Design of a Separating High-Altitude Probe

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Plans to measure the electron density and other characteristics of the ionosphere at several thousand kilometers are based on a capsule that separates into two parts so that radio waves can be propagated between them; relative phase shifts will thus provide "local" measurements that can be telemetered to a ground station. The antennas of the two sections must be aligned within a specified angular tolerance. Although both sections are spin-stabilized, precessions and nutations of the launch vehicle and imperfections in the various separation operations give rise to important misalignments. This paper describes the construction of the payload and the various mechanical devices involved, including a technique for measuring relative velocity of the two sections by a nylon tape striped at intervals with contactors. The dynamic behavior of the system is analyzed, and the governing parameters are discussed. Partially successful ground tests of the separation are described.

Nomenclature

A, C = moments of inertia about the body-fixed X and Z axes, respectively
$\mathbf{i}, \mathbf{j}, \mathbf{k}$ = unit vectors in X, Y, and Z directions, respectively
p, q, r = angular velocity about the body-fixed X, Y, and Z axes, respectively
$\mathbf{Q}$ = impulse
t = time
δ = maximum angular misalignment of the spin axes
ξ = angular velocity parameter $= (p^2 + q^2)^{1/2}$
η = angle between the angular momentum vectors of two bodies
θ, ϕ, ψ = Eulerian angles
$\boldsymbol{\omega}$ = angular velocity vector

Subscripts

= condition immediately prior to complete separation
0 = initial condition
1 = body 1
2 = body 2

Introduction

To date, the measurements of the electron density in the various regions of the ionosphere have been based on the dispersion between signals propagated between a rocket or satellite and a ground station, from which the integral of the electron density along the phase path to the vehicle is found as a function of time.[1, 2] This method is quite successful in the D, E, and lower F regions of the ionosphere,[1] but at greater altitudes the longer time of measurement involved, refraction effects, horizontal stratifications, and temporal variations in electron densities introduce inaccuracies in the measurements, so that this method appears to be limited to a maximum altitude of the order of 600 km. In order to extend the range of measurements to several thousand kilometers, the use of a payload that separates into two parts at a predetermined height has been proposed.[3] Radio waves are propagated between the two sections, and their relative phase shifts are measured. Thus, a "local" measurement of the absolute electron density is made and telemetered to a ground station.

Initial experiments are planned to cover altitudes to about 1100 km. The launch vehicle chosen is the Argo D-4, a four-stage rocket consisting of an "Honest John," two "Nike" stages, and an Allegheny Ballistic Laboratory (ABL) X-248 motor on which the payload is mounted. The payload is to be ejected from the fourth stage 135 sec after liftoff, and 10 sec later, at 380 km, the two sections of the payload are separated by a compression spring that imparts to them a relative velocity of 6 m/sec (Fig. 1). A maximum altitude of 1100 km is reached in 510 sec, and the experiment terminates in 970 sec at 200 km.

An orientation control problem arises from the requirement that the directional antennas carried in each half of the payload be aligned with each other within a specified angular tolerance (Fig. 2). Gyroscopic stability is imparted to the payload by the fourth stage, which spins at 540 rpm, and consequently, under ideal conditions, the axes of the two sections should remain in alignment as they travel in a ballistic trajectory. In practice, precessions and nutations of the launch vehicle-payload combination and imperfections in the various separation operations cause disturbances whose magnitudes must be determined.

Description of the Payload

The payload consists of three units. The cone on the left of Fig. 3 is part of the ABL X-248 motor and contains a "Yo" mechanism (a 1.25-lb-despin weight on a cable) and a 300-lbf coil spring that effects separation. A steel ball is used to center the spring force as accurately as possible on the axis of symmetry. The Yo mechanism is provided in order to exclude any possibility of accidental impact of the motor after separation because this motor is known to experience sporadic terminal thrust impulses; it is released approximately 3 sec after separation by squib-type cable cutters. The resulting force unbalance and the reduction in the angu-

Received February 20, 1964; revision received May 26, 1964. The authors wish to express their appreciation to John S. Nisbet, Technical Director of the Program, and to T. P. Quinn, both of The Pennsylvania State University, as well as to Olin B. King of Space Craft, Inc. for their many suggestions and contributions. This work was carried out under NASA Grant No. NsG-134-61.

