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AN EXPANDABLE GAS BAG CONCEPT FOR A STOWABLE, OMNIDIRECTIONAL, MULTIPLE-IMPACT LANDING SYSTEM

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Abstract

A landing system consisting of a payload surrounded by a radially compartmented spherical gas bag is proposed. Vehicle kinetic energy is dissipated as a consequence of gas flow characteristics through orifices in the compartment walls. Multiple impact capability is obtained by retaining the gas within the bag. The impact characteristics of a simple test vehicle consisting of a compartmented cylinder attached to a collapsible gas bag were investigated experimentally to determine the energy dissipation capabilities of such a system. Analytical expressions based on one-dimensional-flow theory were obtained for acceleration, velocity, stroke, and compartment pressures for the test vehicle as well as for spherical gas bag landing systems. Experimental and analytical results were in good agreement; computed and experimental values of kinetic energy dissipated by the test system agreeing within 5 percent. In the experiments the kinetic energy dissipated was as great as 90 percent of the kinetic energy of test vehicle at touchdown. Comparable energy dissipation was also obtained from preliminary computations for an earth landing of the proposed spherical gas bag landing system.

I. Introduction

NASA is planning programs which will require survivable landings of instrumented capsules on planets and satellites. The task of designing landing systems for this type of capsule is complicated by uncertainties associated with the landing of a vehicle in an unknown atmosphere and on an unknown surface.[1,2] These uncertainties could lead to multiple, unoriented impacts of the landing vehicle occurring after initial touchdown. Hence, as indicated in reference 3, "first look" landings may well be done with ball-type capsules having omnidirectional and multiple-impact capabilities even if later missions are to be made with a more controlled type of landing where a directionally restricted landing system (such as a legged system) may be used.

A variety of gas-compression systems have been proposed, investigated, or actually used as velocity-dissipating landing systems.[4 to 12] For example, the military services have investigated the use of air bags for the aerial delivery of cargo[9,10] and the Mercury spacecraft were equipped with an air bag system for shock attenuation during landings.[4] Spherical gas bags with the payload suspended at the center have been proposed and investigated by Martin and Howe[5,6] for use as omnidirectional landing systems. However, the systems previously investigated did not have a multiple-impact capability since they were designed to release gas from the bags through orifices during the compression cycle or by bag rupture when the payload velocity had been dissipated.

This paper presents the results of an investigation of a gas bag landing system concept having both omnidirectional and multiple-impact capabilities. Experimental results of the impact characteristics of a simplified test vehicle of the system were obtained and the results are compared with analysis. Results of preliminary computations for an application of the system in an earth landing are also presented and discussed.

II. Description of Concept

The stowable, omnidirectional, and multiple-impact capabilities may be obtained by surrounding the payload with a radially compartmented spherical gas bag such as is shown in figure 1. In transit the gas bag would be collapsed and stowed within the entry vehicle. In the terminal phase the bag would be deployed and pressurized to the design initial pressure. Vehicle kinetic energy dissipation is achieved in the following manner. During impact, gas is compressed locally in certain compartments and is forced through orifices in the compartment walls into adjacent compartments. Eventually, the force resulting from the overall pressure generated in the gas bag system is just sufficient to overcome the inertial forces of the vehicle so that vehicle rebound is initiated. However, at this instant, internal gas flow is still occurring. Thus, there is a phase lag between the internal gas flow cycle and the impact-rebound cycle which produces a situation wherein all the potential energy stored during impact is not available during rebound. The orifice flow characteristics may be thought of as valves which partially block or throttle flow during vehicle rebound to prohibit full recovery of the initial vehicle kinetic energy. After the vehicle loses contact with the impact surface, internal gas flow continues. Multiple-impact capability of the system results because all gas is retained within the bag, hence the bag recovers to initial conditions during rebound and is capable of protecting the payload from additional impacts.

III. Test System

To investigate the capabilities of this type of landing system, the impact characteristics of a test system consisting of collapsible cylindrical bags and storage compartments of fixed volume were investigated.

The test system shown in figure 2 was designed to represent volumetric conditions occurring for an impact on the surface of a sphere with 20 equal-volume compartments at a juncture point of five compartments. Impact at this point results in the compression of five compartments with gas flow initiated sequentially through orifices into the remaining three sets of five compartments (each set of five having the same volume as the compressed volume). The collapsible air bags of the test system shown in figure 2 represent the compressed volume (five compartments) of the sphere. Multiple air bags were used, instead of a single bag, to provide increased test system stability. The cylindrical upper body was divided by partitions with circular orifices into

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three compartments, each having a volume equal to that of the collapsible air bags. These three volumes represent the three storage volumes of the sphere. The test system was not a model of a prototype configuration but was investigated to illustrate the principle of operation of the landing systems.

