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Journey Into Space Research

Continuation of a Career at NASA Langley Research Center

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by
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Cover photograph (L-05136): Little Joe rocket being launched from Wallops Island. Several of these rockets were launched to study separation of the escape capsule from the Mercury capsule.

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Phillips in 1963 at the age of 45. At this time, he was chief of the Space Mechanics Division.

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CHAPTER 1

Introduction

Space flight has long been a subject of interest both to scientists and to the general public. Science fiction became popular with the works of Jules Verne, whose fanciful stories of space exploits inspired many later science fiction publications. These stories were usually not based on valid science and technology or they were ahead of the developments that might have made them possible. These works, however, served to stimulate thought on space flight for many years. Some groups, such as the British Interplanetary Society, made serious studies of the requirements for space flight. These efforts failed to lead to practical developments because of lack of financial support or interest from governmental organizations or from the public. These early studies had little effect on actual developments in the space program because, with greater support and larger numbers of investigators, the results were quickly rediscovered and not until later was it found that some important results had been worked out previously.

Studies of the possible military applications of space flight were started by military organizations in the United States about 1950, but these studies were classified secret. I, like the general public, was unaware of any activity in this field until the nation was startled by the Russian launching of Sputnik. The last chapter of the preceding volume on the history of my work at Langley (ref. 1.1) describes how the nation was galvanized into action and started a national space program. These developments are described in more detail in the book *Spaceflight Revolution* (ref. 1.2).

The advent of the space program was a welcome event to many of the research groups at Langley. One reason for this attitude was that aeronautical research had reached a plateau at this time. Many of the research contributions of Langley and other National Advisory Committee for Aeronautics (NACA) centers had reached fruition in the design and production of advanced airplanes. These airplanes included jet bombers and transports, and supersonic fighter airplanes. Research and design work on the supersonic transports, the British Concorde and the Russian TU144, had progressed to a point that construction could proceed with some assurance of success. No really revolutionary advances for atmospheric aircraft were envisioned at that time or have occurred in the ensuing years. Some of the wind-tunnel organizations, however, expressed concern that their work might be cut back or otherwise affected by the emphasis on space research.

In the case of my work and that of the Flight Research Division, another event occurred that required a change in direction. A NACA Headquarters edict, published in 1958, stated that no further testing of high-speed airplanes would be done at Langley. All future flight research on such airplanes was to be done at the Edwards Air Force Base in California (now called the Dryden Flight Research Center). The engineers in my division therefore were available for assignments in the field of space research.

CHAPTER 2

Blast Off Into Space

With the start of the space program, a rapid transition occurred in the types of research performed at Langley. At first, the emphasis was on educating research personnel so that they could become acquainted with the new disciplines and skills required in space research. Second, there was a diverse effort in space research, applying the newly acquired knowledge to the solution of problems that were recognized as being important in this field. Soon, however, a national space program was established, involving both unmanned and manned satellites. Space flight centers were established to take the lead in specific types of work, such as scientific satellites, interplanetary probes, and manned space flight. The various groups at Langley generally initiated work that would contribute to a specific phase of the national space program, and general research programs were phased out. In some cases, research programs were stopped by management because they did not fit in the national space program or because the work being done had been assigned to other centers.

The discussion that follows applies mainly to the work being done under my direction in the Guidance and Control Branch of the Flight Research Division (1959–1962), the Aerospace Mechanics Division (1962–1963) and the Space Mechanics Division (1963–1970). No attempt has been made to present the dates or time periods of different research programs. Because over 40 years has passed since the start of the national space program, however, many readers today may be unfamiliar with the progress of space flight and the times at which certain goals were accomplished. To assist the reader in relating the work described to the progress in space flight, an abbreviated chronology of space launches and missions, both Russian and American, is presented in appendix I. These data were obtained from the TRW Space Log (ref. 2.1). Much more detailed discussions of the various NASA space programs are available in the NASA Historical Publications that have been prepared to describe each major program. Some of these publications are given in references 2.2, 2.3, and 2.4. Others are given in the lists of reference works included in these publications.

Education in New Fields of Research

The start of the space program was a time of rapid transition for most aeronautical research organizations in the country. The Russian feats of orbiting Sputnik satellites had captured the interest of the general public, first from a sense of wonder that space vehicles actually existed and second from a sense of fear that these vehicles, with unknown capabilities, might signal the start of an era in which the enemy would have technical expertise exceeding our own. The engineering community was perhaps less alarmed but nevertheless realized that a great deal of study and research was necessary to become familiar with the disciplines involved in this relatively unknown field.

The effect on the administrators in Washington, as is well known, was to cause them to initiate the change of the NACA, the National Advisory Committee for Aeronautics, from a small government organization reporting directly to the president, to the NASA, the National Aeronautics and Space Administration, a large government agency reporting to Congress and involving many new research centers and operational centers in addition to those in the original NACA. This change, however, did not immediately affect the research programs at the Langley Research Center. The change in research emphasis at this center came primarily from the interest of the center personnel in new fields of work involving flight in space and the desire to learn as much as possible about a promising new area of research.

In the Flight Research Division, I was still assigned as Head of the Stability and Control Branch. At this time, Henry A. Pearson, Head of the Aircraft Loads Branch, initiated a program in which various engineers would look up some subject involved in space research and give a lecture on it to the whole division. The notes on these lectures were collected in a volume (ref. 2.5), the table of contents of which is given in figure 2.1. These notes were widely distributed in the NASA centers but were never published. A copy of this volume is available in the Langley Research Center Library. As stated in the preface of the volume, the initial demand for the notes was so great that, "for the sake of expediency, this goal (of rapid distribution) is best achieved by making the material available in its present unedited form instead of following the usual NACA editing procedure." Later, most of the engineers involved had become involved in specific space projects and therefore had no time for the work of preparing the volume for more formal publication.

Similar studies and lectures were continued after the distribution of the volume. Among the subjects I studied were the rotational motion of a free body in space and later, the relative motion of two bodies, a subject of importance in connection with space rendezvous. Many other research organizations, in this period, were equally involved in an intense educational effort to learn everything possible about space flight. These organizations included the aeronautical departments of engineering colleges and government research groups in the Army, Air Force, and Navy.

In studying these problems, it was impressive to find how much famous mathematicians centuries ago, who had no idea of applying their theories to space travel, had learned in studying the motions of planetary bodies. These brilliant men had studied these problems as pure academic exercises, without modern computing facilities and without the incentive provided by experimental research with artificial satellites.

FIGURE 2.1. **List of topics covered in Henry A. Pearson's lecture series.**

I	Elementary Orbital Mechanics	W. B. Huston and J. P. Mayer
II	Satellite Time and Position With Respect to a Rotating Earth Surface	T. H. Skopinski
III	The Motion of a Space Vehicle Within the Earth-Moon System: The Restricted Three-Body Problem	J. P. Mayer
IV	Orbital Transfer	A. P. Mayo
V	Reentry With Two Degrees of Freedom	A. P. Mayo
VI	Six Degree of Freedom Equations of Motion and Trajectory Equations of a Rigid Fin Stabilized Missile With Variable Mass	J. J. Donegan
VII	Inertial Space Navigation	D. C. Cheatham
VIII	Guidance and Control of Space Vehicles	C. W. Mathews
IX	Elements of Rocket Propulsion	H. A. Hamer
X	Characteristics of Modern Rockets and Propellants	J. G. Thibodaux, Jr. and H. A. Hamer
XI	Aerodynamic Heating and Heat Transmission	W. B. Huston
XII	Heat Protection	W. S. Aiken, Jr.
XIII	Properties of High Temperature Materials	E. M. Fields
XIV	The Solar System	C. R. Huss
	Appendix on the Earth's Atmosphere	W. J. O'Sullivan and J. L. Mitchell
XV	Communication and Tracking	P. A. Gainer and R. L. Schott
XVI	Some Dynamical Aspects of the Special and General Theories of Relativity	D. Adamson
XVII	Environmental Requirements	W. A. McGowan

In many cases, they originated mathematical techniques used in space research, particularly the techniques required for the calculation of satellite orbits.

I was also impressed by the progress made by astronomers. These scientists, who devoted their lives to abstract studies to understand the nature of the universe, soon realized that they had knowledge of value in the space program. An example of this research, which could be classed as an engineering study as well as a scientific effort, is given in a brief note entitled *Exploration of Space from the University of Virginia,* published in the University of Virginia News Letter in January 1959 (ref. 2.6). This note points out that the exploration of space there had been going on for 75 years, since the acquisition of a large telescope in 1888. The main object of these studies is the field known as astronometrics, the study of the distances to and relative positions of the stars and other heavenly bodies. The University of Virginia at Charlottesville, Virginia is one of the colleges closest to Langley with an astronomy department, and valuable contacts were established there that later aided in the work on the Apollo program.

The subjects presented in these lectures included many disciplines that had little relation to the aeronautical work previously conducted by these branches. For example, a lecture on hypersonic flow was included because such flow conditions would be involved in the flight of rockets or space vehicles while entering or leaving the atmosphere. Orbital mechanics was considered important because vehicles operating in space would be subject to the same laws that had been developed for planets and other heavenly bodies. The theory of relativity was considered important because it had been involved previously in astronomical studies. This theory becomes important when the motion of the bodies involved approaches the speed of light. Such speeds were not contemplated in the type of space operations required in the early years of the space program. Nevertheless, the desire to understand the laws governing the universe made relativity a subject of interest in the new field of space flight. It was known that a slight motion of the perihelion of the planet Mercury had been detected that was not explained by Newtonian mechanics and was one of the examples presented by Einstein as a method of verifying his theory of general relativity. Thus, relativity might have an effect even on the motion of objects in the solar system. In later space projects involving precise measurements of time or in the use of spacecraft for navigation purposes, inclusion of relativistic effects was found necessary to obtain the degree of precision desired.

Fortunately, an engineer with a knowledge of Einstein's theories, working in the Physical Research Division at Langley, was available. He was David Adamson, an Englishman who studied physics at Durham University but was employed at the Royal Aircraft Establishment (RAE) in England during WWII in research on airplane handling qualities. After the war he came to work at Langley. As a result of his experience in engineering as well as in physics, his lectures on the complex subject of relativity were presented to the engineers with unusual clarity.

