Engineering Notes

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Free Fall Stability and Base Pressure Drop Tests for Planetary Entry Configurations

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Introduction

THE current trend in the design of planetary entry probes is to take advantage of the high drag of blunt bodies to produce a low-ballistic coefficient (W/C_DA) vehicle which decelerates to a low velocity at high altitude. The subsonic velocity of the probe allows a relatively long period of time to make atmospheric measurements[1] and to perform experiments in addition to allowing aerodecelerator deployment for a survivable impact. In order to successfully perform these missions, a prime requirement is that the probe must have dynamic as well as static stability over the whole flight regime to provide a stable platform. In addition, one of the atmospheric measurement missions may include monitoring of the base pressure of the probe during the subsonic terminal velocity phase of the flight; this would provide pressure data to reconstruct the static freestream pressure profile of the planet. Accordingly, the base pressure characteristics of the probe configuration must be known.

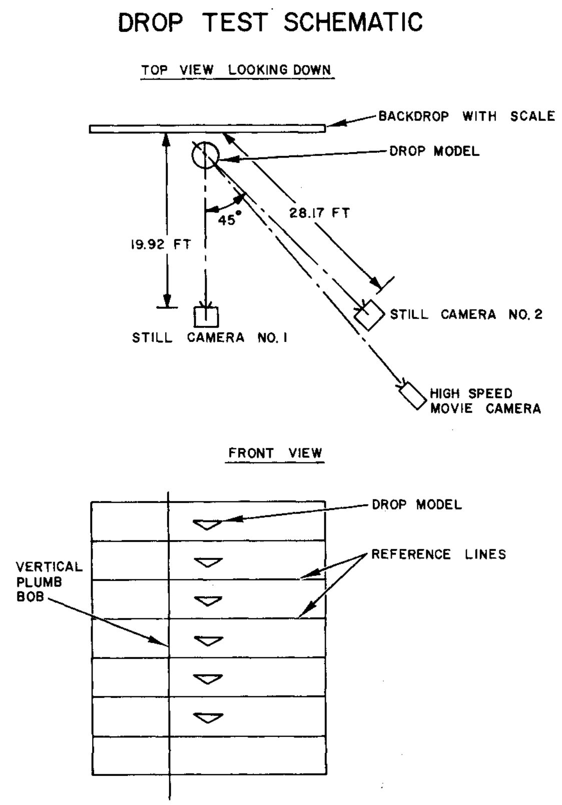

Fig. 1 Drop test schematic.

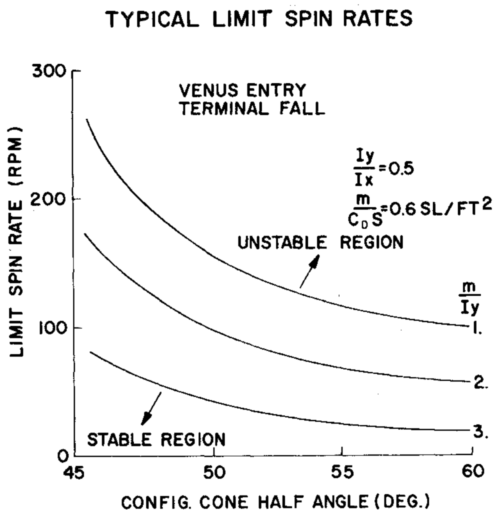

Fig. 2 Typical limit spin rates for full-scale Venus probe.

Background

Stability

Computer simulations[2] of blunt vehicle configurations entering the atmosphere of the planet Venus showed a sig-

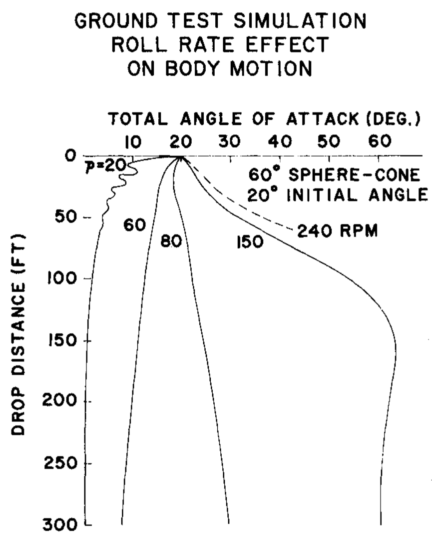

Fig. 3 The effect of roll rate on body motion for ground test conditions based on predictions.

