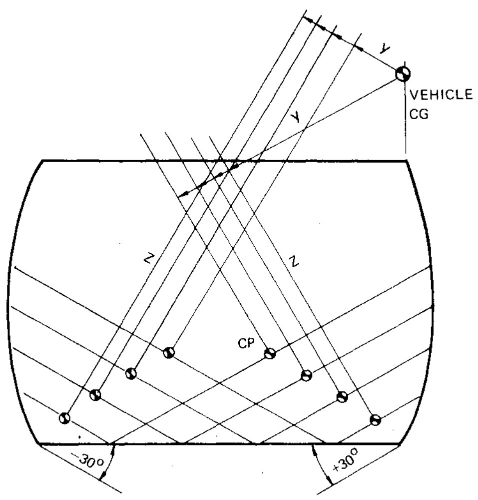


Fig. 12 Footprint analysis of impact bag for ±30-deg pitch, 0-deg roll condition.

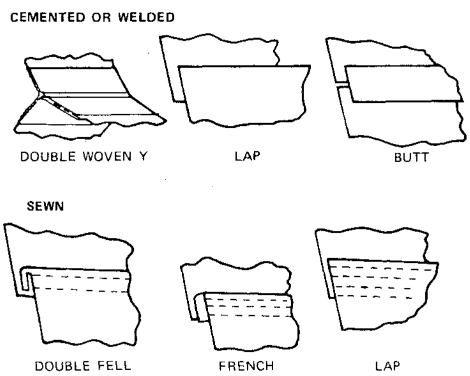


Fig. 13 Typical attachments for flexible structures.

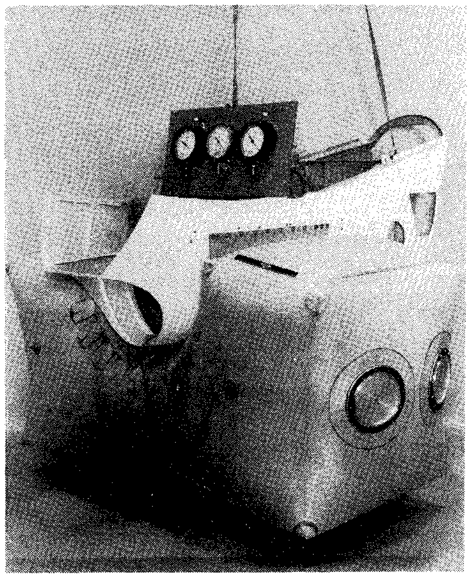


Fig. 14 Impact bag installation on typical RPV nacelle.

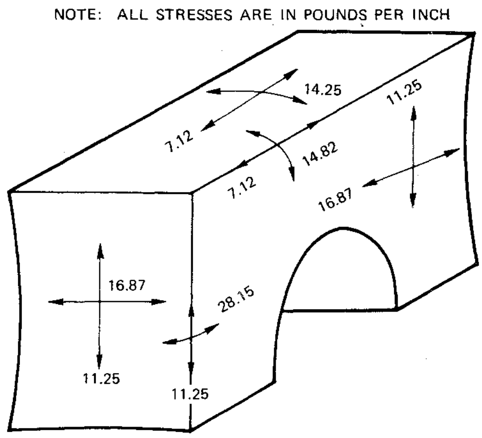


Fig. 15 Impact bag stresses encountered for 1-psig pressure (bag shown inverted).

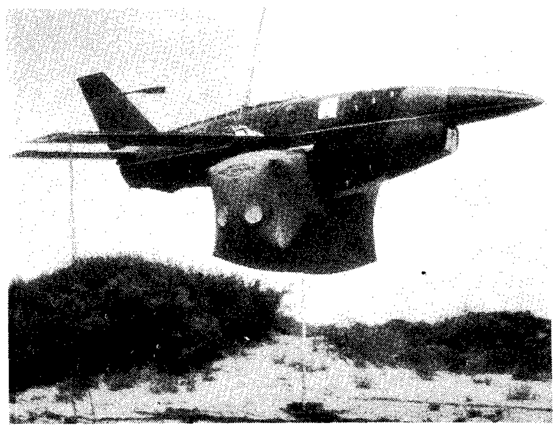
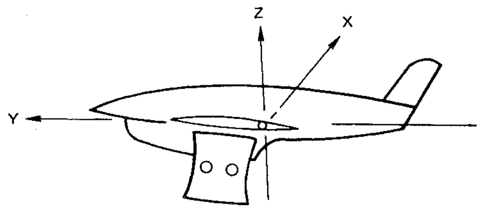


Fig. 16 Inflated impact bag mounted on MQM-34D RPV.

process involved the seaming together of patterned pieces of fabric to form a gas-tight bladder. Both fabric-to-fabric and fabric-to-metal seams are required. Figure 13 shows typical attachments for flexible structures.

