NASA TECHNICAL NOTE

NASA TN D-2191

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NASA TN D-2191

DYNAMIC-MODEL INVESTIGATION OF A 1/20-SCALE GEMINI SPACECRAFT IN THE LANGLEY SPIN TUNNEL

by Henry A. Lee, Peter J. Costigan,
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Langley Station, Hampton, Va.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • MAY 1964

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Technical Film Supplement L-788 available on request.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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SUMMARY

An investigation has been conducted at low subsonic speeds to determine the behavior of the Gemini spacecraft in vertical descent. The investigation was made to study (1) the stability of the spacecraft alone in vertical descent, (2) the motion of the spacecraft during the deployment of a drogue parachute, and (3) the drogue-parachute configuration required to stabilize the spacecraft in vertical descent. The results of the investigation are given in terms of full-scale dimensions. The dimensions of the parachutes were determined by using an assumed drag coefficient of 0.55 based on the laid-out-flat diameter.

The results of the investigation indicate that the Gemini spacecraft alone is very unstable. In various cases the spacecraft oscillated, tumbled, or entered spinning motions about the vertical wind axis with the symmetrical axis of the spacecraft inclined as much as 90° from the vertical. The tests also indicate that the deployment of a 6-foot-diameter drogue parachute during any spinning or tumbling motions of the spacecraft will quickly terminate these motions. The results of a study to determine a satisfactory drogue-parachute configuration for stabilizing spacecraft which are to be used as Gemini training vehicles indicate that the use of an 8-foot-diameter drogue parachute with a towline approximately 32 feet long attached to the spacecraft by a bridle approximately 9 feet long at three equally spaced points around the periphery of the rendezvous and recovery canister is advisable.

INTRODUCTION

As part of the Gemini development program, an investigation utilizing a dynamically scaled model has been conducted at low subsonic speeds in the Langley spin tunnel to determine the dynamic stability characteristics of the Gemini spacecraft in vertical descent. This investigation was similar to the investigation conducted in support of Project Mercury (ref. 1). Deployment of a drogue parachute, attached to the rendezvous and recovery canister (subsequently referred to as the R-and-R can) of the spacecraft at two points, has been proposed to separate the R-and-R can from the top of the spacecraft and to initiate the deployment of a parawing which is the proposed terminal recovery device for the Gemini spacecraft. In the final operation, this drogue parachute is not intended to stabilize the spacecraft since stabilization during reentry will be provided by the reaction control system. Prior to the Gemini orbital missions, however, a number of spacecraft will be used as training vehicles and will be dropped from aircraft to test the proposed recovery systems. These training vehicles will be manned and will be stabilized by a drogue parachute instead of the reaction control system. Thus a drogue-parachute configuration that will give satisfactory stability will be needed for these training vehicles.

The present investigation therefore includes: (1) tests to determine the dynamic stability of the spacecraft alone in vertical descent, (2) tests to determine the motion of the spacecraft during the deployment of a drogue parachute, and (3) tests to determine a satisfactory drogue-parachute configuration for stabilizing spacecraft training vehicles.

SYMBOLS

The reference system of the spacecraft is shown in figure 1.

A	projected area of spacecraft based on maximum diameter, $\pi d^2/4$, ft^2
d	maximum spacecraft diameter, ft
g	acceleration due to gravity, 32.17 ft/sec^2
I_X,I_Y,I_Z	moments of inertia about X-, Y-, and Z-body axes, slug-ft^2
M	aerodynamic pitching moment of spacecraft-parachute combination, ft-lb
m	mass, W/g, slugs
R	radius of curvature of heat shield, in.
t	time, sec
W	weight, lb
X,Y,Z	body axes
y_{cg}	distance of center of gravity offset from symmetrical axis, in.
z_{cg}	distance of center of gravity from plane of maximum diameter, in.
α	angle of attack of symmetrical axis of spacecraft, deg
μ	relative density, $m/\rho Ad$
ρ	air density, slugs/ft^3
Ω	rate of rotation about vertical axis, rps

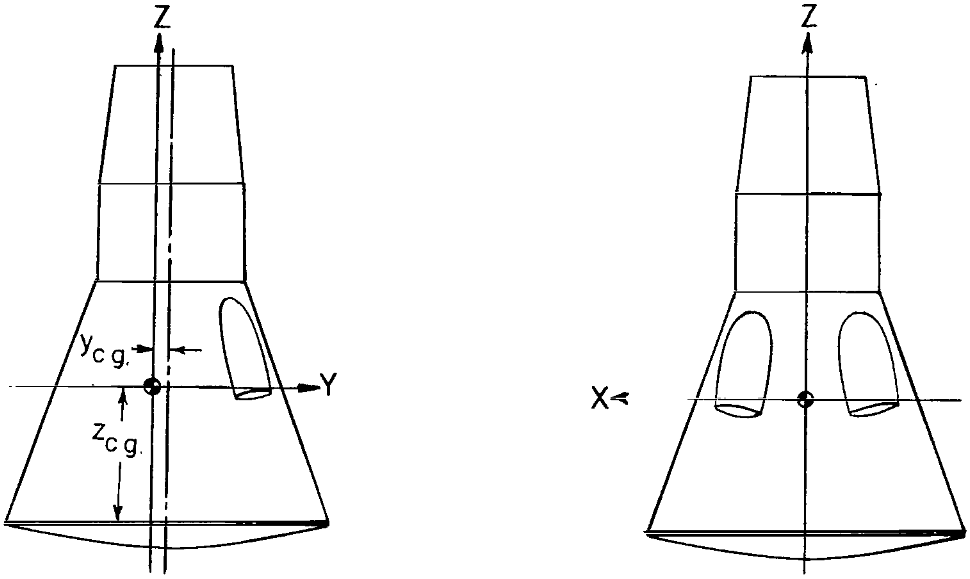


Figure 1.- Axis system of Gemini spacecraft. Directions indicated by arrows are positive.