The instrumentation of the test system consisted of a single-component, strain-gage-type accelerometer, four strain-gage-type pressure transducers, a 20-kilocycle amplifier, a pressure control unit, and a recording oscillograph. The accelerometer was rigidly mounted to a lead mass, which accounted for more than half of the total mass, to record acceleration along the longitudinal axis of the test system. A pressure transducer was mounted to record the gage pressure in each of the four volumes. It should be noted, however, that the pressure in the collapsible gas bags was measured in only one of the bags. All tests were made by a free-fall method. All landings were made on concrete at approximately a symmetrical contact attitude.

IV. Analysis of Test System

The impact analysis consisted of the derivation of equations for the computation of time histories of acceleration, velocity, stroke, and compartment pressures. The following assumptions were made in deriving the equations: the landing of the test system was assumed to occur along a vertical flight path and at a symmetrical contact attitude; the only force causing deceleration was the gas-pressure force; the gas bags were inextensible and flexible; and the discharge parameter for the open circular orifices was 0.6. A closed-form solution for these equations was not obtained; instead, the computations were made by an incremental procedure. Given the impact velocity and assuming an incremental time interval Δt, an incremental stroke Δy is computed. The resulting volume change and hence the ratio of instantaneous volume to original volume for the cylindrical bags is computed. The incremental time, Δt, was chosen sufficiently small so that the pressure and density at the beginning of any time interval may be taken, within the accuracy limits, as the average pressure and density during the time interval. Since the footprint area of the test system is independent of stroke, the decelerating force is solely a function of the pressure in the collapsible volume. This pressure may be determined from the pressure-volume relation and the mass flow equations. In this analysis both adiabatic and isothermal processes are considered but results are presented for the isothermal case only. For the isothermal case the pressure may then be determined from the following equations:

$$P_{I,t} = \frac{P_{I,i}V_{I,i}}{V_{I,t}}\left(\frac{m_{I,i} - m_{Ie,t}}{m_{I,i}}\right) \qquad (1)$$

where

m air mass, slugs

P pressure, lb/ft^2

V volume, ft^3

I collapsible volume

e air mass exhausted

i quantity prior to contact

t quantity occurring at time t

The gas mass transfer is primarily proportional to the pressure difference and is approximated by the following equation:

$$m_{Ie,t} = K_I CA \sum \left[2\rho\left(P_I - P_{II}\right)\right]^{\frac{1}{2}} \Delta t \qquad (2)$$

where

A orifice area, ft^2

C discharge coefficient

K_I flow direction index $= \dfrac{P_I - P_{II}}{|P_I - P_{II}|}$

Δt time increment, sec

ρ mass density of air, $slugs/ft^3$

II,III,IV quantities in storage volumes (see fig. 2)

When $K_I = 1$, $\rho = \rho_I$ and conversely, when $K_I = -1$, $\rho = \rho_{II}$.

Since the storage volumes remained undeformed, the pressures in these volumes were determined from the appropriate air mass ratios.

$$P_{II,t} = \left(\frac{m_{II,i} + m_{Ie,t} - m_{IIe,t}}{m_{II,i}}\right) P_{II,i} \qquad (3)$$

$$P_{III,t} = \left(\frac{m_{III,i} + m_{IIe,t} - m_{IIIe,t}}{m_{III,i}}\right) P_{III,i} \qquad (4)$$

$$P_{IV,t} = \left(\frac{m_{IV,i} + m_{IIIe,t}}{m_{IV,i}}\right) P_{IV,i} \qquad (5)$$

The equation for the air mass exhausted from each of these volumes at any time after contact is the same as equation (2) with the appropriate volume subscripts inserted for the pressure and density terms.

V. Experimental Results

General Performance

The results of the experimental investigation of the test system are presented in figures 3 through 5.

Typical time histories of acceleration and pressures obtained from the experimental investigation are shown in figure 3. It has been previously noted that the pressure measured in the collapsible volume was measured in only one of the air bags. Therefore, the time for peak acceleration and peak pressure in volume I may not be coincident, as would normally be expected, since variation of the impact attitude from a perfectly symmetrical attitude would result in the measured pressure not fully representing the pressure-causing deceleration. The time lag shown between the peak pressures of the several volumes is indicative of the orifice-throttling characteristics.