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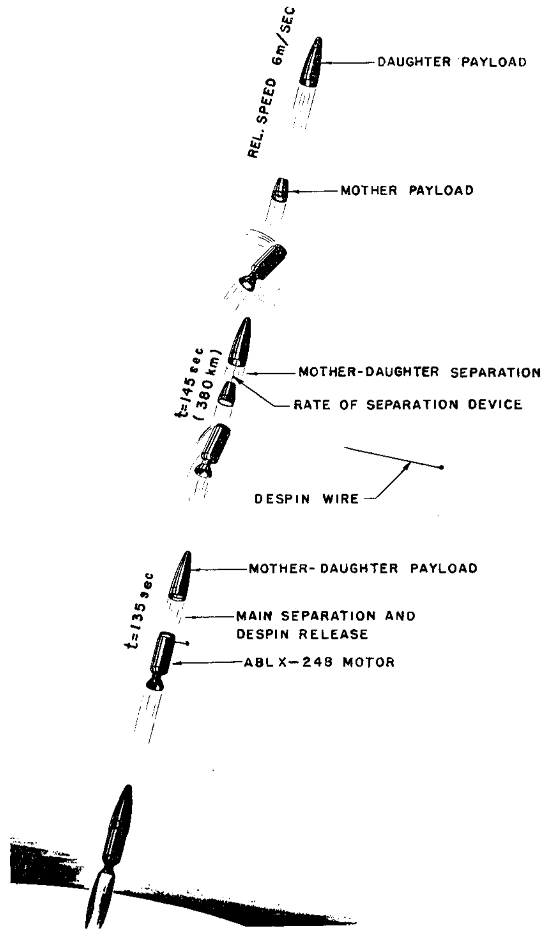

Fig. 1 Separation sequences of the payload.

lar momentum of the motor give rise to high precession angles (Fig. 1), so that any chuffing of the motor serves to move it clear of the payload.

The electronic equipment is carried in the mother and daughter sections, shown at the center and right in Fig. 3, respectively. The basic structure of the daughter payload is the Argo D-4 Fiberglas nose cone, which contains the 6-, 12- and 72-Mc transmitters, the battery pack, the antenna system, and the separation spring assembly. The structure of the mother payload consists of a stiff aluminum alloy instrument container and a central tube that guides the pay-

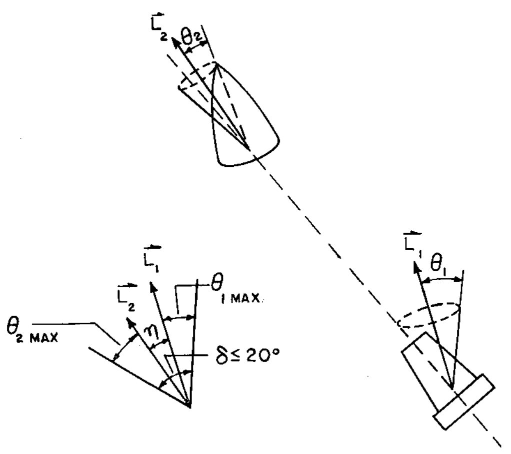

Fig. 2 Payloads after separation and definition of angles θ_1, θ_2, and η. Both packages precess about individual angular momentum vectors (L_1, L_2) with constant angle (θ_1, θ_2).

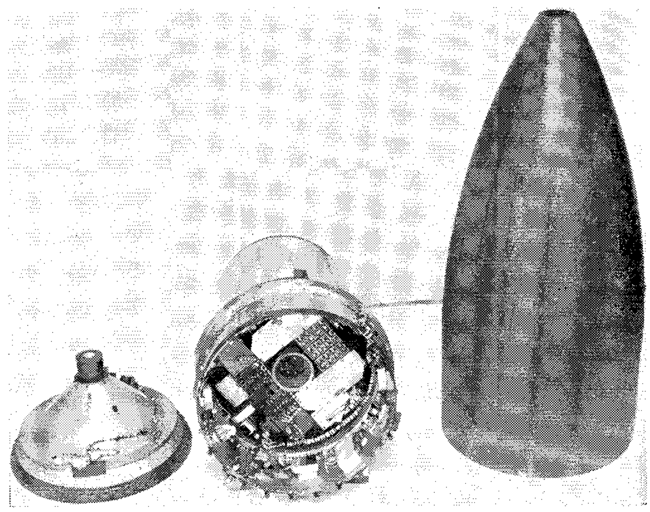

Fig. 3 Major payload components.

load components during separation. The antenna package is located on top of the instrument container and consists of Fiberglas sheets secured to each other and to the instrument container. Two loop antennas and a telemetering antenna are rigidly mounted to the Fiberglas structure, and the entire assembly is filled with a low-density foam.