MODELS AND TESTS

Drawings of the full-scale Gemini spacecraft are presented in figure 2. This figure shows the dimensional characteristics of the spacecraft and various drogue-parachute-attachment configurations. The model tested was a 1/20-scale dynamic model which was ballasted for simulated altitudes of sea level and 20,000 feet and for nominal center-of-gravity positions of 32.2, 42.2, and 52.2 percent of the maximum spacecraft diameter above the plane of maximum diameter. The center-of-gravity position of 42.2 percent is considered normal for the Gemini reentry configuration. Center-of-gravity positions of greater than 42.2 percent are referred to herein as higher than, or above, the normal position; and center-of-gravity positions of less than 42.2 percent are referred to as lower than, or below, the normal position. The mass and inertial characteristics of the full-scale spacecraft and the values simulated by the various loadings of the model used in this investigation are presented in table I.

The parachutes used were of the stable, flat, circular type constructed of 400-porosity material. (Porosity is defined as the volume of air in cubic feet that will flow through 1 square foot of cloth in 1 minute at a pressure of 0.5 inch of water.) These parachutes were not actually scale models of the ribbon parachutes likely to be used on the full-scale Gemini spacecraft, but the results are interpreted in terms of the full-scale ribbon parachute required to represent the scaled-up drag of the model parachutes.

The model was studied to determine the dynamic stability characteristics of the spacecraft in vertical descent both with and without a drogue parachute. Several sizes of parachutes were used with each loading of the model to determine

