load-deflection curves in Fig. 2b show buckling, self-locking, contacting (point B), and bifurcation phenomena. Here E is Young's modulus, I_{33} is the area moment of inertia, θ is the twisting angle, R is the radius of the band, and b and h are the width and thickness of the cross section, respectively. The deformed geometry in Fig. 2a corresponds to point B ($\theta = 140$ deg) in Fig. 2b, and it shows that the midpoint of the upper half ring is in contact with the midpoint of the lower half ring. If the ring is allowed to cut through itself (e.g., a half ring) when $\hat{M}_3$ increases, the deformation follows the solid line in Fig. 2b. Otherwise, the load-deflection curve follows the broken line, and the upper and lower half rings start to tangle together. This contact problem is nonlinear. To prevent such impossible cut-through phenomena in analysis, the deformation path of every point of the structure needs to be checked against all other points because the neighboring points of an observed point vary when large displacements occur. Hence monitoring the deformation process using three-dimensional dynamic graphics is necessary for the analysis and design of HFSs. Moreover, the numerical results show that a ring can be twisted into three small rings with a diameter of one-third of the original diameter when $2\theta = 360$ deg only if the cross-section aspect ratio $b/h \geq 1.52$. Figure 2b also shows the load-deflection curves with $b/h = 1.542$, 1.7, and 3.0, where the deformed configurations at $\theta = 180$ deg are self-locked because $\hat{M}_3 = 0$.

Figure 3a shows the undeformed and deformed configurations of a cantilevered rectangular isotropic plate subjected to two opposite transverse corner loads F when $F = 316.31$ N. The dimensions are $22.86 \times 17.78 \times 0.0660$ cm, Young's modulus $E = 1.570 \times 10^{11}$ Pa, and Poisson's ratios $\nu = 0.3$. Figure 3b shows the several possible stable and unstable equilibrium paths of node N30, where w is the transverse displacement. Locating the bifurcation points B_1, B_2, and B_3 and tracing the bifurcated paths requires the development of special computational algorithms, which is an important but difficult task. The bifurcation points (especially B_1) in Fig. 3b are the type of information important for the design of such HFSs. Figure 3c shows the four possible deformed configurations corresponding to (1), (2), (3), and (4) in Fig. 3b when $F = 63.19$ N (i.e., one-fifth of the load used in Fig. 3a).

Conclusion

In this Note we present some modeling, formulation, computation, and design issues of HFSs. Our numerical and experimental studies on HFSs show that transverse shear deformations, in-plane shearing, stretching, and thickness change are usually small. Other issues to be solved include measuring large deformations involving large rotations, influence of gravity, the use of initial stresses in design, and how to design loadings to have the required deformed shape (i.e., an inverse problem). Moreover, assembling TL finite elements of different types (i.e., cable, beam, plate, and/or shell elements) at a node but maintaining the geometrically exact formulation is still a challenging problem to be solved.

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Avionics Module Recovery System for Expendable Launch Vehicles

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Introduction

THE high cost of launch services is a serious problem for the U.S. commercial satellite industry and for NASA in the conduct of its scientific space program. In seeking a way to lower launch costs for small expendable launch vehicles (ELVs) using solid rocket motors (SRMs) in several stages, the idea of trying to recover the lower stages for reuse is not really practical, for a variety of reasons. Moreover, the value in recovering burned out SRM casings, nozzles, and control equipment from the lower stages is questionable. However, it does make sense to consider recovering all or part of the final stage, which includes the avionics module, in addition to the payload, SRM, and attitude-control equipment. The avionics module is the nerve center of the ELV and performs a variety of functions in vehicle guidance, navigation, and control (GN&C). In general, it contains an inertial measurement unit (IMU), a flight computer, a telemetry multiplexer, a telemetry transmitter, a flight-termination receiver, a radar transponder, reaction control system thrusters, other control units, and batteries in a relatively small volume. Advanced avionics architecture includes Global Positioning System microelectronics to enhance navigation and guidance of the final stage into a precise orbit. If the avionics module and related equipment could be recovered intact after each launch, with minimal cost and effort, it is believed that the savings in small ELV replacement costs could be substantial. Moreover, development of a practical avionics module recovery system could lead to a new kind of hybrid launch vehicle (HLV), which combines advantageous features of expendable and reusable systems. Such a partly reusable HLV might have a recoverable solid- or liquid-rocket final stage containing payload and avionics atop expendable solid- or liquid-rocket lower stages.