These payload units are held together by a stainless-steel ring on the mother package and a copper lock ring on the daughter payload which have numerous, accurately machined interference fingers. The former is preloaded by 24 small coil springs that, when separation is initiated, rotate this ring and thereby release the mother from the daughter package. To prevent cocking and binding, the two units are guided at two points having different diameters over a distance of 4 in.

The success of the experiment depends on an accurate measurement of the relative velocity between the mother and daughter units. Numerous devices were considered; the one adopted consists of a magazine mounted in the mother unit which contains 8 ft of a thin, $\frac{1}{4}$-in.-wide Fiberglas tape impregnated with an acrylic plastic and painted with conductive strips of a silver-based epoxy at 1.5-in. intervals. At separation, the daughter package withdraws the tape, and each time a conductor passes over the contact bar an impulse is telemetered, until finally the tape separates too. The contact bar consists of 10 gold-plated $\frac{1}{32}$-in.-thick copper disks mounted on a Fiberglas shaft and separated by $\frac{1}{64}$-in.-thick mylar disks. Every other disk is wired to a bus bar, which in turn is wired to the output connector. The tape must be long enough to give a sufficient number of counts (precessional motions contribute to errors) but not so long that rotation of the packages could lead to a "skip rope" effect.

Analysis of the Dynamics of the Mother-Daughter System

The major disturbances in the relative orientation of the two sections of the payload are due to nutations and precessions of the payload-rocket combination before separation and to tipping moments occurring during the various stages of separation. In particular, the motion before, during, and after the (guided) mother-daughter separation must be analyzed, since the solution of each of the first two steps provides the initial conditions for the subsequent differential equations of motion. Barnes[4] and Scott[5] have done this on basis of the following assumptions: 1) the bodies are rigid (justified by the high natural frequencies of the capsules and equipment relative to those of the exciting forces); 2) the motion takes place in a vacuum (justified for separation at

380 km); and 3) no external forces act on the system as a whole after separation of the ABL X-248 motor. These assumptions imply the invariance of the angular momentum vector and of the kinetic energy of the system. We make the additional restriction that the payloads, combined and individually, are symmetrical about their axes. They are carefully mass-balanced during manufacture, and the effect of slightly uneven burning of the ablative coating of the nose cone is negligible.

Before separation, Euler's equations govern

$$A\dot{p} + (C - A)qr = 0 \qquad A\dot{q} - (C - A)pr = 0 \qquad \dot{r} = 0 \tag{1}$$

The largest possible angle between the spin axes of the two bodies can now be determined in terms of the known conditions before separation is initiated (refer to Fig. 2):

$$\delta = \theta_{1\max} + \theta_{2\max} + \eta \tag{9}$$

According to the requirements of the experiment, this angle must not exceed 20°.

For simplicity, let $Q_x = Q$ and $Q_y = 0$ in Eq. (7). The maximum values of the components of δ are then given by

$$\theta_{1\max} = \tan^{-1}(A_1{}^2\xi_f{}^2 + 2p_fQA_1 + Q^2)^{1/2}/C_1r \tag{10}$$

$$\theta_{2\max} = \tan^{-1}(A_2{}^2\xi_f{}^2 - 2p_fQA_2 + Q^2)^{1/2}/C_2r \tag{11}$$

$$\eta = \cos^{-1}\frac{A_1A_2\xi_f{}^2 + p_fQ(A_2 - A_1) - Q^2 + C_1C_2r^2}{\{(A_1{}^2\xi_f{}^2 + 2p_fA_1Q + Q^2 + C_1{}^2r^2)(A_2{}^2\xi_f{}^2 - 2p_fA_2Q + Q^2 + C_2{}^2r^2)\}^{1/2}} \tag{12}$$