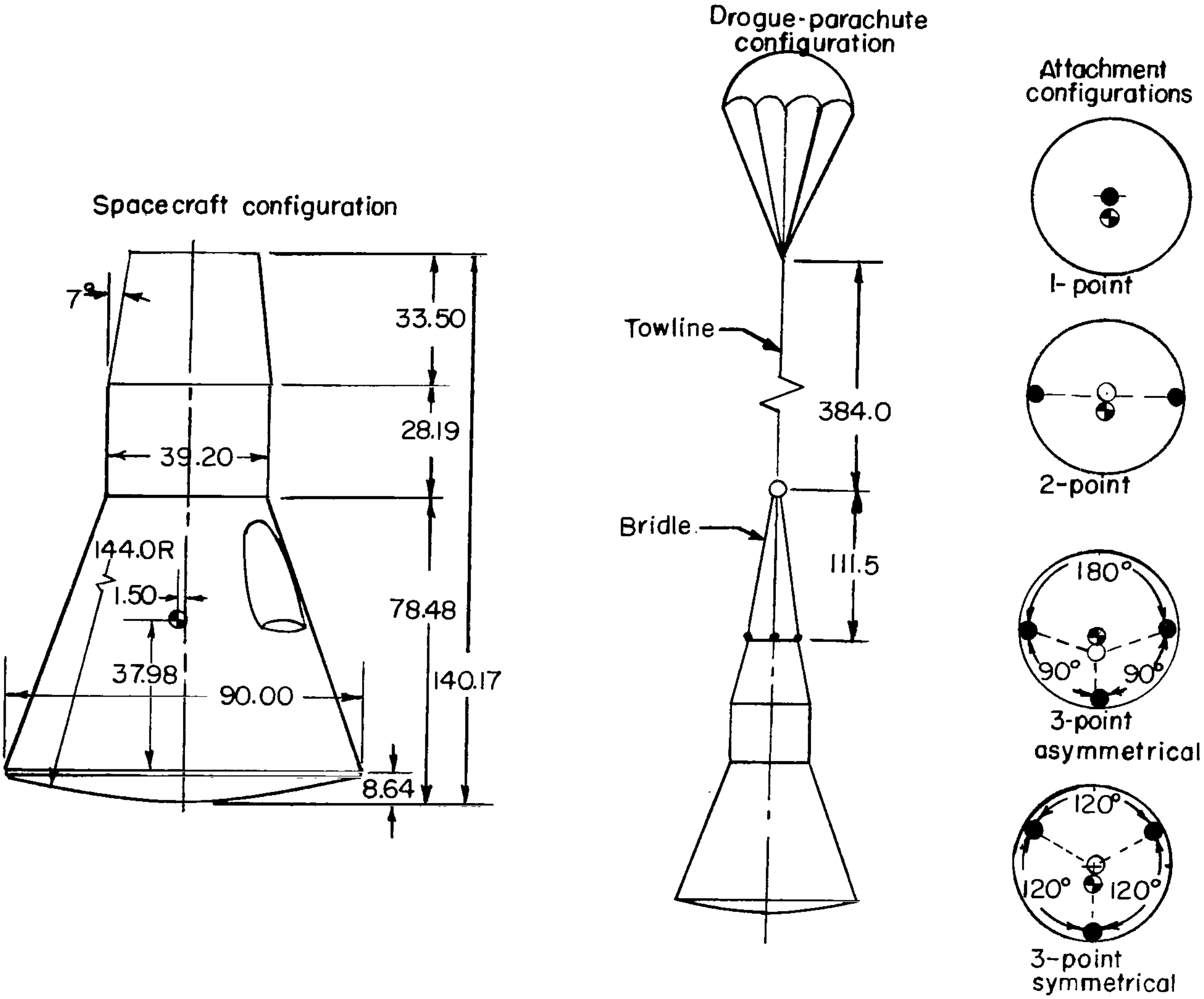


Figure 2.- Gemini spacecraft and drogue-parachute systems tested in the Langley spin tunnel. All dimensions are in inches full scale. Center of gravity shown is 42.2 percent d.

their effectiveness in stabilizing the spacecraft. A study was also conducted to determine the effectiveness of the deployment of a drogue parachute in terminating spinning and tumbling motions of the spacecraft. During the deployment study, the parachute and its various lines were folded and held against the top of the R-and-R can until the parachute was released and became inflated by the airstream. The study thus did not determine deployment characteristics, but determined the effects of successful deployments.

The parachutes were attached to the spacecraft either by a towline and bridle or by a single line attached to the center of the R-and-R can. The bridle was either a double or a triple line attached at the two or three attachment points shown in figure 2. The three-line-bridle configuration was attached to the R-and-R can in either a symmetrical or an asymmetrical manner as shown in

TABLE I.- MASS AND INERTIAL CHARACTERISTICS FOR LOADINGS TESTED ON THE GEMINI SPACECRAFT

[Values given are full-scale and moments of inertia are about the center of gravity]

Loading no.	Weight, lb	Center of gravity from the plane of maximum diameter $\frac{z_{cg}}{d}$, percent	Center-of-gravity offset along the Y axis, y_{cg}, in.	Altitude, ft	Relative density, $\mu = \frac{m}{\rho A d}$	Moments of inertia, slug-feet^2		
						I_X	I_Y	I_Z
Full-scale configuration								
3	4,584	42.2	-1.50	Sea level	181	1,608	1,598	662
4	4,584	42.2	-1.50	20,000	339	1,608	1,598	662
Dynamic model								
1	4,357	31.3	-1.78	Sea level	172	1,696	1,696	570
2	4,549	32.7	-1.63	20,000	337	974	974	459
3	4,515	42.5	-1.64	Sea level	178	1,699	1,699	583
4	4,568	42.1	-1.57	20,000	339	1,577	1,577	623
5	4,498	52.6	-1.68	Sea level	178	2,309	2,309	578
6	4,539	52.8	-1.60	20,000	336	1,298	1,298	446

figure 2. For some of the tests, a swivel was used at the juncture of the towline and bridle to insure that the results were not altered by the twisting of the multiple lines of the bridle.

The investigation was conducted in the Langley spin tunnel. The tunnel is an atmospheric wind tunnel with a vertically rising airstream in the test section and a maximum airspeed of approximately 90 feet per second. The general test procedure used in the vertical tunnel is described in reference 2. For this investigation, the model was hand launched into the vertically rising airstream. At times the model, both with and without a drogue parachute, was launched gently with as little disturbance as possible to determine what motions of the spacecraft were self-excited. At other times, the spacecraft with predeployed drogue parachute was launched into various spinning motions to determine the effectiveness of the drogue parachute in terminating these spinning motions. During drogue-parachute deployment tests, the spacecraft was launched into various spinning and tumbling motions and the drogue parachute was deployed. The motions of the model were photographed with a motion-picture camera, and some of the film records were read to obtain typical time histories of the model motion.

The angles of attack indicated in the time histories presented herein are believed to be accurate within $\pm 1^{\circ}$. The mass and dimensional characteristics of the dynamic model shown in table I are believed to be measured to an accuracy of: ±1 percent for the weight, ±1 percent for z_{cg}/d, ±15 percent for x_{cg}, and ±5 percent for the moments of inertia. The towline and bridle-line lengths were simulated to an accuracy of ±1 foot full scale.

RESULTS AND DISCUSSION

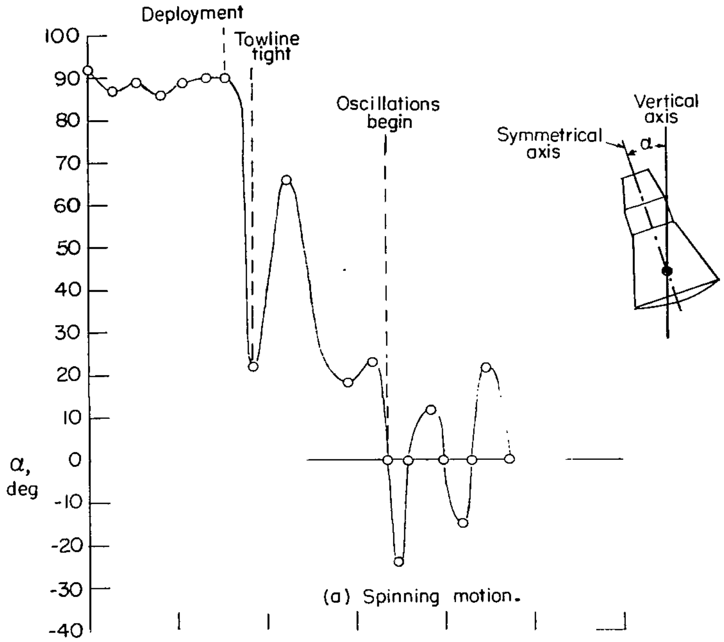
A motion-picture film supplement showing some of the tests has been prepared and is available on loan. A request card form and a description of the film will be found on the page with the abstract cards.