Item 3 in the list of topics in figure 2.1 is a lecture by J. P. Mayer on the subject of the three-body problem. This notable problem concerns the motion of three bodies in space, such as, for example, the Sun, Moon, and Earth, under the influence of their mutual gravitational attraction. This problem has been studied by many famous mathematicians over the centuries. Despite the amount of effort expended in its solution, this problem, in all its generality, has never been completely solved. As often happens when brilliant mathematicians work on a very difficult problem, however, the work led to advances in many fields of mathematics. As an aside, John P. Mayer later joined the Space Task Group working on the Mercury Project and was later in charge of all the computing facilities at the Johnson Space Center during the Gemini and Apollo programs. Practically all the engineers in the Aircraft Loads Branch later joined the Space Program, either in the Space Task Group or at the new Goddard Space Flight Center. In the list of lecturers given in figure 2.l, these engineers include Wilbur B. Huston, John P. Mayer, Ted H. Skopinski, Alton P. Mayo, James J. Donegan, and Carl R. Huss. Others on the list, who worked in my branch, are Donald C. Cheatham and Charles W. Mathews. Mathews later moved to NASA Headquarters in Washington and became head of the Gemini project, one of the most successful space flight projects. Cheatham worked at the Johnson Space Flight Center and did important work in the design of the Space Shuttle control system.

Initial Space Research at the Flight Research Division

One of the main objectives of many research organizations both in the NACA and in the armed services was to beat the Russians in a race to place a man in space. The Air Force had its MISS program (Man in Space Soonest). At Langley, the Pilotless Aircraft Research Division (PARD) was in charge of Robert R. Gilruth, formerly my boss in the Flight Research Division. Members of PARD, who had developed experience in handling rockets by using them to propel test vehicles used in aeronautical research, proposed placing the astronaut in a capsule that could be launched into space by the existing Atlas Rocket and recovered by parachute with a splashdown in the ocean. This imaginative program, largely the concept of Maxime A. Faget, an engineer in PARD, later won the approval of NASA and developed into the Mercury Project. The Air Force Program, meanwhile, continued with several studies of vehicles called the Robo, Brass Bell, and Hywards. Finally these studies were consolidated into the Dynasoar project, also called the X-20. This program received considerable support and reached an advanced state of engineering development, but was cancelled in 1963. The reasons for the cancellation were that no well-defined military mission for the vehicle could be found, that the cost was excessive, and that by 1963 the NASA Gemini program planned to accomplish many of the objectives of the Dynasoar program. During the early stages of the Mercury program studies, there was much concern that the ocean splash-down would be impractical and that the vehicle should allow the astronaut to land "like a gentleman," with a conventional airplane-type landing at an airport.

In considering this problem, I tried to take advantage of the concept developed by H. Julian Allen and A. J. Eggers, Jr. of the NASA Ames Research Center that a blunt-faced object would be much more suitable for entry into the atmosphere than a pointed, rocket-like object (ref. 2.7). This concept was based on the fact that such an object would dissipate the tremendous energy of the vehicle entering the atmosphere in the form of shock waves that carried the energy away from the vehicle, rather than in the form of heat that would produce temperatures high enough to melt or decompose most materials. The same concept was employed in the Mercury project by having the capsule enter the atmosphere blunt end first, with a suitable heat shield on the blunt end.

In considering the application of this concept to an airplane-like configuration, I visualized that the airplane could enter the atmosphere at near 90° angle of attack, then pitch down to normal gliding attitude after the speed had decreased sufficiently that heating would not be a problem. A delta-wing configuration seemed suitable for this purpose, but controls had to be provided to control the attitude of the vehicle during entry and to pitch the airplane down to normal attitudes for landing. A sketch of the resulting vehicle is shown in figure 2.2. To pitch the airplane down after entry into the atmosphere, a set of tail surfaces was provided that folded into the shielded region behind the vehicle during entry, but unfolded for the pitch-down maneuver and subsequent glide. In addition, four hinged surfaces were provided around the outline of the vehicle, which, by suitable combination of deflections, could provide pitch, yaw, and roll control during entry. Such controls are now known as controllable strakes and are now being used on the nose of a fighter airplane to assist in control at high angles of attack. The advantage of these controls for an entry vehicle was that they simply extended the outline of the vehicle at angles of attack near 90° and were not subject to any more heating than the lower surface of the vehicle, on which the heating was reduced because of its large area.

Soon, considerable interest was generated in further studies of a vehicle of the proposed type. I made a small model to illustrate the concept. Many engineers in my branch, with some assistance

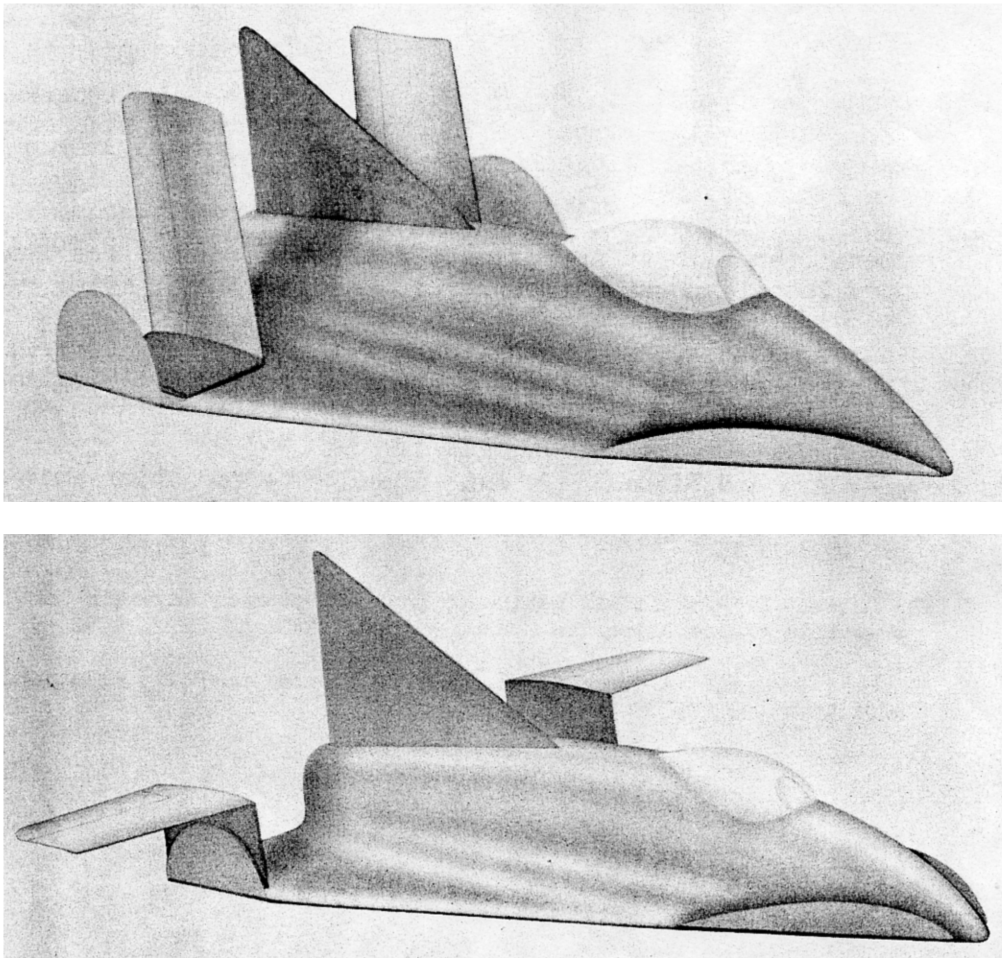

FIGURE 2.2. **Drawing of concept for entry vehicle studied by members of Flight Research Division.**

(a) Reentry.

(b) Landing.

from others in the Aircraft Loads Branch and the Performance Branch, made detailed studies of such aspects as heating, structural loads, and stability and control. The vehicle was sized to weigh about 2000 pounds, the same as the Mercury capsule, so that it could be carried on the nose of the Atlas Rocket. Preliminary calculations showed that a vehicle capable of carrying a single astronaut could be made within this weight limitation.

The heating studies were made by John A. Zalovcik of the Performance Branch. He had previously gained considerable familiarity with this branch of aerodynamics in his studies of airspeed measurements and heating problems of supersonic aircraft.

Among the phases of flight studied were the orbital phase, the atmospheric entry, the transition from flight in the vacuum of space to flight in the atmosphere, and the control of the vehicle as the airspeed decreased from hypersonic speed during the initial entry to supersonic speed and finally to low subsonic speed for landing. Most of these operations were unfamiliar to aeronautical engineers who had previously dealt with conventional airplanes. Some of the newly acquired knowledge of the dynamics of orbital flight was applied in this work.

The return from an orbit around the Earth required firing a rocket to cause the vehicle to change its orbit from a near-circular path around the Earth to an orbit that entered the atmosphere. Though the initial thought based on airplane experience would be to fire a rocket perpendicular to the flight path, studies showed that a much smaller rocket impulse would be required if the rocket were fired along the path in a direction to slow the vehicle down. Then the force of gravity would take over to bring the vehicle down into the atmosphere. This rocket was therefore called a retro-rocket, a term now familiar in discussions of space flight operations. A study was made of the effect of the magnitude of the retro-rocket impulse on the angle at which the vehicle entered the atmosphere and the distance traveled before entering the atmosphere.

With too shallow an entry angle, the vehicle would skip back out of the atmosphere, whereas with too steep an entry, the vehicle would experience excessive deceleration, resulting in intolerable loads on the human pilot. Tilting the vehicle from an attitude in which the lower surface was perpendicular to the flight direction to one in which the longitudinal axis of the vehicle made a smaller angle with the flight direction, provided a lift force to slow the vehicle's entry into the denser region of the atmosphere and a desirable reduction in the deceleration of the vehicle. In general, the entry angle needed to be between –0.5° and –1°. Some of these results are illustrated in figure 2.3. The range of –0.5° to –1° appears small, but the accuracy of the direction and magnitude of the retro-rocket burn was well within the capability of existing rockets and control systems. A fortunate effect of the laws of orbital motion is that the entry angle is very insensitive to the tilt of the deorbit impulse. Variations of this angle by as much ±10° from the flight direction produced less than a 0.02° change in the entry angle. In general, at shallow entry angles, the entry angle had little effect on the variation of deceleration, which reached a maximum value of about 8 g for the conditions considered. Tilting the vehicle longitudinal axis from the perpendicular position by just 10° shortly after the start of the buildup of deceleration reduced the maximum value to the more desirable value of about 5 g, as shown in figure 2.4.

