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DYNAMIC STABILITY OF SPACE VEHICLES

Volume IX - The Effect of Liftoff Dynamics on Launch Vehicle Stability and Control

by L. C. Engbrenghof

Prepared by
GENERAL DYNAMICS CORPORATION
San Diego, Calif.
for George C. Marshall Space Flight Center

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Volume IX - The Effect of Liftoff Dynamics on Launch Vehicle Stability and Control

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

FOREWORD

This report is one of a series in the field of structural dynamics prepared under contract NAS 8-11486. The series of reports is intended to illustrate methods used to determine parameters required for the design and analysis of flight control systems of space vehicles. Below is a complete list of the reports of the series.

Volume I	Lateral Vibration Modes
Volume II	Determination of Longitudinal Vibration Modes
Volume III	Torsional Vibration Modes
Volume IV	Full Scale Testing for Flight Control Parameters
Volume V	Impedence Testing for Flight Control Parameters
Volume VI	Full Scale Dynamic Testing for Mode Determination
Volume VII	The Dynamics of Liquids in Fixed and Moving Containers
Volume VIII	Atmospheric Disturbances that Affect Flight Control Analysis
Volume IX	The Effect of Liftoff Dynamics on Launch Vehicle Stability and Control
Volume X	Exit Stability
Volume XI	Entry Disturbance and Control
Volume XII	Re-entry Vehicle Landing Ability and Control
Volume XIII	Aerodynamic Model Tests for Control Parameters Determination
Volume XIV	Testing for Booster Propellant Sloshing Parameters
Volume XV	Shell Dynamics with Special Applications to Control Problems

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1/INTRODUCTION

Liftoff dynamics concerns the motion of a rocket vehicle while in the vicinity of its launch site. For its dynamic analysis both rigid body and elastic motions are investigated. The study begins at engine ignition and ends when the rising vehicle clears all launch site facilities that could constitute a flight path constraint. Engine thrust, winds, launcher restraints, umbilical disconnects, and ducts are the forcing functions for the elastic and rigid body motions. Launcher structures, umbilical towers and booms, silo or tube walls and covers, ducts, and tubing provide obstructions that could constrain the vehicle flight path.

Liftoff dynamics is analyzed to evaluate the possibility of a mishap due to some incident during launch. The four primary mishaps, in descending order of importance, are:

1. Destruction of the vehicle while on the launch site.
2. Destruction of the vehicle at a safe distance from the launch site.
3. Damage to the vehicle which would compromise mission objectives.
4. Excessive damage to the launch site.

Of lesser import but nevertheless a consideration in liftoff dynamics studies is the attainment of the highest value of launch availability* based on ground wind restrictions, consistent with cost and safety.

Liftoff motions ordinarily do not produce severe vehicle design constraints. Therefore, liftoff problems are usually subordinate to other flight phase problems when airborne systems are designed. The airborne system parameter variations used in the past to solve liftoff dynamics problems include: 1) flight control system activation time, 2) engine thrust vector angular alignment at liftoff, 3) engine ignition sequence, for multiengine vehicles, and 4) thrust buildup time histories, for liquid propellant vehicles.

The primary function of the launch site facility is to provide ground-supplied services to the airborne systems. Some of these services are needed right up to the instant of liftoff, since their removal is a commitment to flight. To some degree, therefore, launch-site-induced vehicle loads and flight path constraints are inevitable. Launch site parameter variations used to solve liftoff dynamic problems include: 1) removal of all nonessential hardware that might offer a flight path constraint, 2)

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*Launch availability is the ratio, expressed as a percentage, of days it would be safe to launch over days in a given period. The period of interest could be an entire year but more often is a season or sometimes a given month.

specification of acceptable retraction times for umbilical booms and other moving parts, and 3) specification of force-time histories of launcher constraints or of "pop-up" devices in the case of underwater tube-type launchers.

Even if the vehicle and site facility design requirements are met, high wind velocities in critical directions could still cause liftoff dynamics problems. The solution here is to specify ground wind restrictions. For some missions, however, maintaining a predetermined launch schedule is of critical importance and may influence the choice of vehicle. Severe ground wind restrictions thus may reduce the usefulness of a particular vehicle.

2/STATE OF THE ART

Investigators in early rocketry were interested in liftoff dynamics only to the extent of establishing the vehicle flight path and keeping the angle of attack small until aerodynamic stability was achieved. The vehicles were propelled by gunpowder. The launch site facilities usually consisted of a stick or pole set in the ground. Clearance with ground equipment was assured by a judicious arrangement of the launch site.

The first work in stabilization other than aerodynamic stability was performed in England in 1846 by William Hale. His spin-stabilized rockets required only a simple launch site; collision during liftoff was not of much concern. In 1926, with the advent of liquid-propellant rockets first launched by R. H. Goddard, launch complexes became more elaborate. Failures due to collision between the vehicle and launch site structures occasionally occurred. Flight path control, and in some cases vehicle stability, was achieved by thrust vector angular changes.