As noted earlier, the impact bag used for the MQM-34D application was a modified B-1 impact bag. For the B-1 program, the original material system that was selected included a chlorobutyl fabric and a chlorobutyl gum stock seaming system. Uncured fabric was used in fabrication, and the fabric coating and the seams were cured in an autoclave after assembly over metal tooling. Since the chlorobutyl-coated fabrics failed to meet the −65°F cold-temperature deployment requirement, Goodyear developed a synthetic material rubber compound called Natsyn™, following a comprehensive development program on natural rubber



DROP NO.	V_Z (FPS)	V_X (FPS)	V_Y (FPS)	
1	−19	0	0	WITH BAG DEPLOYED
2	−19	0	0	
3	−19	0	0	
4	−19	0	17	
5	−19	17	0	
6	−19	0	−17	
7	−19	12	−12	
8	−19	17	0	NO BAG

Fig. 17 Drop-test velocity conditions.

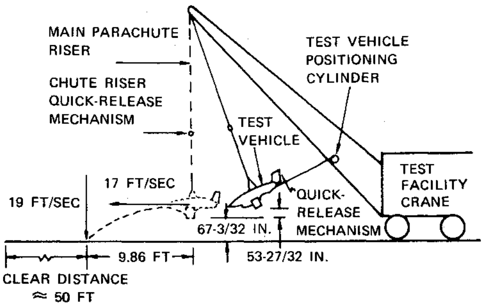


Fig. 18 Drop-test installation.

coatings. This material was used in fabrication in the precured state. An autoclave cure was used after bag assembly to cure the seam materials. Natsyn bladders successfully passed leakage tests both before and after cold temperature deployment.

Figure 14 shows the bag installation on a typical nacelle of the RPV. The radii of the material were determined in key areas of the bag while pressurized to 1 psig. These radii generally do not change much up to the maximum pressure of 6 psig expected for this application. Figure 15 shows the bag stresses encountered for pressures of 1 psig at various seams and midpanel locations. Since the maximum fabric stress of 28.15 lb/in. was encountered at 1 psig, it was determined that an adequate factor of safety was achieved. A minimum fabric strength of 291 lb/in. was measured in tests, whereas the fabric strength requirements for 6 psig are 160 lb/in.

A curtain length of 28 in. attached the impact bag to both sides of the nacelle. The initial bag pressure of 1 psig put a 14.3 lb/in. preload into the curtains. Maximum curtain loads of approximately 46 lb/in. were determined for drops with drift or a horizontal velocity component.

Drop Tests

The drop test procedures and results are given in Ref. 4. Figure 16 shows the inflated impact bag mounted on a fully configured MQM-34D RPV having a gross weight of 1600 lb. This installation was used in the drop tests to demonstrate air bag performance and verify prediction techniques. (The installation is the same as that shown in Fig. 14.) No attempt was made to deploy the bag from a packaged condition, since only bag performance and dynamic data during and after ground impact were investigated. The vehicle CG and weight were representative of a typical MQM-34D at recovery.

Figure 17 summarizes the drop test conditions. As indicated, there were 8 drop tests – 7 with the impact bag attached to the RPV and 1 with no impact bag attached. All 8 drops had vertical velocities of 19 fps; drops 4 through 8 had added horizontal velocities.

In order to achieve the horizontal velocity components, a crane and quick-release mechanism were used, as depicted in Fig. 18. Instrumentation was installed to monitor impact bag pressure and the acceleration of the test vehicle during the dynamic impact landing. The data were recorded on a high-speed, direct-writing oscillograph. The signals from installed transducers were transmitted through a flexible umbilical land line harness to the oscillograph recorder.

TEST DIRECTIONS

DROP NO.	VELOCITY (19 FPS VERTICAL)	MAXIMUM BAG PRESSURE (PSIG)[a] PREDICTED	MAXIMUM BAG PRESSURE (PSIG)[a] ACTUAL	MAXIMUM CG DECELERATION (G_Z)[a] PREDICTED	MAXIMUM CG DECELERATION (G_Z)[a] ACTUAL
1	VERTICAL ONLY	4.3	3.0	7.5	7.3
2	VERTICAL ONLY	4.3	4.4	7.5	7.5
3	VERTICAL ONLY	4.3	3.9	7.5	6.7
4	[b] 17 FPS AT 0°	4.3	3.5	7.5	5.5
5	[b] 17 FPS AT 90°	4.4	4.4	6.1	5.0
6	[b] 17 FPS AT 180°	4.13	4.0	7.0	6.0
7	[b] 17 FPS AT 135°	4.4	4.4	6.7	6.0
8	[b] 17 FPS AT 90°	N/A[c]	N/A[c]	N/A[c]	>100

[a] Maximum bag pressures and G_Z occur at approximately 0.07 seconds after ground contact.