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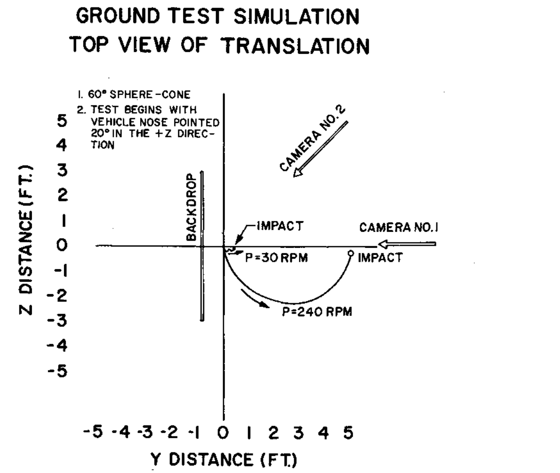


Fig. 4 Predicted translational motion (top view) of model for the drop test.

nificant effect of spin rate on the vehicle stability in near terminal descent. These results, which were at the time unanticipated, inspired an investigation of low-speed blunt body stability. The general solution to the equations of motion had been studied previously,[3,4] but the results were directed toward other flight regimes, so the emphasis was placed on applying the general solutions to the unique problem at hand. Design criteria were derived[2] for blunt body application which take the form:

$$P < 8\,|\tau_1|(I_x/I_y)(-C_{m\alpha}q_\infty A_{\mathrm{REF}}/2ml_{\mathrm{REF}}C_{m_q}C_{L\alpha})^{1/2}$$

$$\tau_1 < 0$$

where

$$\tau_1 = (ml^2_{\mathrm{REF}}/8I_y)C_{M_q} - C_{L\alpha}/4$$

The theory involved in deriving these criteria was subsequently expanded and presented in Refs. 5–7. The stability drop tests reported herein were developed to verify the trends that had been observed in computer simulations and subsequent theoretical stability analyses of Ref. 2.

Base pressure

Base pressure measurements may be considered for the entry science experiment to define the atmospheric structure of the planets (Mars, Venus, or Jupiter). Since base pressure is some fraction of freestream pressure in subsonic flow and is a strong function of Mach number[8] the base pressure measurement can be used as a direct method of deriving the freestream static pressure (P_∞) profile of a planet during the entry trajectory. It is, therefore, important to know the functional relationship between base pressure ratio (P_b/P_∞) and Mach number from ground tests. Accordingly, the present drop test series for stability measurements were also used to obtain base pressure data.

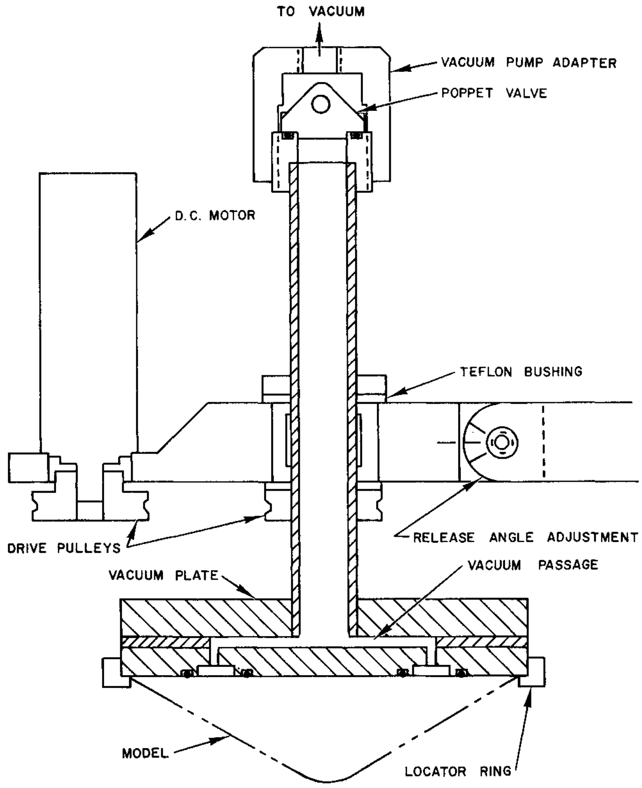


Fig. 6 Drop mechanism schematic.