The effects of variation in the entry angle of the vehicle on the aerodynamic heating were also investigated. Some of these results are shown in figure 2.5. The maximum heating rate remained about the same for entry angles between –1° and –0.25°, but this maximum occurred later in the entry at the shallower angles.

At that time, some studies had been made of the effects of different heat shield materials for use on the research airplanes such as the X-1; heat resistant alloys such as Rene 41, a nickel-chromium alloy, withstood temperatures up to 1600 °F. This material would allow the use of a steeper entry with less total heat input to the vehicle because the high temperature surface would radiate much heat. On the other hand, beryllium has a high heat capacity, so that a reasonable thickness of the material would absorb the heat of entry. These two materials typified what were called radiative and heat sink type heat shields, respectively. A combination of these materials was at that time thought suitable to protect the vehicle from aerodynamic heating. At that time, ablative materials, such as Teflon®, had shown promise in tests in hypersonic wind tunnels, but the amount of data available was not sufficient to allow consideration of their use on a vehicle. Ablative materials decompose at high temperatures.

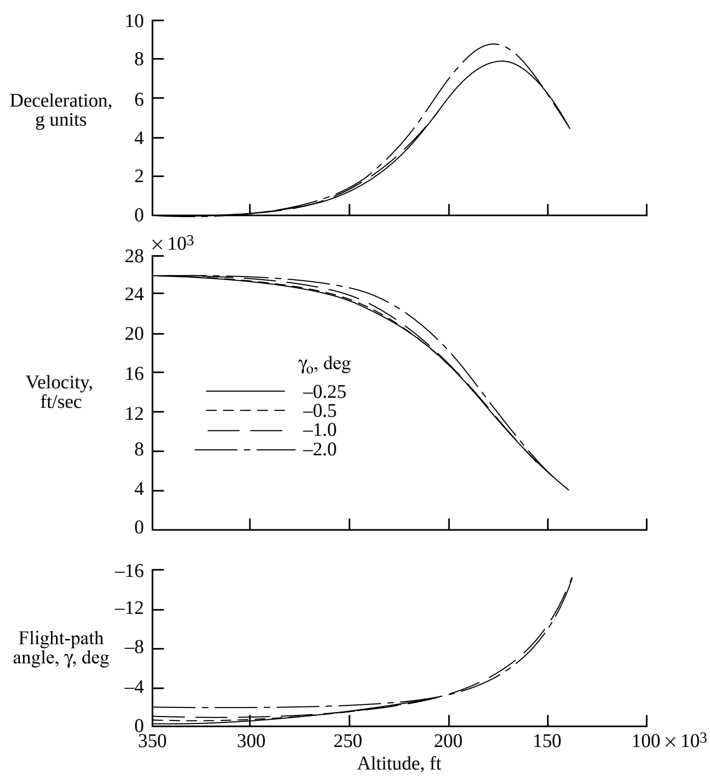

FIGURE 2.3. Effect of entry angle on variations of deceleration, velocity, and flight-path angle, γ, with altitude. Wing loading, 20 lb/ft^2; angle of attack, 90°.

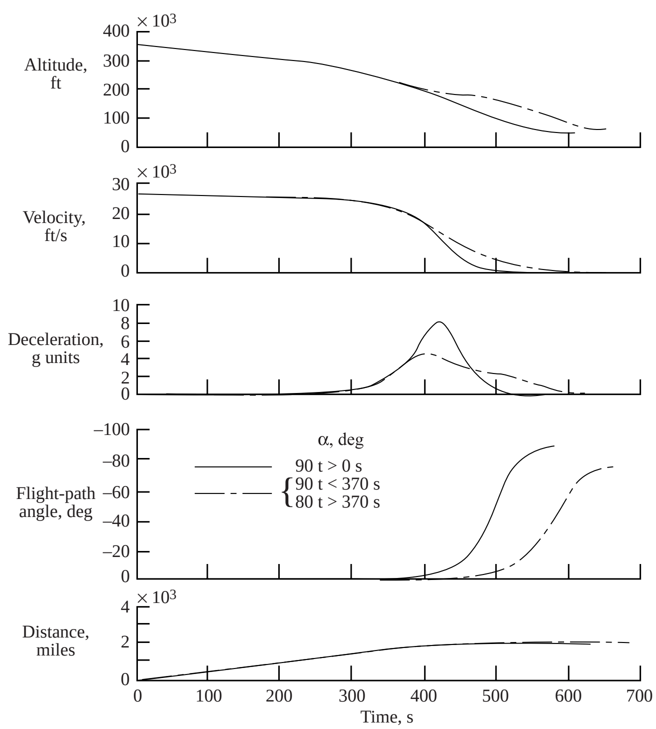

FIGURE 2.4. Time histories showing effect of reduction of angle of attack on deceleration and other trajectory variables. Initial flight-path angle –0.5°, wing loading 20 lb/ft^2.

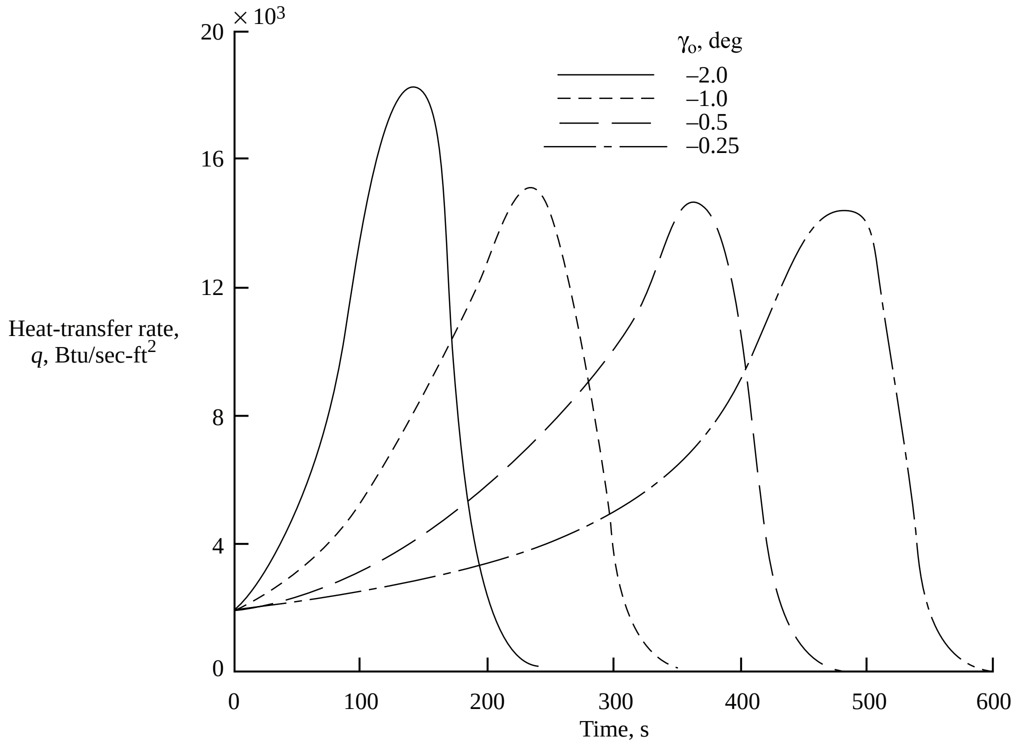

FIGURE 2.5. Effect of entry angle, γ_o, on heat-transfer rates for entries at 90° angle of attack. Wing loading, 20 lb/ft^2; entry altitude, 350,000 ft.

This process absorbs heat and the outer layers turn to gaseous products that carry the heat away from the vehicle. Later, many additional developments were made both in ablative and radiative heat shields, as typified by the heat shields on the Apollo capsule and on the Shuttle Orbiter, respectively.

The studies associated with the winged entry vehicle were published as NASA Technical Memorandum X-226 entitled *A Concept of a Manned Satellite Reentry Which Is Completed With a Glide Landing* by the Staff of Langley Flight Research Division, compiled by Donald C. Cheatham (ref. 2.8). This memorandum was originally classified confidential but has since been declassified. Also, a patent was issued in my name entitled *Variable Geometry Winged Entry Vehicle*. At that time, personnel at many of the wind tunnels at Langley wished to contribute to the space program, but not many designs for entry vehicles had been proposed. The results of the Flight Research Division study, however, had been discussed with personnel involved in aerodynamic research. As a result, independently of my efforts, branch heads in a number of the wind tunnels operating in different speed ranges had models with folding wing tip panels constructed and ran tests.

A large model of the Flight Research Division vehicle was built for tests in the spin tunnel. A picture of the model being tested is shown in figure 2.6. These tests were intended to study the ability of the four-hinged surfaces around the border of the vehicle to provide stability and control during descent at 90° angle of attack. These tests showed that the control was easily accomplished. Later, an air jet was fitted to the rear of the fuselage and the model was mounted in a vertical position in the test section of the NASA 30- by 60-Foot Tunnel to