The purpose of this Note is to show how the avionics modules of two small ELVs could be recovered using miniature winged spacecraft incorporated into the final stage of each ELV. Because a detailed accounting of component costs for the small ELVs is proprietary information, it was not possible to quantify the cost benefit. That determination requires a definitive cost analysis, which includes an amortization of system development costs over a projected number of launches. In the final analysis, however, the decision of whether or not to proceed with concept development should not be based solely on economic considerations. There are other valid reasons for considering development of this kind of partly reusable launch system. Perhaps the most compelling reason is that both NASA and the U.S. Air Force would then have a cost-effective launch system with the capability of readily returning small scientific and military payloads from orbit.

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Basic Concept

In spite of its complexity, the avionics module in an ELV has evolved into a very durable and robust assembly of electronic equipment. If it were to be reused, it could be designed for even greater durability. The basic idea behind the concept for recovery of the avionics module is that, because of miniaturization of its various components, it is very compact and could probably be contained in a small winged spacecraft incorporated into the forward structure of the ELV. Together with the payload in the nose and a SRM, this miniature spacecraft or avionics recovery vehicle (ARV) would comprise the final stage of the three- or four-stage ELV. After separation of the payload and the burned-out SRM, the small ARV could initiate return from orbit by applying a small amount of retrothrust at the proper time or location along the orbit. It would then begin a gradually accelerating descent and entry into the sensible atmosphere, followed by a gliding, decelerating descent through the lower atmosphere and a remotely controlled landing at a specified site.

Because of the rotation of the Earth, there is a westward precession of the line of apsides of most Earth orbits, which can be used to good advantage in recovering the avionics modules of ELVs launched from Kennedy Space Center (KSC) on the Florida coast (28.5 deg N, 80.5 deg W) or from Vandenberg Space Center (VSC) on the California coast (34.5 deg N, 120.5 deg W). This favorable precession of the ascending and descending nodes is about 23 deg per revolution for low orbits, which increases slightly with the altitude and period of orbit. Allowable launch azimuths range from 35 to 120 deg at KSC and from 158 to 201 deg at VSC.[1] These launch azimuths produce orbit inclinations ranging from 60 to 40 deg at KSC and from 72 to 107 deg at VSC. For a typical easterly launch (azimuth 90 deg, inclination 28.5 deg) from KSC, the ground track of the first orbit passes close to southern California, so that deorbit of an ARV could be initiated over the south Pacific for a landing at either Edwards Air Force Base (35 deg N, 118 deg W) or Vandenberg Air Force Base (34.5 deg N, 120.5 deg W). For a typical southerly launch (azimuth 180 deg, inclination 90 deg) from VSC, the ground track of the first orbit passes just east of the Hawaiian Islands, so that deorbit of an ARV could be initiated over the Arctic Ocean for a landing on the big island of Hawaii at the Hawaiian National Guard Airfield (20 deg N, 155 deg W) near Hilo.

Pegasus/Taurus ELVs

Pegasus and Taurus are two small ELVs derived from rocket launchers first developed in the 1960s.[2] Pegasus[3] is a three-stage, solid-propellant, inertially guided, all-composite, winged ELV, which is air launched from a carrier aircraft at about 40,000 ft with a 1000-lb (454-kg) payload capability for low Earth orbit (LEO). Taurus[4] is a larger, four-stage, solid-propellant ELV that was derived from Pegasus with removal of both wing and tail and addition of an extra solid-propellant booster stage. Taurus is ground launched and stabilized about three axes with a payload capability of 3200 lb (1452 kg) for LEO.

In Pegasus the avionics components are located in the third stage (Fig. 1) on a subsystem mounting structure.[5] The structure is a graphite conical and cylindrical section with an aluminum honeycomb deck, which also provides a mechanical interface for the payload. Pegasus is controlled by a multiprocessor, 32-bit flight computer, which communicates via serial interfaces with individual microprocessors in the vehicle's actuator and sensor components. These distributed microprocessors manage the actuators, ordinance-initiation devices, and telemetry data-gathering systems. The wing and tail fins mounted on the first stage provide pitch, roll, and yaw control aerodynamically during flight through the lower atmosphere. The second and third stages control pitch and yaw by rotation of their flexseal nozzles and provide roll control by cold-gas jets located in the third stage.