In the following discussion of results, all dimensions presented are in terms of full-scale values. The dimensions of the parachutes are given on the basis of an assumed drag coefficient of 0.55 based on the laid-out-flat diameter. This value of drag coefficient was used because it is a representative value for a ribbon parachute which is the type proposed for the Gemini spacecraft. If parachutes with drag coefficients other than 0.55 are used, an adjustment in the diameter of the parachute should be made such that the product of the area and drag coefficient of the parachutes is the same as that of the parachutes described herein.

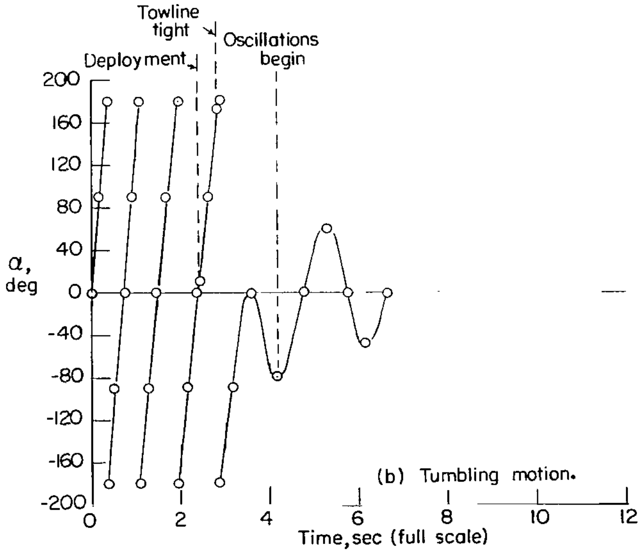
Spacecraft Alone

The results of the study with the spacecraft alone indicate that the Gemini spacecraft is very unstable for all center-of-gravity positions investigated. (The loadings were loadings 1, 3, and 5 in table I.) In various cases the spacecraft oscillated, tumbled, or entered spinning motions about a vertical wind axis with the symmetrical axis of the model inclined as much as 90° from the vertical.

The rate of descent of the spacecraft was approximately 330 feet per second. The spacecraft motions observed for the three center-of-gravity positions were similar and the spinning motions were the most common type of motions. The spacecraft, however, did have a progressively greater tendency to enter the spinning or tumbling motions as the center of gravity was moved from the nominal 32.2-percent to the nominal 52.2-percent position. This increase in the tendency of the spacecraft to enter spinning and tumbling motions at the higher center-of-gravity positions is apparently due to the decrease in static stability as the center of gravity was moved upward.



(a) Spinning motion.



(b) Tumbling motion.

Figure 3.- Effect of deployment of a 6-foot-diameter drogue parachute with a two-point attachment from the spacecraft. Simulated test altitude, sea level; c.g. = 42.2 percent d.

Deployment of Drogue Parachute

Typical results of drogue-parachute-deployment studies are shown in figure 3. These studies were conducted with loadings 3 and 4 of table I. They were made to determine whether the deployment of a drogue parachute would quickly bring the spacecraft to an erect (heat-shield down) position in order to facilitate separation of the R-and-R can; the studies did not determine deployment characteristics of the drogue parachute since the deployment technique proposed for the spacecraft was not simulated. The most adverse conditions for the deployment of the drogue parachute would be with the spacecraft in a spinning or tumbling motion. During these studies the drogue parachute was deployed from various attitudes after the spacecraft had been hand launched into the various spinning and tumbling motions. In every case, the model studies indicated that the successful deployment of a 6-foot-diameter parachute would quickly bring the spacecraft to a generally erect position, although oscillations of fairly large amplitude (±20° to ±40°) might ensue, as shown in figure 3.

Spacecraft Stability With Drogue Parachute Deployed

The following results were obtained in the study conducted to determine a satisfactory drogue-parachute configuration for use on full-scale Gemini spacecraft training vehicles which are to be stabilized by drogue parachutes during drop tests in the Gemini development program. During these studies, typical rates of descent of the spacecraft at a simulated altitude of sea level were 260, 230, and 200 feet per second for the 6-, 8-, and 10-foot-diameter drogue parachutes, respectively; typical rates of descent at a simulated altitude of 20,000 feet were 350, 320, and 290 feet per second for the corresponding parachutes. In the studies described in the following paragraphs, the loading of the spacecraft was loading number 3 in table I, and the drogue-parachute configuration had the following geometric characteristics (full-scale) unless otherwise noted:

Parachute diameter, ft	8
Towline length, in.	384
Bridle length, in.	111.5
Attachment configuration	Three-point symmetrical

The towline and bridle lengths are for the proposed Gemini spacecraft. Other towline and bridle lengths were not investigated. Based on results of reference 1, however, other lines of comparable lengths would be expected to be satisfactory.