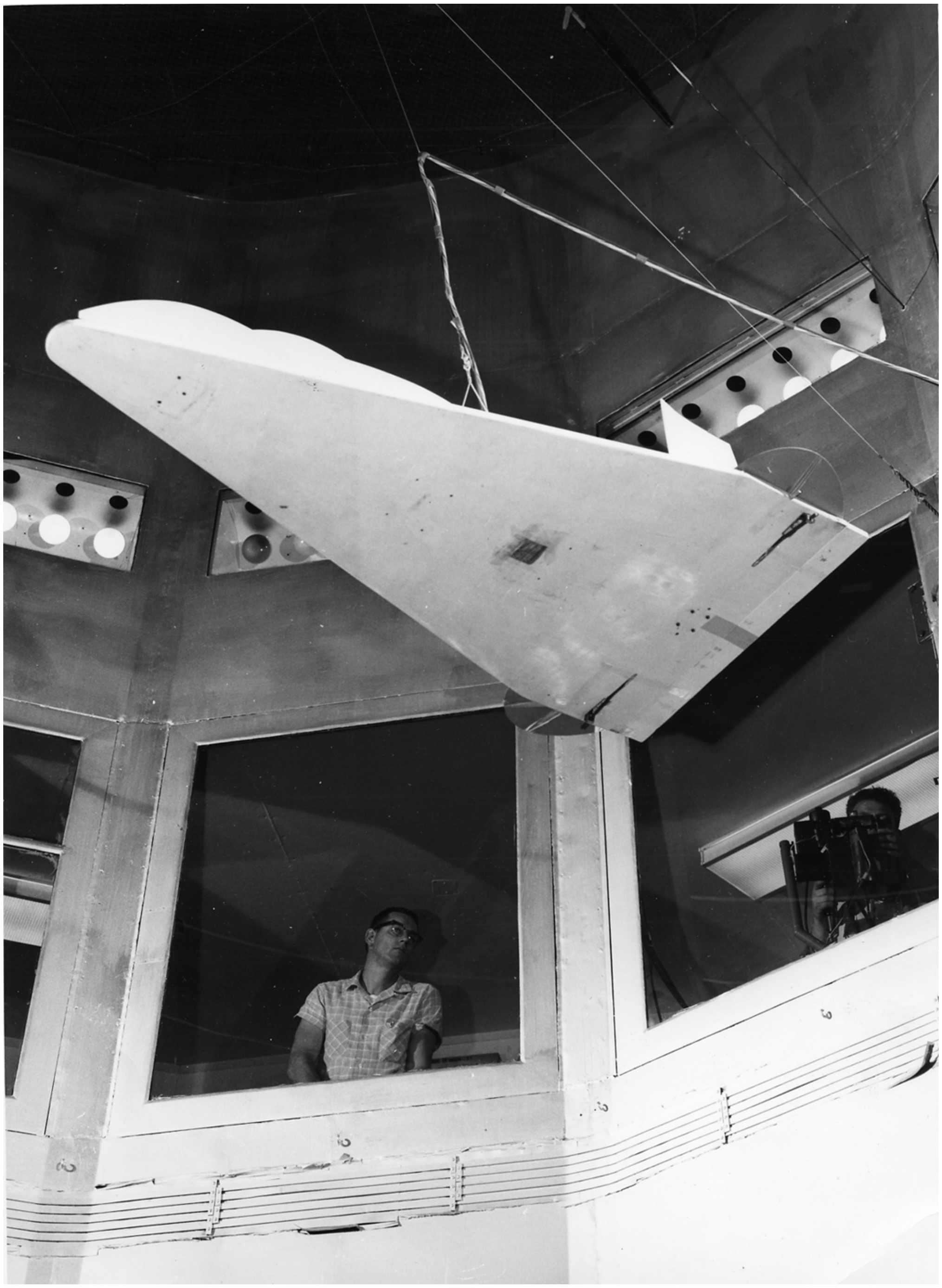

FIGURE 2.6. **Large model of entry vehicle being tested in Langley Spin Tunnel to study control at or near 90° angle of attack.**

study the use of the folding tail surfaces to provide transition from 90° angle of attack to a glide attitude. This maneuver was again easily accomplished by gradually deploying the tail surfaces as the tunnel speed was increased from zero to the speed for horizontal flight. In fact, the configuration showed promise as a tail-sitter vertical takeoff and landing (VTOL) airplane.

This configuration, or some variations of it, for a time acquired the most complete set of aerodynamic data of any winged entry configuration, covering the entire range of Mach numbers within the capabilities of the Langley wind-tunnel facilities. A Langley committee called the Steering Committee for Manned Space Flight served to communicate the research results among the various groups. Several of these wind-tunnel studies were published as NASA Technical Memorandums (refs. 2.9–2.11). These reports also contain long lists of references containing additional tests on these and other configurations made during the same time period. By the time these data were published, the Space Task Group had been formed to implement the Mercury project. This group was relocated in Houston, Texas to form the nucleus of the Johnson Space Flight Center. Before the group moved to Houston, however, they requested a presentation of the results of the Flight Research Division study to compare the relative advantages of the two approaches. The presentation had little effect on the planning for the Mercury project, mainly because, with the desire to put a man in space as soon as possible, the Mercury development was obviously simpler and involved less development. In addition, Mercury included the feature of an escape tower that was considered essential for astronaut safety in case the Atlas rocket malfunctioned on the launch pad.

The beneficial results of the Flight Research Division study included educational background for many of the engineers who later joined the Space Task Group and early analysis of trajectory and heating problems that provided results applicable to most types of entry vehicles. In addition, the later development of the Shuttle Orbiter involved a configuration somewhat similar to that studied by the Flight Research Division. As a result, the engineers who had joined the space task group and later worked at the Johnson Space Center were able to apply this experience in the design of the Shuttle Orbiter.

Initial Space Research at Langley

Just as the Flight Research Division rapidly changed its emphasis from research on airplanes to research on space vehicles, all the other divisions at Langley attempted to use their expertise to investigate many problems of space flight. This research was not confined to studies of the initial brief orbital missions but included studies of unmanned satellites and of manned orbiting space stations intended for long durations in space. Many problems confronting the crew of a space station were immediately recognized. They included numerous biomedical problems, such as the effects of zero gravity, protection from the vacuum of space, protection from ionizing radiation (already discovered by Van Allen in his initial orbital experiments), and provision of food, water, and oxygen over long periods. In connection with the vehicle itself, there were problems of temperature control, generation and storage of energy, protection from meteoroids, and effects of the space environment on materials and structures. It is remarkable that much basic knowledge of many of these subjects was obtained in the first two years of the Space program.

A brief discussion of some of the work done at Langley on these space-related problems is now presented. I was not connected with these projects but learned of them through participation in committee meetings and visits to see items of research equipment. These comments are based on my recollections and may not be historically accurate, but they reflect the opinions of the research that I formed at that time.

In the areas of biomedical research, Dan Popma of the Instrument Research Division (ref. 2.12) headed an extensive program. He proposed ingenious ideas for methods to purify the atmosphere of a space station, to provide oxygen, and to recycle wastewater and urine. Methods of testing these devices in ground-based facilities were suggested. He also considered the medical effects of zero gravity and studied centrifuges, rotating space stations, and other ideas, many of which were finally tested in space many years later. This promising work came to an abrupt halt when NASA Headquarters ruled that all biomedical research should be conducted in a new facility at the Ames Research Center, manned mainly by medical doctors. I considered it a mistake to place this work in the hands of doctors rather than engineers. Dan Popma was an engineer, and his approach was much more logical and could have produced the required information for manned space flight much more quickly than the program that actually evolved. The doctors, who frequently lacked research experience and had no experimental data to go on, feared that unknown effects in space might cause a human being to become disoriented or might even prove fatal, and they therefore proposed that difficult and inconclusive animal experiments should be performed before a man was allowed to go into space. Test pilots, on the other hand, had experienced, in high-altitude flight, many of the problems that at least approached those expected in space and did not see any reason to delay placing a man in orbit. The eventual program represented a compromise of these views. After a few manned space flights had been made, the Ames group became involved in other research, such as theories of the origin of life. Such theories are an important subject for scientific research, but they have little bearing on the problems of manned space flight.

Other groups at Langley were concerned with methods of overcoming the effects of zero gravity. An obvious concept was the use of a rotating space station to allow the centripetal acceleration to simulate gravity. Paul Hill and others in the PARD conceived an inflatable rotating toroidal space station, like a large inner tube. This design would allow the device to be folded compactly for launching and then to be deployed in space. A contract was given to the Goodyear Corporation to build an engineering model of this concept. The model was about 15 feet in diameter and was set up to study inflation, strength, puncture resistance, and leakage. When Charles Donlan, at that time the Deputy Director of Langley, heard of this work, he immediately ordered it stopped because a large space station was not at that time part of the NASA space program. This and other experiences made it clear that the freedom to pursue new ideas that had existed under the NACA was curtailed under NASA, and projects had to fit the overall space program as established by NASA Headquarters.

Several groups studied the problem of durability of materials and electronic equipment in the space environment. An electron accelerator of the Van de Graaf type was acquired for this research. Later, a large laboratory, called the Space Radiation Effects Lab (SREL) was built in Newport News and run in cooperation with the College of William and Mary. A large cyclotron supplied the required radiation. This work continued for many years, but after the end of the Apollo Program, funds for this project were discontinued. Later still, the cyclotron was removed, but the building was used as part of the Thomas Jefferson Research Laboratory, which contains a large, continuous beam electron accelerator for basic research in nuclear physics. My rather surprising involvement in tiding over the use of the facility during the lull in funding between the Apollo era and the development of the electron accelerator is described in a later chapter.

Engineers at Langley also foresaw the need for studies of other aspects of the space environment on many types of materials. Some work could be conducted in vacuum tanks. An example of this research is the study of friction of moving parts in the vacuum of space. Despite the desire to conduct much research of this type, very little was done because instead of first putting up a space station and later proceeding with more complex missions, President Kennedy initiated the Apollo program, which required a relatively short-duration mission. As a result, the effects of long exposure to space have been studied extensively only in recent years by using the Long Duration Exposure Facility (LDEF) satellite launched and recovered by the Space Shuttle.

A number of engineers at Langley investigated space power systems. About the time these studies were being started, I learned about rechargeable nickel-cadmium batteries for powering the transmitters, receivers, and servos of radio-controlled model airplanes. The great advantage of these batteries is that they can be charged and discharged many hundreds of times without deterioration. I contacted one of the engineers working on the space systems and found that he had not yet heard about these batteries. This experience shows that hobbyists are sometimes more alert to new developments than professionals. Nickel-cadmium batteries, or NiCads as they are called, have since been used extensively in spacecraft power systems.

Another engineer who turned his attention to space power systems was Albert E. Von Doenhoff, a former airfoil expert who was mentioned in reference 1.1 for his aircraft landing study. Assisted by Roland Ohlson and Joseph M. Halissy, he made an analysis of solar regenerative space power systems (ref. 2.13). In this type of system, a solar collector heats and vaporizes a working fluid, which drives an engine similar to a steam engine or steam turbine. The working fluid is then condensed for reuse by a radiator that radiates heat to the blackness of space. The steam engine, of course, may then drive an electric generator. I thought that Von Doenhoff's analysis was excellent, but in that same period, solar photovoltaic cells were developed to a usable stage. These cells, together with NiCad batteries to store the energy, have been used since then on practically all space missions. The weight and complication of the regenerative power systems have discouraged their use. Such systems still might be candidates for power on very large spacecraft or on planetary bases.