The experimentally obtained acceleration-time histories were used to determine the kinetic energy dissipated in percent of the kinetic energy of the test system at contact with the landing surface. This was accomplished by integrating the acceleration-time history to obtain a velocity. The velocity obtained from this integration represents the velocity in the test system at contact with the surface plus the rebound velocity. Assuming the decelerated mass remains constant, the kinetic energy dissipated is represented by the difference between the initial contact velocity squared and the maximum rebound velocity squared.

Comparison with Analysis

Comparisons between experimental and computed pressure-time histories for a typical test are shown in figure 4 for the collapsible volume and the three storage volumes. The computed data shown for volume I (collapsible bags) were obtained for a perfectly symmetrical impact and rebound. The experimental data for volume I were obtained from a landing in which perfectly symmetrical compression of the air bags did not occur. The major difference between the computed and experimental data for volume I is attributed to unsymmetrical attitudes occurring during the experimental program rather than fallacies in the computational procedure. The agreement between the computed and experimental data for the three storage volumes is good, since these volumes are not as sensitive to contact attitude as volume I.

Kinetic-Energy-Dissipation Capability

The kinetic energy dissipated, expressed in percent of kinetic energy of the test system at contact with the landing surface, is shown in figure 5 as a function of initial bag pressure. Test system experimental and computed data are presented. Experimental data obtained from tests made at an initial bag gage pressure of 0 pounds per square inch show that approximately 90 percent of the kinetic energy was dissipated. Tests conducted at the same touchdown velocity for initial bag pressures greater than atmospheric show a decrease in kinetic energy dissipation with increases in initial bag pressures. Increases in initial bag pressure for landings made at this velocity resulted in less stroking of the collapsible bags and consequently less air mass flow. Since flow losses should vary with the amount of flow involved, greater energy dissipation should occur at the higher initial bag pressures if the collapsible bags could be stroked further. To check the foregoing premise, the test system was impacted at a higher velocity for initial pressures of approximately 1.8 and 3.2 pounds per square inch gage. As shown on figure 5, an increase in kinetic energy dissipation of approximately 10 percent was obtained for the range of gage pressures investigated.

The computed kinetic energies for the test system at the lower velocity are within 5 percent of the fairing of the experimental data throughout the range of initial bag pressures investigated. The computed data for the higher velocity, although very limited in scope, are also within 5 percent of the experimental data. Thus, within the accuracy of the experimental investigation, it would appear that the computational procedure is adequate for predicting kinetic energy dissipation.

VI. Application Study

The analysis presented has resulted in equations which permit the computation, within engineering accuracy, of time histories of acceleration, velocity, stroke, and compartment pressures and also permits the determination of kinetic energy dissipation capability for a given set of initial conditions. Experimental and computed values agree within experimental accuracy. A study, employing a similar computational procedure with the additional stipulation that the velocity in the orifice was limited to sonic velocity, has been conducted to establish the variation of landing data with pertinent payload, spherical gas bag, and atmospheric parameters and to investigate the operation of the principle in a practical case. For the case of the impact of the spherical gas bag, the equations presented previously must be modified to account for geometrical changes due to the distortion of the spherical bag by the landing surface. The equations for these geometrical distortions are involved and lengthy and in the interest of brevity are not presented in this paper.

Preliminary computations have been made for an earth landing of an instrument payload and a compartmented spherical air bag landing system to determine the variation of kinetic energy dissipation with initial bag pressure and orifice area. These computations are simplified since impact was limited to only one point on the surface of the sphere and volume distortion was limited to those compartments initially in contact with the landing surface. In order to determine the variation of kinetic energy dissipation with the aforementioned parameters, it was necessary to arbitrarily select bag geometry, impact velocity, vehicle (instrument payload and landing system) mass, and limiting load. The spherical gas bag was assumed to have 20 equal-volume compartments and to be 6 feet in diameter. The impact velocity was assumed to be approximately 150 feet per second which corresponds to a flight-path velocity that has been considered in connection with a proposed Mars landing of an instrument payload. The vehicle mass was assumed to be approximately 6 slugs. The instrument payload had an assumed diameter of 2 feet and a limiting deceleration load of 1000 earth g-units.

The variation of kinetic energy dissipation with air bag initial pressure is shown in figure 6. Kinetic energy dissipation increased as bag initial pressure decreased and the maximum kinetic energy dissipation (minimum rebound) occurred near a bag initial pressure of 1 atmosphere absolute. For the range of bag initial pressures investigated, doubling the orifice area had very little effect on the kinetic energy dissipated.