Test Techniques/Conditions

Both the stability and base pressure problems were investigated experimentally in one basic test program using a free fall gravity drop test technique. Terminal velocities and Reynolds number conditions ($V \approx 50 \rightarrow 100$ fps, Re/ft $\approx 10^6$) simulating a planetary entry trajectory which could apply either to a Mars, Venus or Jupiter probe can be obtained with conventional free fall gravity drops from moderate altitudes. A Venus trajectory has been chosen to illustrate the drop technique. The facility provided a drop altitude of 60 ft which produced a terminal velocity on the order of 50 fps. A vacuum rig drop mechanism was fabricated which allowed the model to be released at the same condition with near zero tipoff rate for each test. Photographic coverage was obtained using two still cameras and strobe lights to obtain multiexposure photographs, and a high-speed movie camera as shown in Fig 1. The models were planned to be caught in a net and reused.

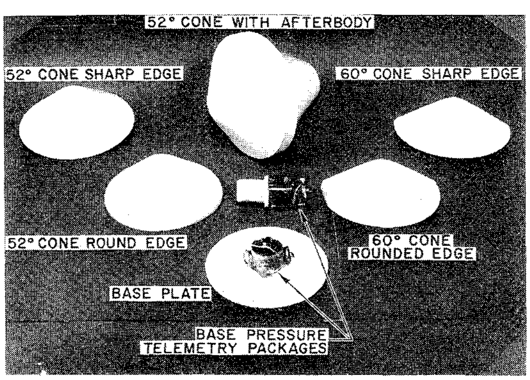


Fig. 5 Model configuration matrix for free flight stability and base pressure tests.

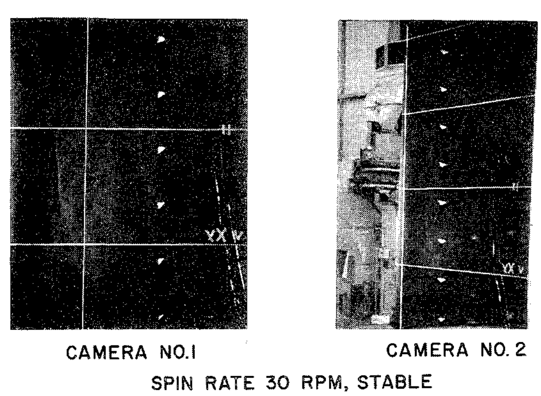
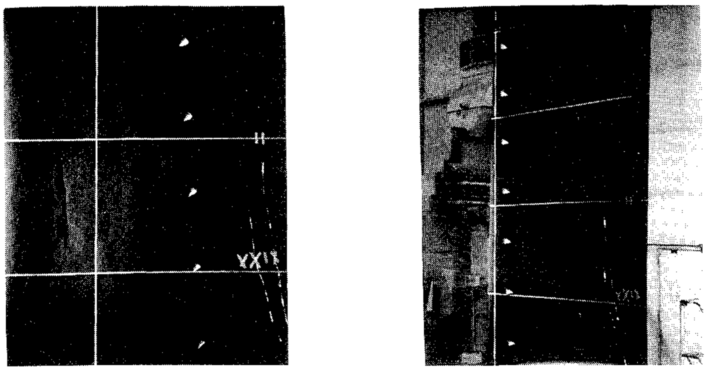


Fig. 7 Drop test photos of 52° cone at 30 rpm (stable).



CAMERA NO.1 CAMERA NO. 2

SPIN RATE 240 RPM, UNSTABLE

Fig. 8 Drop test photos of 52° cone at 240 (unstable).

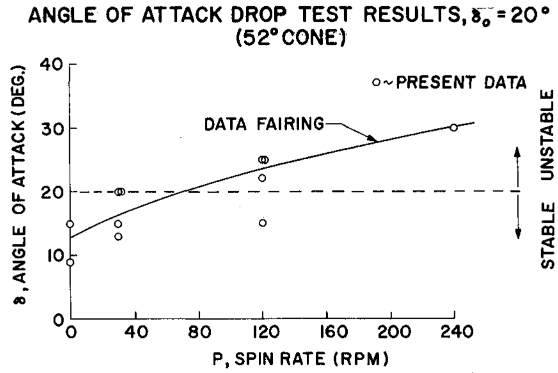


Fig. 9 Angle-of-attack drop test results, δ_0-20° (52° cone).