In Taurus most of the avionics components are identical to those used with Pegasus.[4] The Taurus avionics are contained in a module (Fig. 2) and provide electrical power, sequencing, telemetry, and GN&C for the vehicle. The avionics also include a radar tracking transponder, electronics for a flight-termination system, and provide mechanical and electrical interfaces with the payload. Thrust-vector control (TVC) for pitch and yaw in the first-stage motor is provided by rotation of the flexseal nozzle. Roll control in this stage is provided by cold-gas jets. The second-stage motor uses a government-surplus, Pershing-1A, jet-vane assembly to provide TVC in pitch, roll, and yaw. Attitude control in the upper two stages is the same as for Pegasus.

Avionics Module Recovery System

Although the avionics components are configured differently in Pegasus and Taurus, there is no apparent reason why similar avionics modules could not be developed for these ELVs. It is envisioned that the avionics modules could be reusable, if encased in miniature,

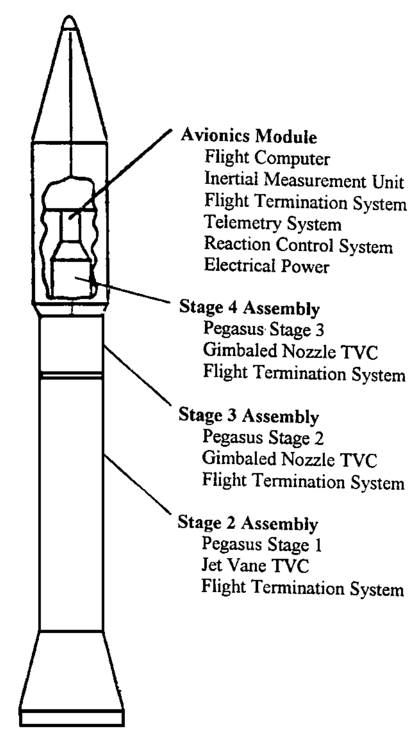

Fig. 2 Second, third, and fourth stages of Taurus.

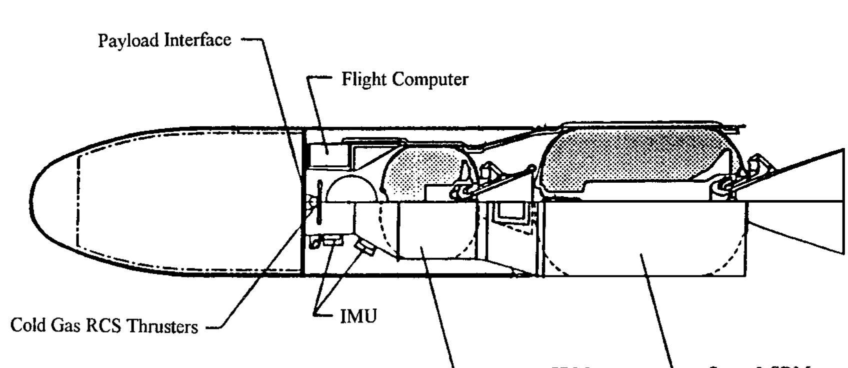

Fig. 1 Second and third stages of Pegasus.

recoverable spacecraft, which would be designed to return to Earth from orbit. Such avionics recovery vehicles or ARVs should have wings like the Space Shuttle Orbiter with sufficient high-speed lifting capability for considerable downrange and cross-range maneuvering. The size of ARV for each ELV depends, to first degree, on the size and weight of the avionics module. It is reasonable to consider the basic shape for the ARVs as being similar to that of the Space Shuttle Orbiter, but other shapes could also be suitable and should be considered. The highly evolved Orbiter design has proven to be as good as any yet devised for handling the aerodynamic forces and the aerothermodynamic heating loads encountered during reentry into the atmosphere from orbit. Moreover, the Orbiter has good stability and control characteristics at all speeds, which make it a suitable design for a small, automatically controlled spacecraft, which could either deploy a parachute and an airbag for final descent or be flown by remote control to a conventional, gear-down landing. There would be some Reynolds-number or scale effects in the aerodynamic characteristics of the ARVs at all flight speeds, but they should not pose a serious problem to stability and control. With development of new heat-resistant materials,[6] the small ARVs could have improved thermal protection systems over that used with the Orbiter.