The variation of the kinetic energy dissipation with orifice area is shown in figure 7 for three values of initial bag pressure. The curves indicate that there is one value of orifice area for maximum kinetic energy dissipation at each initial bag pressure. The dashed line connects the orifice areas at which maximum kinetic energy dissipation occurs for each of the pressures shown. This line indicates that as initial bag pressure decreases, the orifice area, at which minimum rebound velocity occurs, also decreases.

Time histories of acceleration and velocity for an earth landing of the assumed vehicle are presented in figure 8 for values of orifice area and initial bag pressure which yield maximum kinetic energy dissipation (minimum rebound velocity). The maximum deceleration was approximately 1000 earth g-units and the rebound velocity was approximately 35 feet per second, which corresponds to a value of energy dissipated of approximately 90 percent.

A landing system such as the one presented in this paper could be designed to land certain types of instrument payloads on any planetary body. However, prior to the design of such systems, a more comprehensive parameter study would be required.

VII. Concluding Remarks

The results of the experimental investigation show that the landing system concept is valid and that a kinetic energy dissipation capability of approximately 90 percent of the kinetic energy of the vehicle at touchdown may be obtained with proper design. Agreement between experimental and computed results for the test system was good. The results of the preliminary application study of an earth landing of a compartmented spherical bag indicate that initial bag pressure has a major influence on kinetic energy dissipation and that minimum rebound is achieved for initial bag pressure in the order of 1 atmosphere absolute. The study also revealed that orifice area must be decreased as initial bag pressure is decreased in order to obtain minimum rebound velocity. Computations were made for a landing of the spherical bag using values of initial bag pressure and orifice area for maximum kinetic energy dissipation. The computed results show that the vehicle can be stopped within the load limitation of 1000 earth g-units with less than 10 percent of the initial kinetic energy appearing in the form of rebound velocity.

VIII. References

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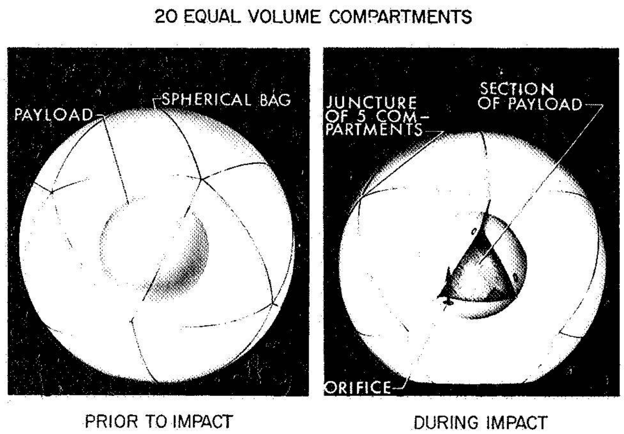

Figure 1.- Spherical gas bag landing system.

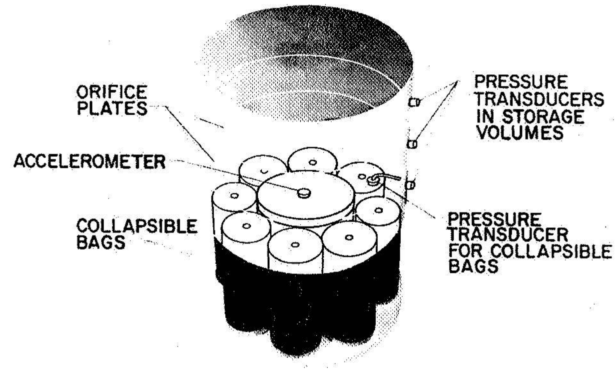

Figure 2.- Conceptual model.

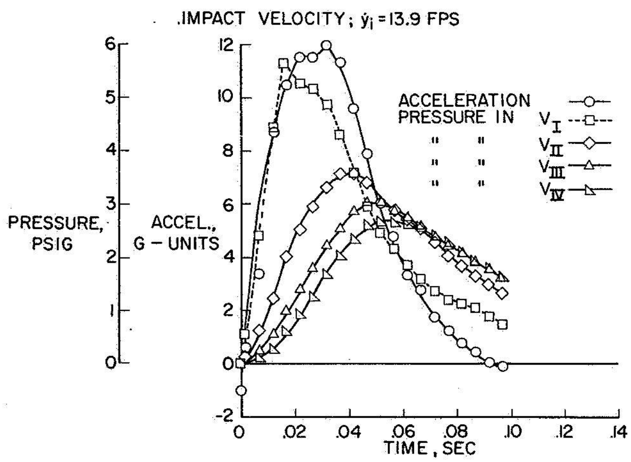

Figure 3.- Typical experimental time histories of acceleration and pressures of test system.