Roland Ohlson, who formerly worked in the NACA towing tank testing seaplanes and flying boat hulls, complained to me after his retirement that nothing he had ever worked on was used anymore. I suppose that many research engineers must expect this outcome of their career specialties in this time of rapid development of scientific and technical ideas.

CHAPTER 3

Stability and Control of Space Vehicles

This historical document is not intended to present a theoretical discussion of the problems encountered in designing space vehicles. The conditions in space, however, are so different from the familiar Earth-based environment that some appreciation of the effect of these conditions on the dynamics and control of space vehicles is required to understand the reasons for the research studies conducted in the course of the space program. In flight in free space, far removed from any influence of other heavenly bodies, a vehicle experiences no disturbances. This condition is not attainable on Earth. In the solar system and in particular in Earth orbit, some very small disturbing influences exist. These influences include effects of gravity, forces due to flight through rarified gas, moments from magnetic fields, and effects of solar radiation. Although these effects are small, they are of great importance because they provide the only means of controlling a spacecraft without the expenditure of fuel or energy. This chapter is therefore intended to give a discussion of these problems with as little dependence as possible on mathematical derivations. Primary emphasis is placed on a physical appreciation of the phenomena involved.

A term used in analyzing the rotational motion of a body is the moment of inertia about some specified axis. The moment of inertia resists rotational acceleration of the body, just as its mass resists linear acceleration. The moment of inertia of a small element of mass in the body is determined by multiplying the mass of the element by the square of the perpendicular distance from the axis. The moment of inertia of the entire body is determined by summing the contributions of all the elements of mass.

To allow calculation of the motion of the body resulting from torques (also called moments) applied about arbitrary axes, the moments of inertia are first determined about three mutually perpendicular axes through the center of gravity of the body. In all rigid bodies, these values of inertia serve to define an ellipsoid, called the ellipsoid of inertia, the formula for which is given in the following text. The axes defining the maximum and minimum values of inertia, together with the third axis perpendicular to these two, are called the principal axes of inertia. These axes are of special importance in determining the rotational motion of bodies.

The ellipsoid of inertia may be the same for many different bodies that have the *elements of mass distributed differently. The angular motion of all these bodies in response to a given applied torque would be the same.*

Rotating Vehicles in Free Space

One of the most obvious problems encountered in studying the motion of rigid bodies is the motion of an arbitrary body when it is started with a rotating motion. Students of elementary physics learn that the translational motion of the center of gravity of a body depends on the external forces applied at this point and that the rotational motion about the center of gravity is independent of the translational motion. The problem of the rotational motion can therefore be studied independently of the forces acting at the center of gravity of a body.

Although the rotation of a rigid body in the absence of all external moments would appear to be the first problem to study in this field, the solution of this problem is not well-known. In my graduate course at MIT, *Introduction to Theoretical Mechanics*, I do not recall this problem being mentioned. There are probably two reasons for this neglect. First, for bodies rotating on the Earth, there are always eternal moments applied during the course of the motion. A rather complex mounting system would be required to reduce these moments to very small values. Actual freely rotating vehicles, such as baseballs, airplanes, boats, etc. have relatively large moments applied by the surrounding air or liquid medium. Second, the solution to this problem of motion with no external moments is very complex, and little was to be gained by teaching this solution when no practical examples existed.

Many problems of rotating bodies occur when external moments are applied. The equations for the solution of these problems are known as Euler's dynamical equations. These equations are taught in standard courses in mechanics. I used these equations in the analysis of the effect of steady rolling on stability of airplanes, a problem later known by the name "roll coupling" (ref. 1.1).

In 1957, before the start of the space program, I had some introduction to the problem of rotation of rigid bodies without external moments. I became familiar with a report by G. W. Braün, an engineer at the Wright Air Development Center, on an analysis of the spinning of airplanes (ref. 3.1). Braün assumed that at high altitudes, the aerodynamic forces on a spinning airplane would be small compared to the inertial forces. As a result, the equations with no external moments appeared to be a good starting point for the studies of such spins. With the advent of space flight, bodies in space outside the Earth's atmosphere experience extremely small external moments. The rotational motion of these bodies in space is therefore a problem of practical importance. I also looked up further information in a book on classical mechanics by Goldstein (ref. 3.2), on which the subsequent discussion is based.

Although the mathematical details of this problem are too complex to present herein, a novel geometric solution of this problem obtained in 1834 by Louis Poinsot, a French mathematician, is presented. To describe this solution, a brief discussion of the method of specifying the applicable characteristics of a rigid body is considered desirable.

For studying the rotational motion of a rigid body, the detailed distribution of the elements of mass in the body or the shape of the body is not required. The

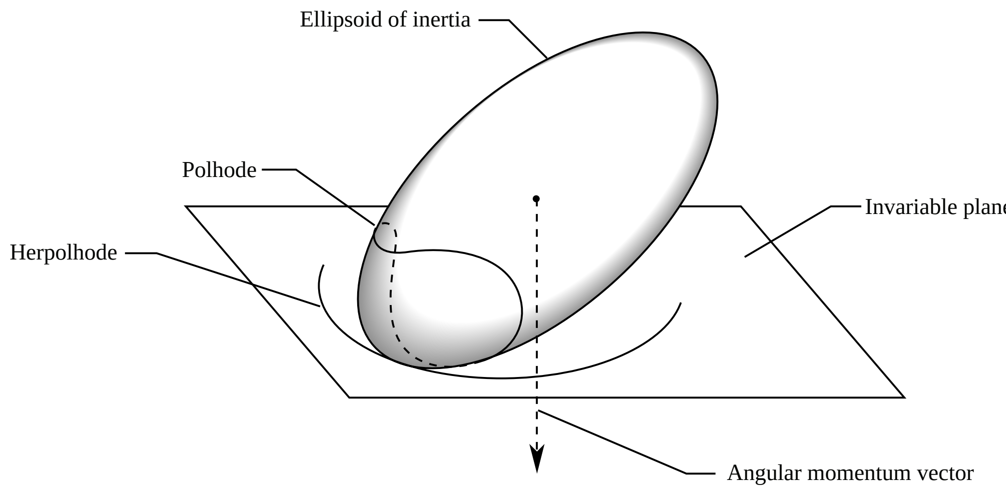

FIGURE 3.1. Illustration of motion of ellipsoid of inertia during free rotation of body in space. (Taken from ref. 3.2.)

body may be described by the moments of inertia about three mutually perpendicular axes, with their origin at the center of gravity, called the principal axes of inertia. These values of moments of inertia, represented as vectors I_X, I_Y, and I_Z along the three principal axes, can be used to determine the axes of an ellipsoid, called the ellipsoid of inertia. The shape of the ellipsoid is determined by the mathematical formula for an ellipsoid:

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2} = 1$$

where *a*, *b*, and *c* represent the distances from the center of the ellipsoid to its surface along the X, Y, and Z axes, respectively. The ellipsoid of inertia is defined by setting

$a = 1/\sqrt{I_x}$, $b = 1/\sqrt{I_y}$, and $c = 1/\sqrt{I_z}$

Vectors drawn from the origin to other points on the ellipsoid may be used to calculate the values of moments of inertia about any other axes through the center of gravity by using similar formulas. Different bodies with different detailed distribution of mass elements may have the same ellipsoid of inertia.

For any given ellipsoid of inertia, a solution of Euler's dynamical equations with the external moments set equal to zero allows the calculation of the motion following a disturbance in terms of elliptic integrals. A closed-form solution is thus available, but the calculations required are quite lengthy. Poinsot gave a very ingenious method of visualizing the motion of a freely rotating body in space. During the motion, in which the body rotates about the center of gravity, the ellipsoid of inertia rolls on a plane, called the invariable plane. Poinsot called the curve on the invariable plane traced out by the point of contact of the ellipsoid and the plane the herpolhode, and the curve on the ellipsoid traced out by the point of contact the polhode. Thus, the brief explanation of the motion, as quoted in Goldstein's book on Classical Mechanics (ref. 3.2) is "The polhode rolls without slipping on the herpolhode lying in the invariable plane." A sketch of this construction is shown in figure 3.1.

The assumption that no external moments act on the body implies that there are no damping moments. A motion once started, therefore, will continue indefinitely. The only steady rotations occur when the body is rotating about one of its principal axes, as seen from the fact that the tip of the axis then touches the invariable plane in just one point. In general, the motions started in any other manner would be highly oscillatory; that is, the principal axes would oscillate through large angles with respect to a fixed reference system. Such oscillatory motions would be very undesirable for most practical applications.

A question also arises as to the stability of the motion when it is started about one of the principal axes. The moments of inertia may always be classified as minimum, intermediate, and maximum. If the body is rotating about the axes of minimum or maximum moment of inertia, and is slightly disturbed, it will acquire a small oscillation or wobble. If it is rotating about the axis of intermediate inertia, however, and is slightly disturbed, it will immediately swing through a large angle and continue in a large-amplitude oscillation. The rotation about the axis of intermediate inertia may therefore be considered statically unstable and is unsuitable for a vehicle intended to perform a steady rotation.

In the early days of the space program, there was considerable discussion of the design of rotating space stations intended to provide a centrifugal force on the bodies of the astronauts to simulate the gravitational force existing on Earth. Once, in a meeting of one of the research coordinating committees chaired by Eugene Draley, an Assistant Director of Langley at that time, a presentation was made for the design of a rotating space station that rotated about its axis of intermediate inertia. I pointed out that the vehicle would be unstable as a result of the considerations described previously. This fact was not known to any other member of the committee. The design of the vehicle was stopped at this point for further study. As a result, we avoided some embarrassment to Langley that might have occurred had the design been proposed to NASA Headquarters.

A simple method of visualizing the tendency of a rotating body to rotate about its axis of maximum inertia is to consider that each element of mass in the body experiences a centrifugal force tending to pull it into the plane of rotation. The body as a whole will then tend to move to a condition in which its elements are as close as possible to the plane of rotation. This tendency will cause a pancake-shaped body, for example, to approach a condition in which the rotation is about an axis normal to the plane of the pancake. With no source of damping, however, the body, if started in an orientation displaced from the plane of rotation, will overshoot this orientation and continue to oscillate back and forth about it.