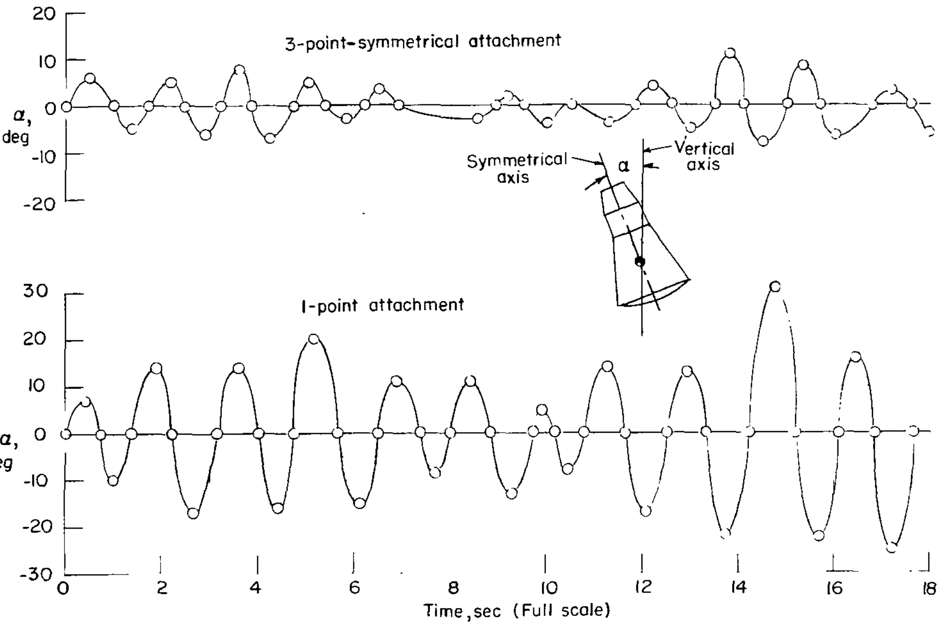
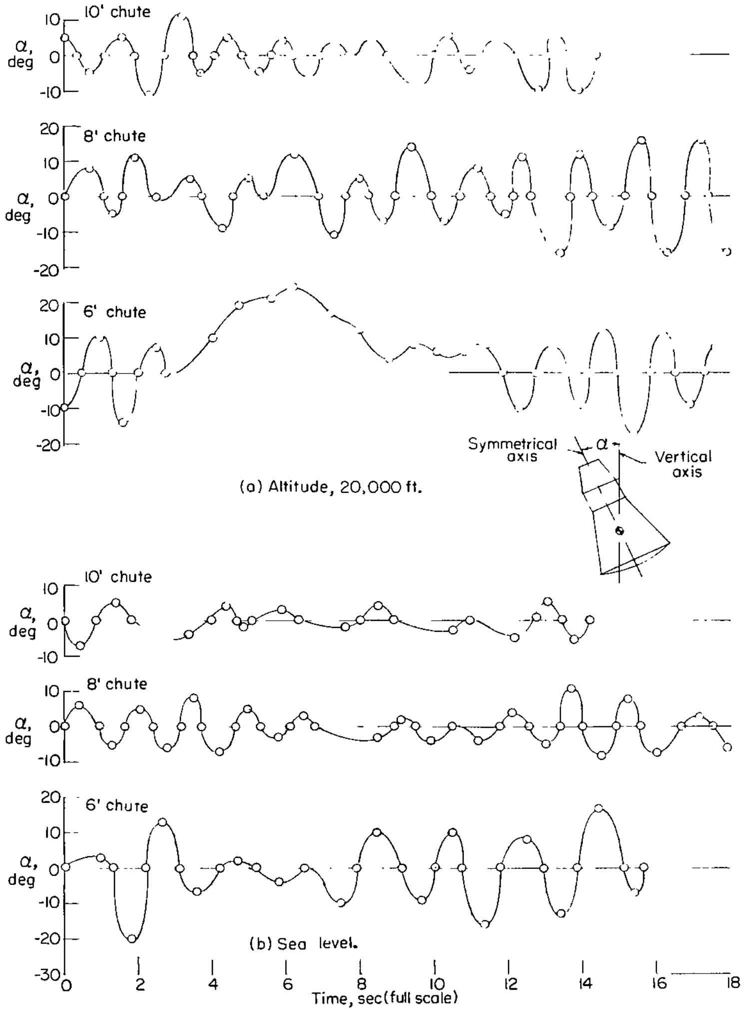


Figure 4.- Effect of attachment configuration on spacecraft stability for 8-foot-diameter drogue parachute. Simulated test altitude, sea level; c.g. = 42.2 percent d.