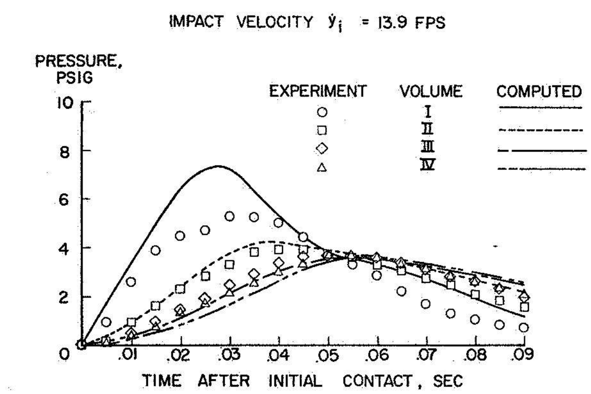

Figure 4.- Comparison of experimental and computed pressure-time histories of test systems.

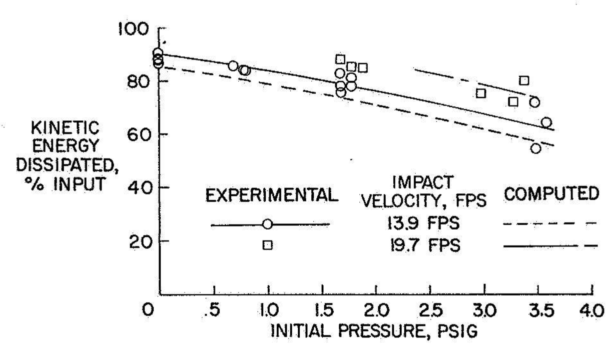

Figure 5.- Kinetic energy dissipation capability as obtained from the test system.

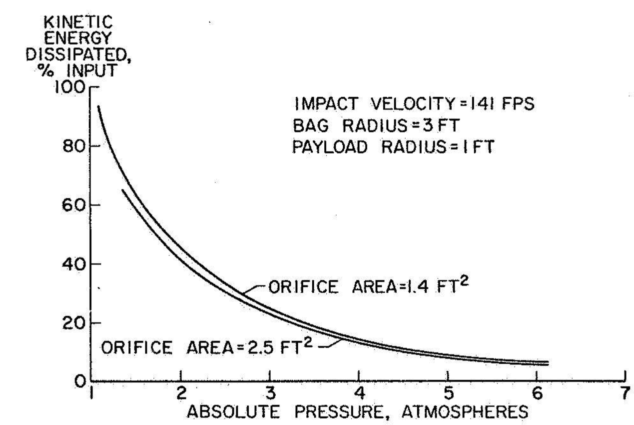

Figure 6.- Kinetic energy dissipation as a function of initial pressure in spherical air bag.

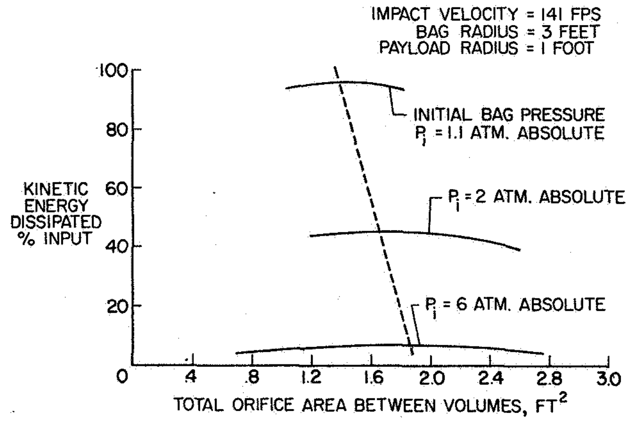

Figure 7.- Kinetic energy dissipation of spherical air bag as a function of orifice area.

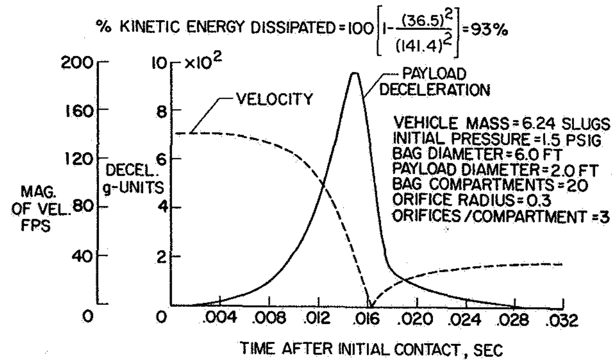

Figure 8.- Spherical air bag landing system performance.