To illustrate these points further, I had a model constructed, sketched in figure 3.2, in which a flat slab of aluminum was pivoted on a universal joint and could be rotated about a fixed axis by turning a handle. The aluminum slab represented the dynamic characteristics of a rotating space station. If the rotation were started with the plane of the slab in the axis of rotation, a condition of rotation about the intermediate axis of inertia, the slab performed a large-amplitude oscillation. The oscillation damped out fairly quickly because of air resistance and bearing friction, and the slab ended up with its plane normal to the axis. In space, where the damping forces are much less, such an oscillation would continue much longer. If the rotation is started with the plane of the slab perpendicular to the axis of rotation, corresponding to rotation about its

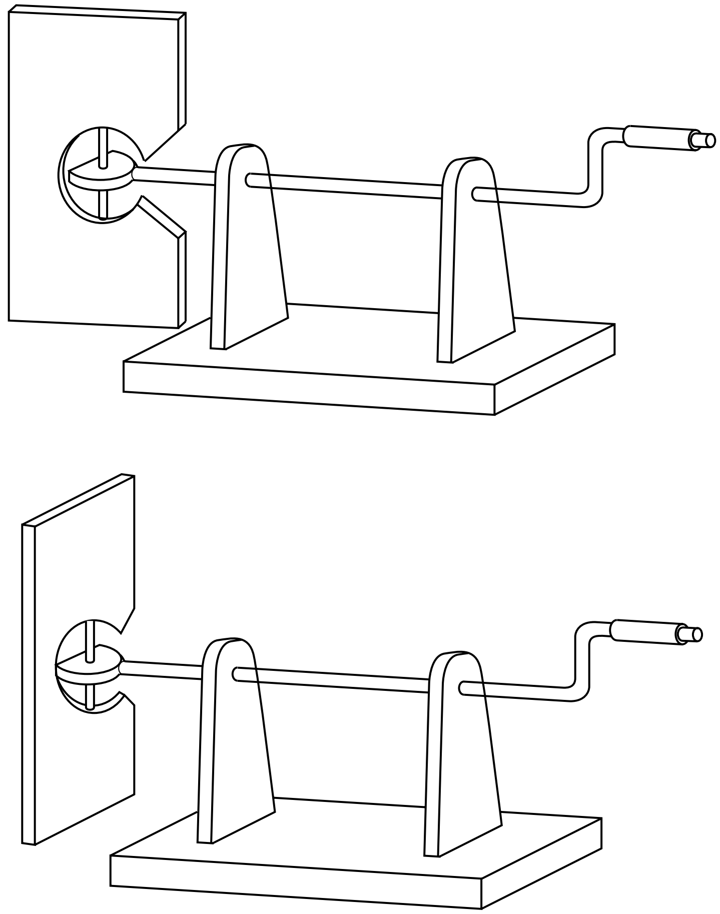

FIGURE 3.2. **Model used to illustrate stability of rotation of body in space.**

(a) Rotation about axis of intermediate inertia. When rotation is started with the plate in this position, it immediately swings through the position shown in part (b) and continues to oscillate back and forth until the oscillation damps out.

(b) Rotation about axis of maximum inertia. When rotation is started with the plate in this position, it remains in this orientation during the rotation.

axis of maximum inertia, the steady rotation continues.

The theory discussed so far assumes a rigid body. All space vehicles, in practice, have some flexibility, or some movable parts. When the body distorts, or when parts move, some energy is dissipated by internal damping or friction. This energy can come only from the rotating body itself.

Newton's laws state that the angular momentum of a body will remain constant in the absence of external moments. If energy is dissipated through internal causes, however, the nature of the motion must change. If the rotating motion continues for a long time, the motion will eventually change to a rotation about the axis of maximum inertia, because this motion, for a given angular momentum, has the least energy. Detailed consideration of how damping forces act on various parts of the body might be extremely complicated, but the end result is always the same. The body assumes a steady rotation about the axis of maximum inertia. This condition results even when the body starts rotating about its axis of minimum inertia, a stable condition for a rigid body. So far as I know, this result has been known to designers of satellites launched by the United States, and in some cases intentional damping devices have been installed to speed the settling down to a steady rotation about the axis of maximum inertia. Goldstein, in his book, *Classical Mechanics*, however, states: "This fact was learned the hard way by early designers of spacecraft." In other words, there must have been some spin-stabilized satellite that was launched spinning about its axis of minimum inertia and was intended to continue spinning in this manner, but which, because of internal energy dissipation, ended in a flat spin about its axis of maximum inertia.

Moments Acting on a Satellite

Moments acting on a satellite may come from the following sources that are inherent in the environment or motion of the vehicle. These moments are in addition to those supplied intentionally by mechanisms such as jets, gyroscopes, or inertia wheels.

1. Gravitational fields in space
2. Centrifugal force on parts of the satellite
3. Magnetic fields in space
4. Radiation pressure
5. Aerodynamic forces

In the early days of the Space program, I presented a lecture on these moments to members of the Flight Research Division as part of the Pearson lecture series. Information on these topics was obtained from then current technical papers. Since then, textbooks and reports that discuss these subjects in greater depth have become available (ref. 3.3). These texts, however, necessarily present derivations involving rather complex mathematics. To avoid the need for such derivations, I will confine this presentation to discussion of the illustrative examples worked out in my lecture.

For convenience, the moments are designated as rolling, yawing, and pitching moments in a way analogous to the usual definitions for aircraft. Thus, if a satellite is in an orbit, a rolling moment tends to rotate the satellite about a horizontal axis in the orbital plane, a yawing moment about a vertical axis in the orbital plane, and a pitching moment about an axis normal to the orbital plane.

Gravitational and Centrifugal Moments

Consider first the effects of gravity and centrifugal force on the pitching moments of a satellite in an orbit about a planet. A dumbbell-shaped satellite is used as an example. The dumbbell consists of two equal concentrated masses connected by a weightless rod. This configuration is used because it experiences the greatest gravitational and centrifugal moments of any body of the same total weight and size.

If such a body is aligned with the direction of flight and rotated to various angles about an axis normal to the orbital plane (a pitching motion), the centrifugal forces due to the angular velocity of orbital rotation may be shown to be zero, but the gravitational forces tend to hold the body in a vertical attitude. This effect is usually called the gravity gradient effect; it results because the lower mass of the dumbbell is nearer to the center of the planet than the upper mass. The gravitational attraction, which varies inversely as the square of the distance from the center of the planet, is therefore greater on the lower mass. The moment tending to align the dumbbell vertically is zero when the dumbbell is horizontal or vertical and reaches a maximum at a pitch angle of 45°.

The rolling moment on a dumbbell-shaped body is discussed for the case in which the body is aligned normal to the orbital plane and is rotated to various angles about a horizontal axis in the orbital plane. The analysis for the gravitational effects is identical to that for the pitching moments, but in this case, the centrifugal effects due to orbital angular velocity also tend to align the dumbbell with its long axis vertical. The magnitude of the rolling moment due to centrifugal forces is 1/3 that due to the gravity gradient. As a result, the total rolling moment is 4/3 that of the pitching moment.

The yawing moment on a dumbbell-shaped body is discussed for the case in which the body is aligned with its long axis horizontal and is rotated to various angles about a vertical axis. In this case, gravity gradient effects are zero, but the centrifugal forces create a moment tending to align the body with the flight direction. The magnitude of this effect is the same as for the rolling moment, that is, 1/3 the magnitude of the pitching moment. This effect is caused by the tendency, discussed previously, of all elements of mass of a rotating body to move into the plane of rotation.

All pitching, rolling, and yawing moments on a satellite do not really depend on the fact that the satellite is in orbit. A body on the surface of the Earth, located on the equator and experiencing the Earth's rotation, would feel the moments from the same sources. These moments are so small, however, that only in the weightless condition of space are they noticeable. On Earth, it would be very difficult to mount the body on a bearing supporting its weight that would be sufficiently close to its center of gravity or sufficiently frictionless to avoid masking these effects.

To give an idea of the small magnitude of these moments, the period of oscillation of the dumbbell about its equilibrium attitude in orbit may be calculated. The period is given as a fraction of the orbital period.

Pitch $\frac{1}{\sqrt{3}}$

Roll $\frac{1}{\sqrt{2}}$

Yaw 1.0

The orbital period of a satellite in a low Earth orbit is about 90 minutes; therefore, the period in minutes for these three cases is

Pitch 51.96

Roll 63.6

Yaw 90

The periods for any other satellite would be longer than those of the dumbbell-shaped body considered.

Another comparison of the magnitude of these effects may be made by comparing the periods of the motion with those of a more familiar vehicle such as an airplane. For a typical light airplane, the period of the lateral oscillation in the cruise condition would be about 3 seconds. For a dumbbell-shaped satellite with the same moment of inertia in yaw as the light airplane, the period of the lateral oscillation would be 90 minutes or 5400 seconds. For a given moment of inertia, the restoring moment in yaw varies inversely as the square of the period. The restoring moment on the body in orbit is therefore $(3/5400)^2$ or 3.1×10^{-7} times as great.

The very small magnitude of the moments acting on a vehicle in space requires the development of new concepts for stability and control. Despite the very small magnitude of moments produced by gravity gradient effects, such moments may be used as the basis of a stabilization system for a satellite. Usually, such moments are used to keep an elongated vehicle in a vertical orientation, to keep an antenna or sensor pointed at the Earth. In addition to the restoring moment provided by the gravity gradient, damping devices must be used to damp out oscillations about the equilibrium attitude. Without the provision of damping, oscillations would continue indefinitely.

Magnetic Moments

Magnetic moments may arise from the interaction of the Earth's magnetic field with a permanent magnet or other magnetized material on a satellite, or from eddy-current damping of a rotating satellite made of conducting material. The interaction of the Earth's field with a magnet on a satellite in orbit is similar to that of the Earth's field on a compass needle. This problem is discussed in many available textbooks and is therefore not considered further herein.

If any conducting body is rotated in a magnetic field, currents are induced in the body. These currents generate magnetic flux that interacts with the original magnetic flux to produce a torque. The torque is always in a direction to oppose the rotation. The energy required to maintain the rotation is lost in the form of heat generated by the ohmic resistance to the current in the body.