The Space Shuttle Orbiter has a nominal planform loading of about 65 lb/(ft^2) (97 kg/m^2) during return from orbit, which causes it to have good handling qualities and not be too sensitive to crosswinds and gusts. At low speed the maximum lift-to-drag ratio (L/D) is about 3 at 18-deg angle of attack for a minimum glide slope of $\tan^{-1}(L/D) = 18.4$ deg. The landing flare and touchdown speed of orbiter-like vehicles are also dependent on the planform loading, which should not be too small for low sensitivity to timing of the landing flare. The assumption has been made that a planform loading of 39 lb/(ft^2) (58 kg/m^2), or 60% of that for the Space Shuttle Orbiter, would be a reasonable objective for the larger, fully loaded ARVs and a value two-thirds of that for the smallest ARV. To provide a comparison of five scaled-down Space Shuttle Orbiters, which could serve as different size ARVs, nominal dimensions and estimated weights of these miniature orbiters are presented in Table 1.

ARVs Incorporated into Pegasus and Taurus

Nominal sizes, weights, and thrust levels for the various stages of Pegasus and Taurus are presented in Table 2. Also indicated are the minor changes in the dimensions and weights of these ELVs when a small ARV is incorporated into the final stage of each launcher. The

Table 1 Specification of size and weight for Space Shuttle Orbiter and five miniature orbiters that could be used to return avionics modules of ELVs from orbit

Specification	Space Shuttle Orbiter full size	Miniature orbiters $\frac{1}{10}$ size	$\frac{1}{12}$ size	$\frac{1}{15}$ size	$\frac{1}{20}$ size	$\frac{1}{30}$ size
Height, ft (m)	46.1 (14.1)	4.6 (1.40)	3.8 (1.16)	3.1 (0.94)	2.3 (0.70)	1.5 (0.46)
Length, ft (m)	122.0 (37.2)	12.2 (3.72)	10.2 (3.11)	8.1 (2.47)	6.1 (1.86)	4.1 (1.25)
Wingspan, ft (m)	78.1 (23.8)	7.8 (2.38)	6.5 (1.98)	5.2 (1.58)	3.9 (1.19)	2.6 (0.79)
Payload bay, ft (m)	15 × 60 (4.6 × 18.3)	1.5 × 6 (0.46 × 1.83)	1.25 × 5 (0.38 × 1.52)	1 × 4 (0.30 × 1.22)	0.75 × 3 (0.23 × 0.91)	0.5 × 2 (0.15 × 0.61)
Planform loading, lb/(ft^2) (kg/m^2)	65 (97)	39 (58)	39 (58)	39 (58)	39 (58)	26 (39)
Gross weight, lb (kg)	180,000 (81,648)	1,080 (490)	750 (340)	480 (218)	270 (122)	90 (40.8)
Inert weight, lb (kg)	150,000 (68,040)	950 (431)	650 (295)	400 (181)	210 (95.3)	60 (27.2)
Avionics module weight, lb (kg)	——	80 (36.3)	60 (27.2)	50 (22.7)	40 (18.1)	20 (9.1)

Table 2 Nominal sizes, weights, and thrust levels of the different stages of Pegasus and Taurus ELVs