[b] Vertical plus horizontal.

[c] Not applicable. No impact bag on RPV.

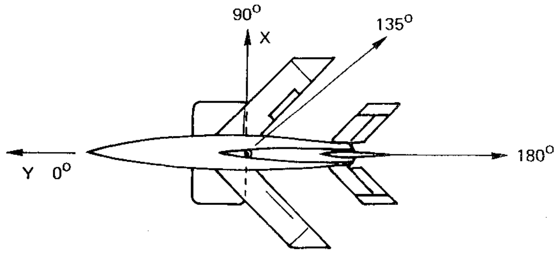


Fig. 19 Drop-test results.

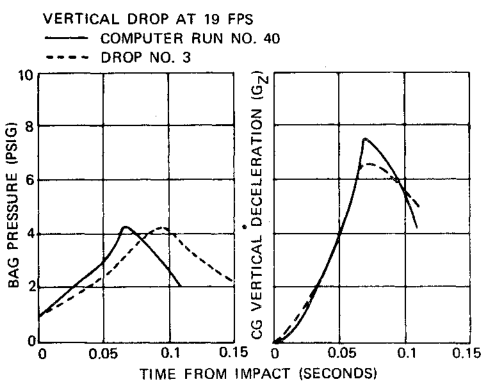


Fig. 20 Comparison of predicted and actual bag pressures.

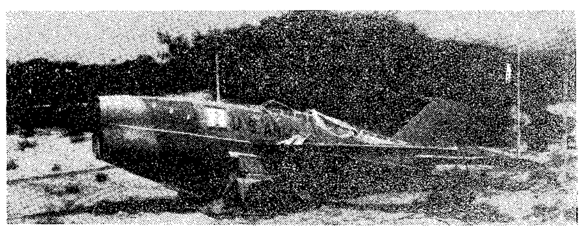


Fig. 21 RPV with impact bag after drop test.

Results and Conclusions

Analysis of the drop-test data is shown in Fig. 19. Predictions of the computer program were that the maximum bag pressure would be less than 4.5 psig, the maximum vertical loading G_Z would be less than 7.5 g, and the maximum velocity at CG would be less than 3 fps. These conditions were met repeatedly as shown in Fig. 19.

Comparisons of predicted and actual bag pressure and vertical decleration G_Z are given for a typical vertical drop condition in Fig. 20. Generally, close agreement is shown between predicted and test data.

Figure 21 shows the vehicle at the conclusion of a typical test. The same bag was used for all of the tests. It was necessary to replace only the shear pins for the tests, since the orifice plates usually were undamaged. No adverse effects were noted on the impact bag or the installation for the seven drops in which the bag was used. A 16-mm movie has been made of the drops and is available for review.

With the impact bag installed, there was either no damage or only minimal damage to the RPV in the three drops having only vertical forces. Only minor nacelle dents resulted from drops having forward and aft velocities. One reusable wing tip was separated during drops having lateral forces. Extensive nacelle damage was encountered in the lateral drop with no impact bag installed. Also, the RPV bounced several times after impact, which added to the damage.

A review of the computer data indicated that the bag pressure, or G_Z buildup, was not as rapid as desirable for efficient operation. It appears that a smaller volume bag will result once a prototype system is specifically designed for this or similar drone applications.

This test program, along with the B-1 program, showed that the 6-DOF computer program enabled prediction of bag experimental performance. Reliable and repeatable bag pressure relief systems were qualified. Rectangular-shaped bag construction without internal restraints improved the stroke-footprint picture. Elastometric materials suitable for total temperature environment proved effective. The vent pressure/vent area design precluded rebound on impact. The bag-RPV interface can be improved to alleviate horizontal velocity impacts.

References

[1]Idomir, K., "TM-76 Mace Landing Mat Design," *Aero/Space Engineering*, Vol. 19, Feb. 1960, pp. 28-32.

[2]"B-1 Impact Attenuator System, Qualification Test Report," Goodyear Aerospace Corp., Akron, Ohio, GER-16084, Rev. A, June 1974.

[3]"Proposal for B-1 Impact Attenuation System," Goodyear Aerospace Corp., Akron, Ohio, GAP-70-6060, Vol. II, Technical, Dec. 1970.

[4]"Final Test Report for the MQM-34D Air Bag Ground Drop Impact Test," Teledyne Ryan Aeronautical, San Diego, Calif., Internal Rept. No. 29242-1, Oct. 1973.