Effect of attachment configuration.- Some of the results of studies conducted to determine a satisfactory attachment configuration are shown in figure 4. This figure shows typical results for the one-point and the three-point-symmetrical-attachment configurations. These data show oscillations of very large amplitude for the one-point attachment and oscillations of much smaller amplitude for the three-point-symmetrical attachment. No data are shown for the two-point-attachment configuration and the three-point-asymmetrical-attachment configurations, but records show that the two-point attachment generally limits the large-amplitude oscillations to axes parallel to a line through the two attachment points but the amplitude of the oscillations about this axis is not noticeably different from that with a one-point attachment. The results for the three-point-asymmetrical-attachment configuration are very similar to those for the two-point-attachment configuration because the additional line is slack most of the time so that it is effectively a two-point-attachment configuration. The results of these studies therefore indicate that the three-point-symmetrical-attachment configuration is the simplest configuration (that is, it has the least number of lines) which will make it possible to take full advantage of the available restoring force of the parachute to limit the oscillations about any horizontal axis.



(a) Altitude, 20,000 ft.

(b) Sea level.

Figure 5.- Effect of drogue-parachute diameter on spacecraft stability for the three-point-symmetrical attachment configuration at simulated test altitudes. c.g. = 42.2 percent d.

Effect of parachute diameter.- The results of a study conducted to determine a satisfactory drogue-parachute diameter for stabilizing full-scale Gemini spacecraft are shown in figure 5. These results indicate that there is a progressive improvement in the motions of the spacecraft with increasing parachute diameter. There are some exceptions to such a generalization as implied in a subsequent discussion of a spinning equilibrium.

Effect of center-of-gravity position.- The results of a study to determine the effect of variation of the vertical center-of-gravity position are shown in figure 6. These tests were conducted with all six loadings presented in table I. The results indicate that the spacecraft is less stable for center-of-gravity positions above the normal 42.2-percent location and more stable for center-of-gravity positions below 42.2 percent. In fact, the results show a very pronounced increase in the amplitude of the oscillations with the 52.2-percent center-of-gravity position. This increase in the amplitude of the oscillations is apparently due to the decrease in static stability of the spacecraft for the higher center-of-gravity positions.

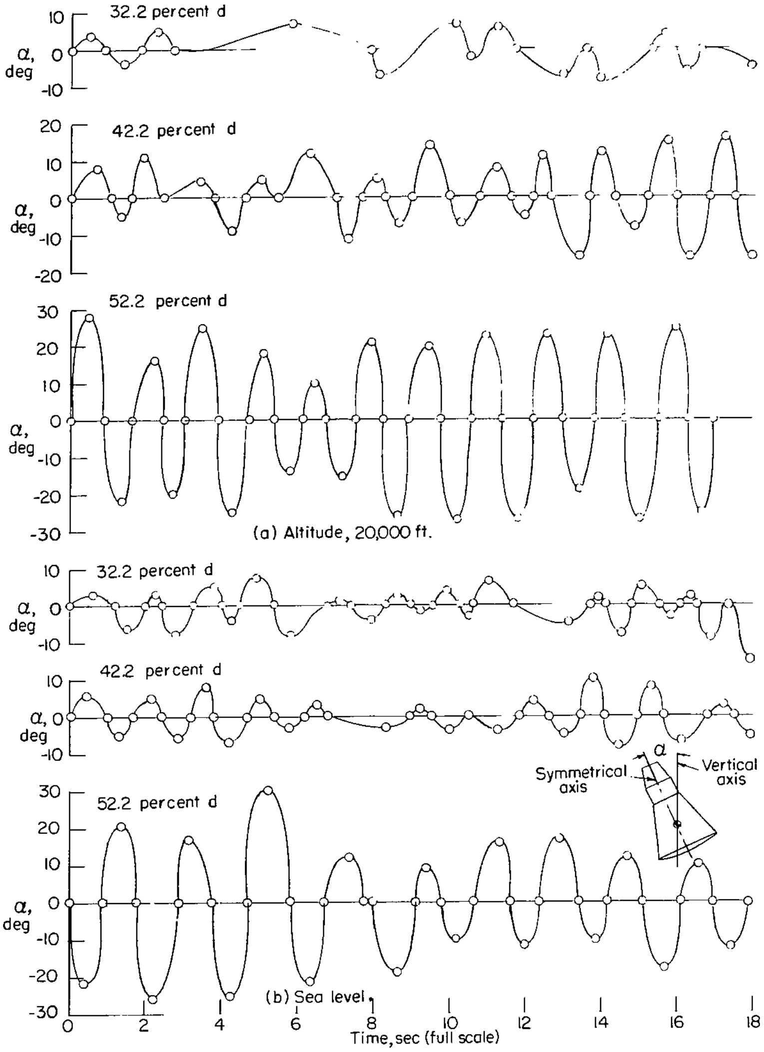


Figure 6.- Effect of center-of-gravity position on spacecraft stability for the three-point-symmetrical attachment configuration and 8-foot-diameter drogue parachute at simulated test altitudes.

Effect of altitude.- The results of studies to determine the effect of altitude on the stability of the Gemini spacecraft in vertical descent are shown in figures 4 and 5. These results indicate that oscillations of a somewhat greater amplitude are to be expected at higher altitudes within the range of altitudes for which the dynamic pressure is constant and for which the spacecraft did not experience any change in aerodynamic characteristics due to compressibility effects. This is the usual effect of altitude and is apparently due to the increase in relative density factor which results from the decrease in atmospheric density.