The moments due to eddy-current damping are quite important in many satellite applications because of the practice of spinning bodies to provide attitude stabilization. An estimate of the time for the original rotation to decay is needed. This problem can be solved analytically only for simple geometric shapes, such as cylinders or spheres (ref. 3.4). As an example, consider an aluminum cylinder that is long compared to its radius spinning about its long axis in a low Earth orbit. If the rotation is such as to cut the magnetic lines of force at right angles, the rotation is shown to damp to half its initial angular velocity in about 3.1 days. To determine the effect of the Earth's field on an actual spinning satellite, however, experimental measurements are usually required. The accuracy of these measurements may be increased and the time for the test may be greatly reduced by spinning the satellite in an artificial magnetic field many times the strength of the Earth's field. If the actual satellite is too large to test in this manner, a scale model simulating the inertial and electrical characteristics of the full-scale device may be used.

Effect of Radiation Pressure

Frequently, persons unfamiliar with space research do not realize that sunlight shining on a surface exerts a pressure. The magnitude of this pressure on a black surface normal to the incident radiation is

$$P = W/c$$

where *W* is the intensity of the incident energy and *c* is the velocity of light. This pressure may be approximately doubled by the use of an aluminized surface to reflect the radiation. At the Earth's radius, $W = 1.3 \times 10^6$ ergs/s cm^2 and $c = 3 \times 10^{10}$ cm/s. Hence *P* for a reflecting surface is 0.866×10^{-4} dyne/cm^2.

A moment tending to point a satellite towards the Sun may be obtained by equipping the satellite with a fin of reflecting material supported on a light structure. The moment provided by such a fin varies as the sine squared of the angle between the sunlight and the fin. The fin is therefore quite ineffective at small angles of deviation. This problem may be overcome by using a pair of fins in the form of a V. The maximum effect is obtained by setting each fin at an angle of 45°.

The magnitude of the restoring moment provided by such an arrangement may be illustrated by the following example. Consider a 20-inch-diameter satellite equipped with a V-shaped pair of fins each 1 m^2. Assume the following characteristics:

Moment of inertia in yaw	2×10^6 gm cm^2
Distance from center of gravity to centroid of V	75 cm

The period of small oscillations about the equilibrium position is 13.5 minutes. The period is a much smaller fraction of the orbital period than that obtained by gravity gradient or centrifugal effects.

The effect of radiation pressure acting on large, light "solar sails" has been studied as a means of propulsion in space. The acceleration produced by this method is small, but because of the lack of aerodynamic resistance in space, large changes in velocity may be obtained by allowing this force to act over a long period of time.

Effect of Aerodynamic Forces

The forces and moments acting on an object in the rarified atmosphere at high altitudes above the Earth are governed by aerodynamic effects existing in a flow condition called Newtonian flow. The laws for aerodynamic forces in Newtonian flow are equivalent to those for radiation pressure. The density of the atmosphere falls off continuously with increasing altitude. A point of interest is the altitude at which the impact pressure due to this rarified gas on a satellite traveling at orbital speed would be equivalent to the radiation pressure. A rough calculation indicates that this condition exists at an altitude of about 420 miles. The satellite with V-shaped fins discussed previously, flying at this altitude in the shadow of the Earth would have the same oscillation period due to aerodynamic forces alone (13.5 minutes) as that of the satellite exposed to solar radiation in a complete vacuum. At lower altitudes, the period due to aerodynamic forces would decrease until at an altitude of 200 miles; the period would be about 48 seconds.

At an altitude of 420 miles, assuming a nearly circular orbit, the loss in altitude per orbit due to aerodynamic drag on the fin-stabilized satellite would be only 0.0058 miles (30.6 feet) while at an altitude of 200 miles, the loss would be 1.47 miles. These figures illustrate that aerodynamic forces can have a large effect on the angular motions of a satellite while they are still small enough to have a minor effect on the trajectory.

Another application of this effect is the ability of aerodynamic forces to align an entry vehicle in the correct direction before aerodynamic heating and deceleration become large. For example, consider a vehicle weighing 4000 pounds and having directional stability equivalent to a fin area of 18 $feet^2$ acting at a moment arm of 3 feet from the center of gravity. If the vehicle enters the atmosphere at a sideslip angle of 90°, the aerodynamic forces at an altitude of 350,000 feet will be sufficient

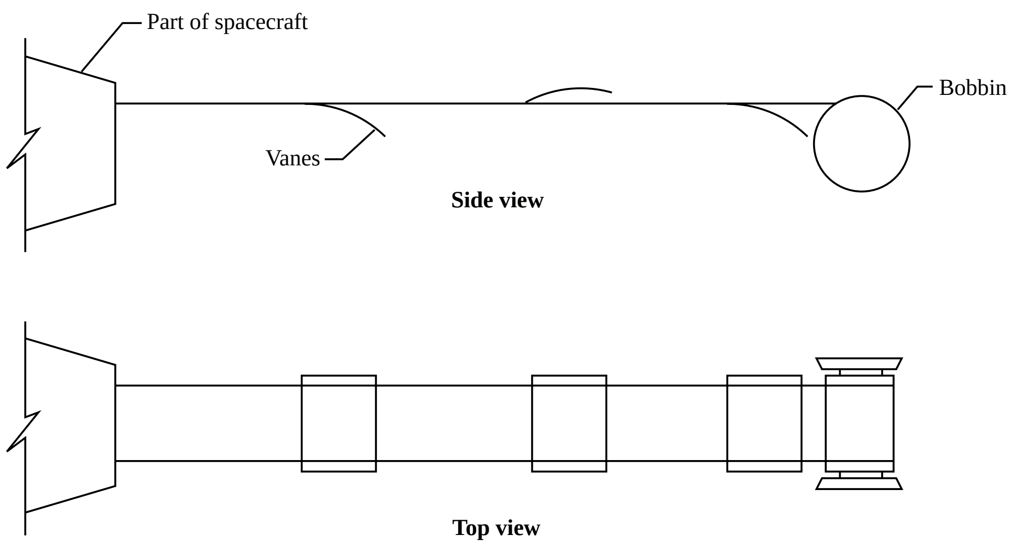

FIGURE 3.3. Sketch of drag device proposed for causing an orbiting spacecraft to enter Earth's atmosphere in case of failure of retro-rocket. Many small vanes could produce required drag.

to produce an angular acceleration of about 0.5° per second^2. The vehicle would pick up an angular velocity of 5° per second in 10 seconds and would pass through zero sideslip in about 20 seconds. Other studies have shown that the aerodynamic heating rate does not start to build up, at least in a flat entry (flight path angle less than –3° at 300,000 feet) until about 100 seconds after this point. The deceleration does not build up until a later time. For successful alignment of the vehicle, however, artificial damping would probably have to be provided; otherwise, it would oscillate back and forth through a large amplitude with very little damping.

At the time the Mercury capsule was under consideration, Mr. Robert Gilruth, then Chief of PARD, expressed concern that if the retro-rocket on the capsule failed to fire, the capsule might be left in orbit so long that the oxygen and other supplies onboard the vehicle would be exhausted. I proposed a device that could be deployed to add a sufficiently large amount of aerodynamic drag on the vehicle to cause it to enter the atmosphere in a reasonable time. A sketch of this device is shown in figure 3.3. My thought was that an ordinary parachute might fail to open because of the small dynamic pressure. In the device proposed, a series of curved vanes would be attached to thin cables wrapped around a bobbin. The bobbin would be expelled from the vehicle by a spring or a small explosive charge. As it traveled back, the vanes would unwind from the bobbin, forming a train long enough to add the required amount of drag. Gyroscopic effect would keep the bobbin itself in a stable attitude, and it would fall free at the end of the deployment. This device would allow placement of the train of drag vanes in a straight line behind the vehicle without relying on the very small aerodynamic drag to stretch out the thin cables and vanes. I made a small model of the device using a bobbin for sewing thread and vanes of paper. The model illustrated the principle successfully. The idea was never used, possibly because the attitude control rockets could serve as a backup to the retro-rocket.

The methods mentioned previously for applying moments to satellites are usually slow acting and limited to applications requiring small moments. For applications requiring larger moments, rockets or flywheels may be used. Both of these techniques have a limited total impulse. For example, the rocket can be used until its fuel is used up, after which it can no longer provide a moment. The flywheel can be spun up by a motor, producing a moment on the satellite in the opposite direction. The motor turns the flywheel faster and faster until it reaches its limiting speed or the flywheel fails due to excessive centrifugal stresses. Alternatively, the flywheel can be run at a constant speed and mounted in gimbals like a gyroscope. A moment applied to an axis perpendicular to the axis of rotation will then cause the gyro wheel to precess, while the gimbal to which the moment is applied will not move. As a result, an opposite moment will be applied to the satellite. The gyro wheel will precess until its axis is in alignment with the axis about which the moment is applied. At this point, the gyroscope is said to be saturated and will no longer resist the applied moment.

A combination of a gyroscope and a rocket may be used so that when the gyro is approaching saturation, a moment may be applied to the satellite with a rocket to precess the gyro so that it its gimbals rotate back to the original orientation. In this way, the gyro may continue to be used until the rocket fuel is exhausted, or perhaps some other slower acting source of torque may be used to desaturate the gyro. The gyroscope method, in some cases, has an advantage that its ability to hold the satellite in the desired orientation is practically unlimited except for effects of structural flexibility.

CHAPTER 4

Rendezvous

Rendezvous of a spacecraft with a target vehicle means maneuvering the spacecraft in such a way that it comes in close to the target vehicle with small or zero relative velocity. Docking, a maneuver that often follows rendezvous, means that the spacecraft is attached to the target vehicle to allow transfer of equipment or personnel.

In this chapter, three aspects of my work on rendezvous are discussed. From the earliest days of the space program, the importance of rendezvous in conducting space operations was realized. If the space program had been influenced primarily by scientific and technical thinking rather than by political considerations, a logical development would have been to test some small manned satellites and then place a space station in orbit. Such a space station would have allowed much basic research on problems of space flight with application to later missions to the Moon or planets. Obviously, rendezvous of supply vessels with the space station would have been necessary to conduct these operations. Many researchers in the space program made studies to determine how a spacecraft should be controlled in a rendezvous maneuver. A brief review will be given of the work that I did in this field.