In setting up for the tests the first item was to determine initial conditions which would provide usable data. A 60 ft drop height and small models were dictated. The problem was thus reduced to determining the spin rates and initial angle of attack required to produce a discernable divergence. Predictions were made of the angle-of-attack history as a function of drop distance for the ground test conditions with initial angles (δ_0) of 1°, 10°, and 20° and 120 rpm spin rate. All cases showed divergence, and in fact they are only phased in drop distance each increasing ~60% in 60 ft, and they would all reach the same trim condition after about 600 ft of drop. The 20° condition was selected because the divergence would be the most easily seen.

The drop model was photographed in flight to obtain the δ history for various spin rates. If the photographed δ was greater than the drop δ, the model was diverging and hence was unstable. Conversely, if the δ was less than the drop δ the model was converging and hence assumed stable. Scaling of the model size was also a consideration. The only scaling factor of concern is $(1/l)^{1/2}$. This scaling was evident in the testing since the test models are dynamically similar to the Venus probe designs. The characteristic length of the actual designs are about $8\frac{1}{2}$ times that of the models, and the limit roll rate ratio is about 3:1. Thus, it can be seen that although the drop test models require a relatively high-spin rate to produce instability (~120 rpm) the rate is substantially lower (and quite reasonable) for a full-scale vehicle (see Fig. 2).

Figure 3 shows the effect of spin rate on the angle-of-attack history for the drop test conditions as determined by six degree-of-freedom simulations. At low-spin rates the usual oscillatory motion is evident, but at high-spin rates this gives way to spiral motion showing up on a total angle-of-attack plot as a nonoscillating divergence. This characteristic of the motion was evident in the test movies.

The impact point shift for the unstable vehicles is a result of the slowly cycling trim lift. Figure 4 is a top view (looking down) of the translational motion of the minimum and maximum spin cases as predicted by the six-degree-of-freedom computer simulation. The impact point and the apparent history agree with the drop tests and are subsequently discussed.

The drop conditions for the stability tests were an initial angle of attack of 20° with initial spin rates that varied from 0 to 240 rpm. The base pressure tests were all conducted at an initial angle of attack of zero and zero spin rate.

Model Configurations and Drop Mechanism

The initial program plan was to test two basic planetary entry configurations, a 52° sphere cone having a bluntness ratio of 0.472 with an afterbody, and a 60° sphere cone having a bluntness ratio of 0.2 with a flat base. Both basic configurations were to be tested with flat bases, flat bases with rounded shoulders, and with afterbodies. Figure 5 is a photograph of the proposed stability and base pressure test matrix configurations. Because of severe stability problems and resultant model damage encountered with the 60° flat base and rounded shoulder cones, many of the desired tests could not be run due to lack of models.

All models were fabricated of Lexan and had a 5-in. base diam. The models for the base pressure tests contained a pressure transducer, telemetry system and battery package. Pressures were measured only at the center of the base, however, this should be indicative of the pressure over the entire base. The stability models were left uninstrumented to provide mass properties giving the best divergence for observation.

The drop mechanism consisted of a flat turntable to which the model was affixed by means of a differential pressure. The turntable contained air passages that were connected to a vacuum pump through a poppet valve which provided the pressure differential to hold the model firmly in place until the poppet valve was opened. Figure 6 is a schematic of the drop mechanism. A dc motor capable of providing variable spin rates was connected to the assembly by means of a pulley. The drop mechanism was capable of being tilted to any initial angle of attack between 0° and 30°. This device provided the authors with a reliable means of releasing the drop models with the same initial conditions and near zero "tip off" rate for each test.

Results

Stability

Two basic sets of data were available to evaluate the effects of initial spin rate on stability (angle-of-attack convergence). The first source provided quantative data and consisted of multiexposure photographs from the still cameras. A test series for the 52° cone is presented in Figs. 7 and 8 and show multiexposure photographs for 30, and 240 rpm, respectively. Note that the stable test (p = 30 rpm, Fig. 7) shows low angles of attack, less than 10°, indicating angle-of-attack convergence. Note also that the trajectory is such that the model appears to be several feet from the vertical plumbline when viewed from Camera No. 2. However, for the higher spin rate (240 rpm, Fig. 8) the model is at a total angle of attack of ~30°, the flight path has changed and the model appears to be closer to the vertical plumbline. In reality, the model has moved away from the reference backdrop resulting in a different impact point than the stable low-spin rate test.