The solutions of these equations are well known. In terms of initial conditions, such as $\boldsymbol{\omega}_0 = \mathbf{i}p_0 + \mathbf{k}r_0$ we obtain

$$p = p_0 \cos r_0(C/A - 1)t \qquad q = p_0 \sin r_0(C/A - 1)t \qquad r = r_0 \tag{2}$$

If the space Z axis coincides with the angular momentum vector, the Euler angle θ, which the body spin Z axis makes with this line, is given by

$$\theta = \tan^{-1}(A\xi/Cr) \tag{3}$$

where

$$\xi \equiv (p^2 + q^2)^{1/2}$$

During the guided separation of the two payload sections, the moment of inertia about the diametric axes varies with time, and Euler's equations take the form

$$A\dot{p} + \dot{A}p + (C - A)qr = 0 \tag{4}$$
$$A\dot{q} + \dot{A}q - (C - A)rp = 0 \qquad C\dot{r} = 0$$

The values of p and q are readily found if the moment of inertia varies linearly with time, $A = A_0 + at$. However, a solution of Eqs. (4) is not necessary to obtain the desired relative orientations, and since the magnitude of the angular momentum vector remains unchanged

$$A\xi = A_f\,\xi_f \tag{5}$$

[The same relationship is also obtained if Eqs. (4) are solved using the linearly increasing moment of inertia.]

At the instant after separation, the vector sum of the angular momenta of the two packages is equal to the angular momentum of the combination just prior to separation, so that

$$A_1\,p_{01} + A_2\,p_{02} = (A_1 + A_2)p_f$$
$$A_1\,q_{01} + A_2\,q_{02} = (A_1 + A_2)q_f \tag{6}$$

Additional equations for the angular velocities may be found by considering the internal forces of the system (because of gyroscopic moments and centripetal forces acting on the precessing bodies) which are released impulsively at separation. Imperfections in the separation mechanism, such as friction in the guide tube, eccentricity of the spring force, and various misalignments, also contribute. For clarity, we assume that the impulsive moment has components along the diametric axes only. Then the initial conditions of the two bodies at the instant of separation are given by

$$p_{01} = p_f + Q_x/A_1 \qquad q_{01} = q_f + Q_y/A_1$$
$$p_{02} = p_f - Q_x/A_2 \qquad q_{02} = q_f - Q_y/A_2 \tag{7}$$

The motions of the two bodies therefore can be found from Eqs. (1); e.g., for body 1,

$$p_1 = \xi_{01}\cos\{(C_1 - A_1)rt/A_1 + \cos^{-1}(p_{01}/\xi_{01})\}$$
$$q_1 = \xi_{01}\sin\{(C_1 - A_1)rt/A_1 + \cos^{-1}(p_{01}/\xi_{01})\} \tag{8}$$

Figure 4 shows the deviation angle of the separated sections of the payload (upper family) and the precession angle of the combined payload (lower family) vs ξ. Note that Eqs. (10–12) involve p_f, so that, for any given value of ξ_f, the maximum δ has to be found in terms of p_f (this was done with a digital computer for Fig. 4).

The foregoing analysis may readily be extended to the more complicated case in which the moments of inertia of the bodies, individually and combined, differ about the three principal axes and where impulsive moments are applied about all three directions.[4]

Experimental Investigations

The experimental set-up and procedures described below were designed to demonstrate that 1) all separation devices functioned properly and within specified tolerances, 2) the springs and guiding structure were adequate to impart the desired relative linear velocity of 6 m/sec, and 3) separation would not give rise to large moments, especially about the diametric axes, which would cause a misalignment exceeding 20° between the spin axes of the mother and daughter packages.