In an effort to overcome the perception that the Russians were ahead of the United States in space research, and, by implication, in all scientific and technical developments, president John F. Kennedy, on May 25, 1961, made his bold commitment that the United States should place a man on the Moon within a decade. This extraordinarily difficult task required new developments in many fields. As it turned out, rendezvous was an important consideration in two of the three mission plans that were considered. The three mission plans were direct ascent, Earth orbit rendezvous, and lunar orbit rendezvous. The part played by engineers in my division and by others at the Langley Research Center in reaching the decision to use the lunar orbit rendezvous technique is described in this chapter.

The third subject discussed in this chapter is the development of the actual guidance and navigation systems used in the Apollo mission. Although the original Langley research was effective in convincing officials of the space program that the lunar orbit rendezvous mode was the correct technique to use, later developments showed that the original Langley concepts were oversimplified, and that much more sophisticated methods were used in the actual

Apollo mission, both in the theoretical developments and in the design of hardware.

Effect of Orbital Mechanics

In the early stages of the space program, I and many other researchers made studies to determine how a spacecraft should be controlled to perform a rendezvous maneuver. Because of the relatively short time usually allowed for such a maneuver, the spacecraft is assumed to be maneuvered by use of jets or rockets that allow control of rotation about three axes and control of velocity along three axes.

If two vehicles are in the vacuum of space and are sufficiently far from other heavenly bodies that the effects of gravitational fields of these bodies are negligible, then rendezvous is a relatively simple procedure. In a two-dimensional analogy, it would be much like one skater on ice maneuvering to catch up with and move along with another skater. Obviously there are many paths that could be followed in such a maneuver. Other constraints would have to be imposed to specify a definite maneuver, such as the time for the maneuver, the energy (or fuel) expended, or vehicle direction and motion as limited by visual or other constraints.

In maneuvers within the solar system, the effects of gravitational fields of the Sun and planets are always of some importance. In most practical cases, both vehicles are in orbit about the same planet. If the two vehicles are at the same altitude and speed, but displaced in different positions in a circular orbit, they continue to move in the same relative position because both vehicles are subject to the same gravitational acceleration. Any attempt to perform a rendezvous, however, places the vehicles in different orbits, requiring the application of more complex variations of force to perform the desired maneuver.

If the vehicles are in sufficient proximity and are moving with small relative velocity, differences in acceleration caused by differences in gravitational or centrifugal force are small. In this case, the maneuver required to perform a rendezvous is only slightly different from that required in space far from the influence of heavenly bodies. As the relative velocity of or displacement between the vehicles increases, the required maneuver becomes different. My initial studies were concerned with calculation of the paths required of the rendezvous vehicle at larger values of the displacement and relative velocity.

Although the derivation of the equations for the motion of the vehicle requires the use of mathematics, in this presentation an attempt is made to give only the method involved. The equations for the orbit of a body around a planet may be set up considering the initial conditions of the body and the acceleration due to the gravitational field of the planet. Adding small increments to the variables in these equations gives the equations of a second vehicle that can be considered the rendezvous vehicle. Subtracting the first set of equations from the second then gives the equations describing the relative motion of the rendezvous vehicle and the orbiting vehicle. Readers familiar with differential calculus will realize that this procedure incorporates the derivation of the methods of calculus. The procedure may be simplified using the methods of calculus by simply taking the differential of the original equation.

The resulting equations are nonlinear because the gravitational force varies inversely as the square of the distance from the center of the planet. In general, there is no closed-form solution of these equations. A closed-form solution is one that can be expressed in terms of known functions, such as trigonometric functions or other tabulated functions. To obtain a closed-form solution, the variables may be expanded in power series and terms higher than the first order may be neglected. If the relative displacements and velocities of the vehicles are sufficiently small, the higher order terms will be very small and the solution of the linearized equations will be reasonably accurate.

As explained in the book *Journey in Aeronautical Research* (ref. 1.1), the linearized equations for the motion of an airplane for small disturbances are highly accurate because the aerodynamic forces and moments vary linearly with the displacements and velocities in the range used in normal flight. It is natural, then, that I should try the same method in the problem of rendezvous. Many other research groups derived these linearized rendezvous equations about the same time that I did. A paper by W. H. Clohessy and R. S.Wiltshire of the Martin Company, containing these equations, was presented in June 1959 (ref. 4.1). As a result, these equations were usually referred to as the Clohessy-Wiltshire equations, although these authors acknowledge that an earlier paper containing these equations was brought to their attention after the presentation of the paper. My work was never published because of the earlier appearance of these other papers in the literature.

Simulation Experiments

A complete chapter devoted to simulation of space operations will be presented subsequently. At this point, however, some early work on simulation of rendezvous is introduced because it was one of the first simulation studies conducted, and because it had an important bearing on subsequent developments in the space program.

The purpose of the simulation was to investigate whether a spacecraft pilot could rendezvous with a target vehicle by observing the illuminated vehicle against a star background. Simulation equipment at that time (about 1959) did not have the advantage of computer-generated displays and digital computer solutions of vehicle dynamics that were available in the nineties. Considerable ingenuity was required to provide a realistic simulation in a short time at low cost.

A planetarium can provide a visual scene of the stars and heavenly bodies, but planetarium projectors and spherical screens of the type used in museums and observatories are quite expensive. Max Kurbjun and other engineers in my division provided the necessary spherical screen by obtaining a hemispherical inflatable radome, about 50 feet in diameter, of the type that was used for protecting radar equipment in Alaska. A sufficiently complete star background was provided by using a point light source to project beams of light through small lenses, providing simulated stars on the inside of the radome. Originally, the simulation was performed under conditions of free space, without the effects of gravitation of a nearby planet. Later, an early type of analog computer was obtained that allowed including the effects of orbital mechanics as represented by the Clohessy-Wiltshire equations.

Carrying out a rendezvous in space was a maneuver that had not been attempted at that time, and many people expressed doubt that such a maneuver would be sufficiently safe to be practical. The main result of the simulation study was to show that the rendezvous could be made quite simply with a minimum of guidance equipment or instrumentation. These runs were made at relatively close range, so that the visual cues played an important role providing the required information to the pilot or astronaut. Furthermore, the rendezvous simulator provided a convenient tool for demonstrating such a maneuver to other personnel involved in the space program.

Implementation of Rendezvous in Apollo Program

The Lunar Orbit Rendezvous mode was selected as the design basis of the Apollo Mission. In this mode, the Lunar Module (LM) must take off from the Moon and rendezvous and dock with the Command Module (CM) that is in orbit around the Moon. Some of the lengthy arguments and conferences involved in selecting this mode of operation are discussed later. For the present purpose, a brief comparison is made between the methods employed in the simulation described previously and the actual guidance and navigation techniques used in the Apollo mission. These methods are discussed in detail in the excellent book by Richard H. Battin (ref. 4.2).

The Apollo mission managers selected the Draper Lab in Cambridge, Massachusetts to design the Apollo guidance and control system. This organization had extensive previous experience in development of inertial navigation systems and in missile guidance. The engineers in this organization obviously had much more experience in the design of sophisticated guidance equipment than the Langley engineers in my division, who just a year or so earlier had been working on stability and control of aircraft.

The Apollo mission could be controlled by radio guidance from the ground or by the astronauts onboard the vehicle by using the navigation instruments provided. The main reason for the onboard navigation capability was to give the astronauts a guidance capability when the vehicle was on the back side of the Moon and as a backup in the unlikely failure of the radio guidance system. Both the LM and the CM were provided with onboard computers of an unusual and advanced (for that time) design that provided a high degree of reliability. These computers were hard-wired to solve the equations representing the orbital motions of the vehicles during the rendezvous operation as well as in all the other phases of the mission.

The lunar orbit rendezvous technique requires that the LM take off from the Moon and rendezvous and dock with the CM that is in orbit around the Moon. At the time, other engineers in the Aerospace Mechanics Division at Langley and I were deriving the rendezvous equations, we were unaware that the exact solution of these equations had been obtained over two centuries ago by famous mathematicians, including Carl Frederich Gauss, Joseph-Louis Lagrange, and Johann Heinrich Lambert. In fact, the equations for determining the orbit of a body to go from one given point in space to another given point with a specified transfer time are known as Lambert's equations. As pointed out previously, these equations cannot be solved in closed form, but the early mathematicians had derived iterative solutions to solve the equations to any desired accuracy. Such iterative solutions, improved by modern developments, were programmed into the computers used in the Apollo mission. Inertial platforms used in conjunction with radar equipment were used to measure the relative positions of the vehicles. Sextants operated by the astronauts were used to determine the location of the vehicles with respect to the Earth, Moon, and other reference objects. Thus the rendezvous navigation was performed in a highly sophisticated manner, taking into account all the gravitational influences of nearby heavenly bodies and allowing accurate calculation of rendezvous trajectories of any length or orientation.

The same equations and navigational equipment were used in all phases of the Apollo mission, such as insertion into translunar orbit, midcourse corrections in all phases of the mission, insertion into lunar orbit, and so on. Many of these mission phases required taking into account gravitational influences of the Sun, Earth, and Moon. In addition, the locations of over 50 navigational stars, as well as the corrections to the position of the Earth and Moon when using the sextant to track the horizons, rather than the centers of these bodies, were all programmed into the Apollo computers. In using these data, the astronauts were required to punch into the computer on a keyboard the data obtained in celestial readings. The computer would then automatically solve the equations to obtain the present and future positions of the vehicle and its deviation from the planned trajectory.

One young engineer in my division, Robert Collins, had learned enough in his college studies to know of Lambert's equations. He devised an iterative technique of solution, using the Langley computer complex, to solve the rendezvous problem using Lambert's equations. This solution brought the possibility of an exact solution to the attention of Langley engineers but was too late to influence the Apollo guidance system. The experience gained in the early simulation studies proved very helpful to the Langley engineers who later joined the Space Task Group and took part in the actual design of the Apollo system. For example, Walter J. Russell, who operated a small analog computer in the Langley rendezvous studies, was later placed in charge of all analog computer equipment at the Johnson Space Center. John Mayer, one of the Langley engineers who participated in the lecture series conducted by Henry Pearson, was later in charge of all digital computing equipment at the Johnson Space Center. John M. Eggleston, who made studies of optimal rendezvous at Langley, participated in the design of the Apollo control system and held important administrative positions at the Johnson Space Center.