Figure 9 presents the maximum divergence angle of attack plotted vs spin rate for the 52° cone drop tests. The data contain a large degree of scatter but the trends are unmistakable. The tests conclusively show that the model

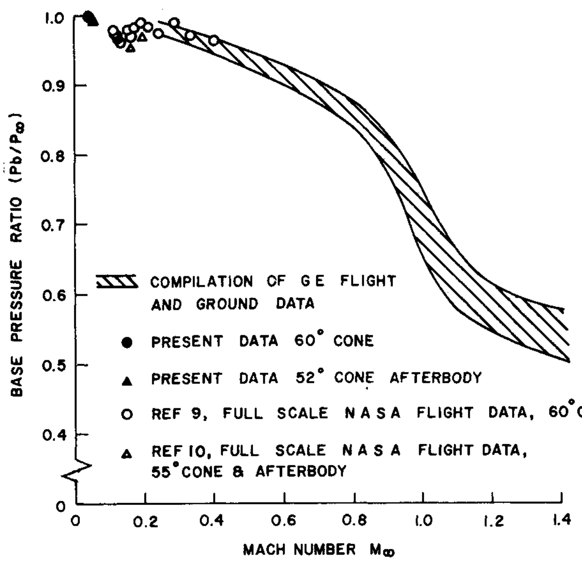


Fig. 10 Subsonic/transonic base pressure data.

angle of attack diverges (and hence the model is unstable) with increasing spin rate.

The second data source (the high speed movie camera) provided a significant amount of qualitative data. The 52° cone configuration appeared to be inherently more stable than the 60° configuration. That is, the 60° cone always diverged more than the 52° cone for the same spin rate. Actual photographic coverage of the 60° cone diverging is lacking, as the model was not tracked well due to the large degree of instability. In addition, the model divergence and hence trajectory perturbations were so great that the drop models tended to land outside the catcher net drop area. This resulted in a loss of a model at each drop, consequently repeat runs were available only until the 60° models were depleted. Two flat based 60° sharp edged models diverged and broke up upon impact and one 60° rounded edge model appeared to diverge even more than the sharp edge model.

The high speed movies show two basic trends which were repeatable: 1) Low-spin rate models tend to oscillate rapidly during the drop and tended to fall straight down and impact one to two feet from the reference back drop. 2) High-spin rate models tended not to oscillate, but rather trimmed up to a large angle of attack which produced a trajectory deflection resulting in an impact point five to seven feet from the reference back drop. Both were predicted by six-degree-of-freedom trajectory simulations for the drop test conditions. Thus the experimental drop test results verified the theoretical and numerical analyses showing a low speed blunt body instability. This phenomenon then places a restriction on the maximum spin rate allowable for some planetary missions.

Base pressure

The present base pressure drop test results[8] are compared in Fig. 10 with NASA Ames data.[9,10] The darkened symbols represent the present subscale drop test data while the open symbols represent full-scale flight results. Both sets of data are for similar configurations so that flight and ground data comparisons can be obtained directly by comparing similar open and closed symbols. Generally the data are in basic agreement and indicate that configuration differences apparently do not significantly alter the base pressure in subsonic flow. In addition the data demonstrate that base pressure varies from 0.95–0.99% of freestream pressure from $M_\infty \approx 0.4$ to 0.04. These results indicate that base pressure data from a planetary entry probe can be successfully utilized to derive the static freestream pressure profile of a planet during subsonic velocity conditions if the Mach number history of the probe is known.

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An Optimal, Analytic Solution to the Linear-Gravity, Constant-Thrust Trajectory Problem

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THE optimal two-point boundary value problem requires determination of the path, from an initial to a final boundary, which minimizes some performance index. If it is assumed that the transfer occurs in a vacuum and that the vehicle is propelled with a continuous constant thrust, then the optimal path is prescribed by the optimal thrust direction (identical to the direction of the primer), and the performance index to be minimized is the fuel consumption or time.

The primer vector and its derivative (the adjoint variables) are related to the position and velocity vectors (the state variables) by a set of linear differential equations, which are obtained by application of the calculus of variation to the differential equations of motion. This set of linear differential equations, which relate the adjoint variables to the state variables, must be integrated along with the state equations to obtain a closed-form solution of the optimal two-point boundary value problem.

In a previous study,[1] the gravitational acceleration vector was assumed to be a function of time only. The integrals of the adjoint equations for this assumption are trivial; the primer is a linear function of time. The state equations can be completely integrated to give six equations in terms of six unknowns. Thus, a closed-form solution is obtained that produces remarkably good results, with the chief limitation being that the thrusting arcs remain small.

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