Component	Pegasus Basic ELV	Pegasus With ARV	Taurus Basic ELV	Taurus With ARV
Booster stage				
Length, ft (m)	Air launch		28.8 (8.78)	28.8 (8.78)
Diameter, ft (m)			7.7 (2.35)	7.7 (2.35)
Weight, lb (kg)			108,000 (48,989)	108,000 (48,989)
Thrust, lb (N)			347,800 (1,530,300)	347,800 (1,530,300)
I_{sp}, s			271	271
First stage				
Length, ft (m)	30.8 (9.39)	30.8 (9.39)	30.8 (9.39)	30.8 (9.39)
Diameter, ft (m)	4.2 (1.28)	4.2 (1.28)	4.2 (1.28)	4.2 (1.28)
Wingspan, ft (m)	22.0 (6.71)	22.0 (6.71)	——	——
Weight, lb (kg)	30,910 (14,021)	30,910 (14,021)	30,910 (14,021)	30,910 (14,021)
Thrust, lb (N)	109,420 (481,450)	109,420 (481,450)	109,420 (481,450)	109,420 (481,450)
I_{sp}, s	295	295	295	295
Second stage				
Length, ft (m)	7.6 (2.32)	7.6 (2.32)	7.6 (2.32)	7.6 (2.32)
Diameter, ft (m)	4.2 (1.28)	4.2 (1.28)	4.2 (1.28)	4.2 (1.28)
Weight, lb (kg)	7,500 (3,042)	7,500 (3,042)	7,500 (3,042)	7,500 (3,042)
Thrust, lb (N)	27,600 (121,440)	27,600 (121,440)	27.600 (121,440)	27,600 (121,440)
I_{sp}, s	295	295	295	295
Third stage				
Length, ft (m)	4.8 (1.46)	10.9 (3.32)	4.8 (1.46)	10.9 (3.32)
Diameter, ft (m)	4.2 (1.28)	4.2 (1.28)	4.8 (1.46)	4.8 (1.46)
SRM wgt, lb (kg)	2,170 (984)	2,170 (984)	2,170 (984)	2,170 (984)
Thrust, lb (N)	7,770 (34,180)	7,770 (34,180)	7,770 (34,180)	7,770 (34,180)
I_{sp}, s	291	291	291	291
ARV wgt, lb (kg)	——	270 (122)	——	270 (122)
Payload wgt, lb (kg)	1,000 (454)	770 (349)	3,200 (1,452)	2,970 (1,347)
Total length, ft (m)	50.9 (15.5)	57.0 (17.4)	90.3 (27.5)	96.4 (29.4)
Total weight, lb (kg)	42,000 (19,051)	42,000 (19,051)	154,000 (69,854)	154,000 (69,854)

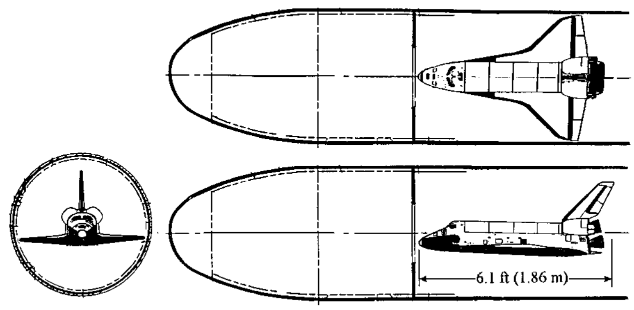

Fig. 3 Miniature ($\frac{1}{20}$-size) orbiter enclosed in fuselage of Pegasus.

assumption has been made that a suitable scale size of miniature-orbiter ARV would be $\frac{1}{20}$ for both Pegasus and Taurus. A three-view rendering of the way a $\frac{1}{20}$-size orbiter ARV could be enclosed in the forward fuselage of Pegasus (just behind the payload) is presented in Fig. 3. Ideally, the avionics module would be contained in the payload bay of the ARV and could provide GN&C capability to enable the small, autonomous spacecraft to return safely from orbit. From Table 2 one can see that the payloads of the small Pegasus and Taurus ELVs would not be severely impacted by inclusion of such small ARVs into their final stages.

Conclusion

Miniature spacecraft patterned after the Space Shuttle Orbiter could be used to return the avionics modules of small expendable launch vehicles from orbit. Miniature replicas of the Orbiter, when properly sized for a given weight, would have similar aerodynamic and aerothermodynamic characteristics during descent through the atmosphere. Thus, they could function in much the same way as the full-size Orbiter by using automatic programming of flight sequences in conjunction with monitoring of operational events and spacecraft welfare from the ground. The final phase of flight could be either a parachute descent or a remote-controlled, conventional runway landing. To determine whether or not recoverable and reusable avionics is a viable concept for lowering recurring launch costs, an in-depth study of the many cost factors involved needs to be undertaken. However, the idea of developing miniature, Orbiter-like spacecraft, of the type required to return avionics modules, is one that NASA and the Defense Advanced Research Projects Agency should probably consider for other than cost-cutting reasons. Such small, recoverable spacecraft could have many useful functions, including those of returning scientific or military payloads from orbit, servicing satellites, and providing courier service to and from the International Space Station.

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