Special case of spinning equilibrium.- Occasionally during the study of the spacecraft-and-drogue-parachute systems, the spacecraft received inputs which caused it to enter steady spinning motions about the vertical wind axis, with the symmetrical axis inclined about 50° from the vertical. This motion is not shown in any of the figures, but occurred when the model was ballasted for a nominal center-of-gravity position of 52.2 percent at a simulated altitude of 20,000 feet, and was stabilized by a 6-foot-diameter drogue parachute. The tests in which this spinning motion was inadvertently obtained failed to indicate definitely whether the motion would persist; so, in order that the conditions under which it might exist could be determined, additional tests were conducted at simulated altitudes of sea level and 20,000 feet wherein the spacecraft was launched into a spinning motion with the parachute already deployed. These tests were conducted for various center-of-gravity positions, parachute diameters, and towline lengths, with the parachute attached to the R-and-R can at a single point. Results of the tests indicate that the spacecraft would sometimes remain in a spinning motion at sea level (fig. 7), but would not remain in a spinning motion at an altitude of

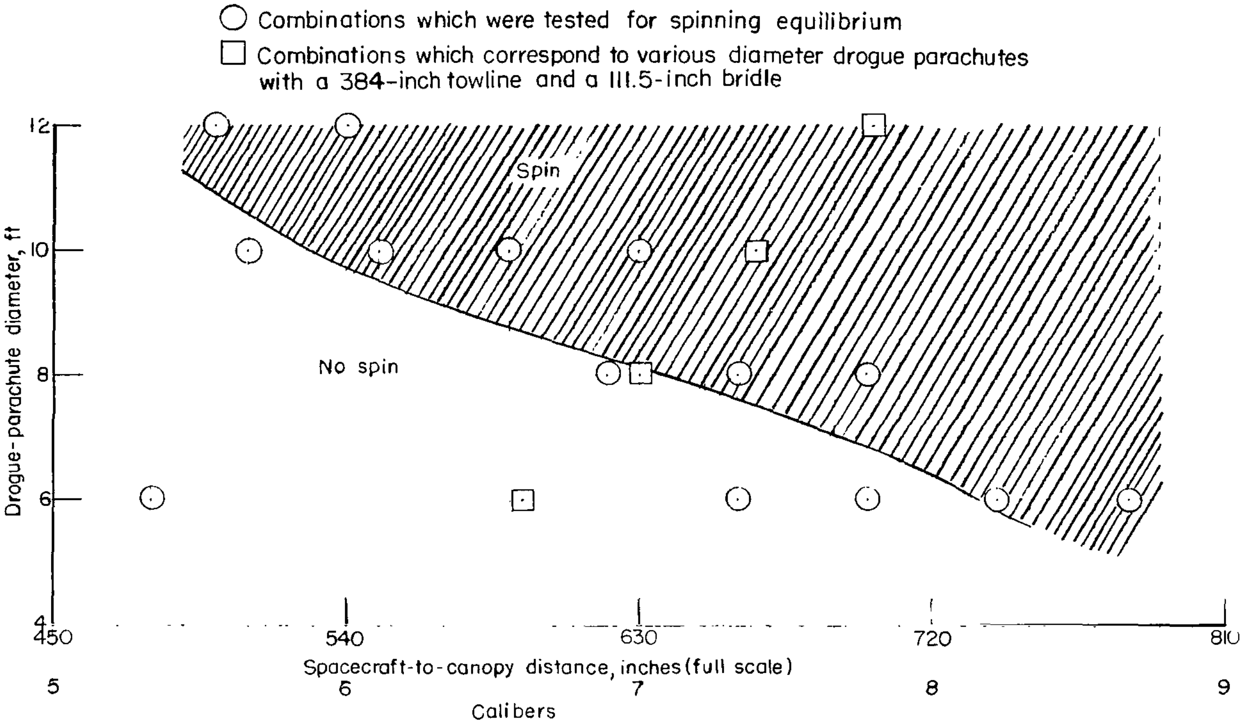


Figure 7.- Combinations of drogue-parachute diameter and spacecraft-to-canopy distance, with a single-point attachment configuration, for which the spacecraft was observed to remain in spinning motions (shaded area) at a simulated test altitude of sea level; c.g. = 42.2 percent d.

20,000 feet for any of the drogue-parachute configurations tested. The results of the studies also indicate that the spinning motion was dependent upon the location of the center of gravity of the spacecraft, the diameter of the parachute, and the distance from the canopy of the parachute to the attachment points on the spacecraft. As the center of gravity was moved from the 52.2- to the 32.2-percent position, the spacecraft had a progressively greater tendency to remain in the spinning motions.

Typical results of the study showing the effects of parachute size and attachment line length are presented in figure 7 for one center-of-gravity position - 42.2 percent - which is the normal condition for the Gemini reentry configuration. The shaded area of the figure indicates the combinations of drogue-parachute diameter and distance from the canopy of the parachute to the attachment point on the spacecraft for which the spacecraft was observed to remain in spinning motions. The tendency of the spacecraft to spin was increased by increases in either the diameter of the drogue parachute or the distance from the canopy of the parachute to the attachment point on the spacecraft.