The test specimen (Fig. 5) consisted of a nose cone containing actual or simulated hardware and a simulated mother package structure. All components affecting separation, however, were identical to those to be used in flight. Relative velocity between the mother and daughter packages was determined by both high-speed movies and the velocity-measuring device carried in the payload. For measuring forces acting on the packages during the action of the ejection springs, three Endevco 2106 piezo electric gages were sandwiched between two $\frac{3}{4}$-in.-thick aluminum plates. Each

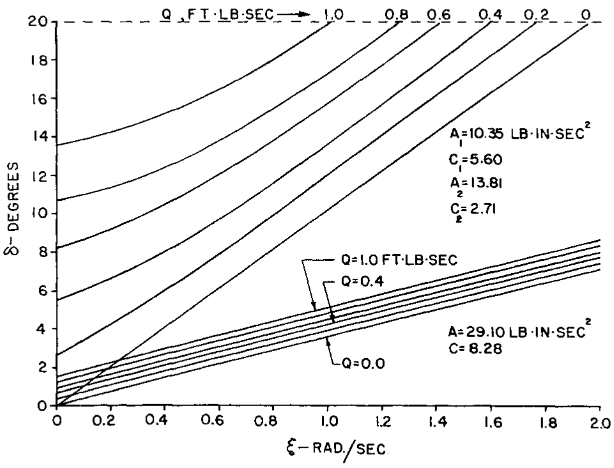

Fig. 4 Deviation angles between the mother and daughter sections as a function of ξ for various impulsive moments.

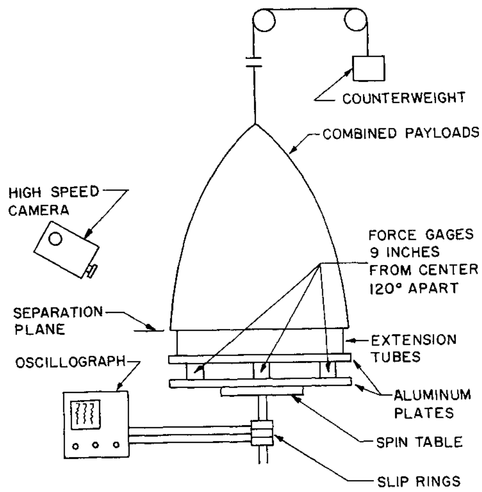

Fig. 5 Separation test set-up.

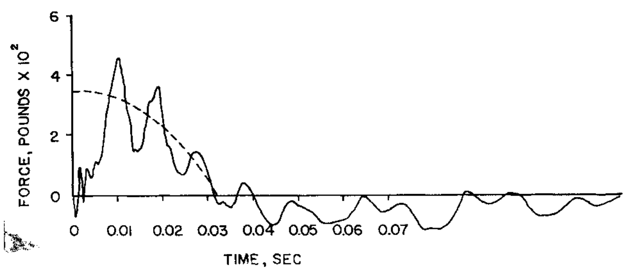

Fig. 6 Typical force gage output during a mother-daughter separation test.

gage was connected to an Endevco 2614 amplifier fixed to the upper aluminum plate. The signals were taken through special low-noise slip-rings and amplified further. A multichannel oscillograph served to make simultaneous recordings of all signals.

In order to prevent an ejected package from falling back onto the spin table, a nylon cord and counterweight were attached to the nose cone. During the relevant first few seconds after separation, the upward displacement of the package was greater than the corresponding downward displacement of the counterweight, so that force-free conditions were simulated. Aerodynamic forces due to wind or velocity of the packages were very small and could be neglected.

However, because of the elasticity of the plates and spin table, the test apparatus did not behave as a rigid structure.

Table 1 Experimental data

Test	Gage outputs, lbf 1	2	3	Total	Q, in.-lb-sec	Angular deviation (from film)
Rocket-payload separation:						
1	71	55	132	258	34.0	Less than 5°
Mother-daughter separation:						
2	247	223	259	729	4.6	3.5°

Initial high-frequency oscillations due to the action of the squibs quickly damped out, but relatively low frequency vibrations resulted from excitation of the plates and the supporting structure during separation; this response (Fig. 6) closely resembles that of a second-order system to an impulsive force such as is produced by the ejection spring. For this reason, test results had to be evaluated by "filtering" a cosine wave having the same area as the actual trace. Nevertheless, the forces estimated in this manner revealed gross effects occurring during separation and, in particular, led to an improvement in the method of application of the spring force between the payload and the rocket motor.

Test results are summarized in Table 1. In test 2, which refers to the mother-daughter separation, it was found that only about one-fourth of the moment listed in Table 1 affects the relative motion of the packages after separation. The moment was caused mostly by the fact that the base ring of the test nose cone was not perfectly circular, resulting in offset frictional forces.

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