The drogue-parachute configurations, for which results are discussed in previous sections of this paper, are indicated in figure 7 by the square symbols. The variation of spacecraft-to-canopy distance shown by these symbols results from the variation in shroud-line length for parachutes of different diameters. The towline and bridle-line lengths remain constant at 32 and 9 feet, respectively, while the shroud-line length is approximately 1.35 times the diameter of the parachute. As shown in figure 7, both the 6- and 8-foot-diameter drogue parachutes mentioned in the previous sections of the paper are in the "no-spin" area. The larger parachutes, however, would sustain a spinning equilibrium condition of the spacecraft.

In analyzing the spin-equilibrium problem, it is significant to point out that the stable autorotation was obtained only at rotation rates greater than 25 radians per second which might indicate that this is a threshold rate below which autorotations will not occur. It is also important to note that the rate of rotation was found to be faster for the larger drogue parachutes. This fact is consistent with the standard equation for spin equilibrium:

$$\Omega^2 = \frac{-2M}{\left(I_Y - I_Z\right)\sin 2\alpha} \qquad \left(\text{for } \frac{d^2\alpha}{dt^2} = 0\right)$$

which is taken from reference 2. This equation shows the relation between the aerodynamic pitching moment applied to a spinning body and the rate of rotation of that body. It is apparent from the equation that if the parachute is small so that the aerodynamic pitching moment it applies to the body is small, the rate of rotation of the spacecraft will be low; and if the rate of rotation corresponding to this pitching moment is below the threshold value for autorotation, no autorotation will occur.

An alternate method of preventing the spinning-equilibrium condition is also indicated by the tests. This second method is to increase the damping in yaw from the drogue-parachute configuration by incorporating a towline sufficiently short to cause the parachute and towline to trail the top of the spacecraft around its circular path. This is essentially the same requirement that pertains to antispin-tail-parachute systems for emergency spin recovery for military aircraft. The subject of antispin-tail-parachutes is discussed thoroughly in reference 3. An added restriction for stabilizing drogue parachute, however, is that the towline not be so short as to place the canopy of the parachute within the wake of the spacecraft.

Reynolds Number Effects

The present investigation was conducted at Reynolds numbers in the range of 100,000 to 140,000 (based on the maximum diameter of the spacecraft model). No direct study of the effect of this low Reynolds number range on the applicability of the aforementioned results to a full-scale spacecraft has been made; but the results of an extensive study of the Reynolds number effect on the Project Mercury spacecraft appear applicable to the present investigation. In that study (ref. 4) of the static and oscillatory stability characteristics of models of the Mercury spacecraft at Reynolds numbers in the range of 300,000 to 4,000,000, there were only slight Reynolds number effects. Based on (1) the geometric similarity of the Mercury and Gemini spacecraft, (2) the similar ranges of Reynolds numbers at which free-spinning tunnel investigations of the two spacecraft were conducted, and (3) the similarity of the motions of the models of the two spacecraft, it is believed that there would be little or no Reynolds number effects in the present investigation. For this reason, the results of the tests on the 1/20-scale model in the Langley spin tunnel are considered to be indicative of the motions that might be obtained on the full-scale Gemini spacecraft.

Recommended Drogue-Parachute-Configuration

Gemini Trainer Vehicles

In determining the drogue-parachute configuration necessary to stabilize satisfactorily a Gemini spacecraft trainer, two requirements should be considered: (1) the parachute must be of sufficient diameter to limit the oscillations of the spacecraft to small amplitudes, but (2) the parachute diameter and line length should not be such as to lead to a spinning equilibrium condition. Based on these considerations, the use of an 8-foot-diameter drogue parachute with towline and bridle-line lengths of no more than approximately 32 and 9 feet, respectively, would seem advisable. This parachute should be attached to the spacecraft by means of a three-point-symmetrical attachment in order to limit the spacecraft oscillations to reasonably small amplitudes.

SUMMARY OF RESULTS

The results of tests conducted in the Langley spin tunnel on a 1/20-scale dynamic model of the Gemini spacecraft are summarized as follows:

1. The spacecraft alone was very unstable; it would at various times oscillate, tumble, or spin about a vertical axis with the symmetrical axis tilted as much as 90° from the vertical.

2. The deployment of a 6-foot-diameter drogue parachute during any spinning or tumbling motions of the spacecraft quickly terminated these motions.

3. A three-point-symmetrical bridle-line attachment is the simplest configuration which will make it possible to take full advantage of the available restoring force of the parachute to limit the amplitude of the oscillations about any horizontal axis.

4. Moving the center of gravity of the spacecraft from its normal 42.2-percent location to positions approaching 52.2 percent of the maximum spacecraft diameter from the plane of maximum diameter will result in a significant decrease in the stability of the spacecraft-and-drogue-parachute system.

5. Oscillations of the spacecraft, for any drogue-parachute configuration, will be somewhat greater at high altitudes than at sea level.

6. Increases in the diameter of the drogue parachute generally caused a reduction in the amplitude of the oscillations of the spacecraft, but it appeared that such increases might also make it possible for the spacecraft-and-drogue-parachute system to develop a spinning equilibrium. From overall stability considerations, therefore, the use of an 8-foot-diameter drogue parachute with tow-line and bridle-line lengths of no more than approximately 32 and 9 feet, respectively, would seem advisable.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., November 12, 1963.

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NASA-Langley, 1964 L-3669

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