Launches of the more intricate liquid-propellant rockets such as the A-3 (the early model of the V-2) in 1938 and the V-2 in 1942 did not present the liftoff problems of today's larger vehicles. A single-engine vehicle, the V-2 rocket was unrestrained and rose off the launch pedestal when the thrust exceeded the weight.

The multiengine liquid-propellatn launch vehicle led to the concept of the present-day holddown launcher. In the event that one or more engines fail to attain full thrust, it is usually advantageous to shut down the other engines and save the launch vehicle. An inherent disadvantage is that the thrust-level variations between engines as well as the holddown mechanism introduce forces and moments on the vehicle. The additional support structure often presents flight path constraints.

The multistage vehicle with its complex payloads further complicates the launcher facility. To deliver ground-supplied services to these upper stages, umbilical towers and booms are often necessary. Extraction of these umbilicals occasionally introduces loads of sufficient magnitude to warrant their inclusion in liftoff dynamics analysis. Of much more concern are the flight path constraints that these towers and booms produce.

Present-day launch vehicles are often required to perform more and more complex missions as their useful life is extended. This increased mission complexity is frequently accomplished by adding more upper stages (more umbilicals) or increasing the weight of existing upper stages. These modifications not only increase the total vehicle weight at liftoff but they usually increase the aerodynamic forces that a given ground wind velocity will apply. This reduced thrust-to-weight ratio and increased wind force leads to more critical liftoff dynamics problems.

While surface launch sites were progressing toward their present complexity, underwater launch sites using pop-up launchers were also under development. For these launches compressed air or a gas generator is used to eject the vehicle from a canister. Engine ignition and powered flight take place after the vehicle clears the surface of the water. Collision with launcher facilities does not appear to be a serious problem; however, loading due to ejection gas and the resultant bubble is a matter of concern.

3/DESIGN CRITERIA

The design of a launch system, including site facilities, involves resolving all overlapping constraints on properties such as vehicle structural strength and flight control response, so that mission objectives are met within a given budget. Liftoff dynamics problems seldom present constraints that seriously conflict with those produced at other flight times. In addition, many liftoff problems can be eliminated through the proper design of site facilities. Therefore the design criteria for liftoff dynamics are often presented in the form of specifications and mission requirements. The specifications define the acceptable maximum or minimum values of critical vehicle parameters. Adherence to these vehicle and launcher parameters assures that any system design solving liftoff dynamics problems will not produce a vehicle failure at liftoff or later in flight.

The design criteria specifications and requirements contain:

1. Maximum launch vehicle loads: lateral, longitudinal, and local loading at launcher attach points.
2. Maximum launch vehicle rotational rates and displacements, in pitch, yaw, and roll.
3. Maximum loading on launch facility elements (umbilical booms, umbilical disconnects, ducts, etc.).
4. Minimum launch availability.

The designer is constrained by at least one additional criteria: there shall be no destructive interference between the vehicle and launcher. It is desirable, of course, to achieve a system design that will deny any collision between the launcher and rising vehicle. In many cases this is not possible and it is left to the designers' intuition to determine which possible collisions could be defined as destructive interference.

4/ANALYSIS

Liftoff dynamics encompasses three distinct periods of time: 1) thrust buildup, 2) liftoff, and 3) post-liftoff (launch drift). Normally, each of these periods is treated by a separate analysis, with the results of previous flights used as initial conditions. Each will be investigated in detail in this section. Before starting this examination, however, a brief look at some general design and analysis considerations is in order.

4.1 HARDWARE REQUIREMENTS

Launch sites and vehicles vary substantially from program to program as required by mission requirements. Rarely does a program warrant the design of a completely new vehicle and launch site. Instead, most programs try to meet mission objectives within a fixed cost by using existing launch vehicles and sites. Regardless of the extent of design freedom, the liftoff analyses remain basically the same. The permissible range of parameter variations becomes restricted when a program requirement allows only minimum modifications to existing hardware.

4.1.1 LAUNCH SITE REQUIREMENTS. Launch sites are categorized by location as surface or subsurface. The subsurface type of launch site, underwater as well as underground, has an advantage over the surface type. The vehicles are not subjected to ground wind disturbances until they are clear of all obstacles.

Underwater launch sites employ the tube-type or pop-up launcher wherein the vehicle is ejected from a tube. Engine ignition and powered flight do not take place until after the vehicle clears the water surface. The major problem is the loading due to the ejection gas and the resultant bubble (see Reference 1). Analysis of the vehicle parameters during ejection properly belong in the field of hydrodynamics and will not be covered in detail in this monograph.

4.1.1.1 Launchers. Launchers are classified functionally as either holddown or free. The holddown launcher restrains the vehicle until the launch control computer receives an indication that all engines have attained preselected thrust levels. This feature is especially useful for launching multiengine, liquid propellant boosters since it allows engine shutdown if the prescribed thrust levels are not achieved. Normally this type of abort will not damage either the vehicle or the launch site. Some holddown launchers release the vehicle using devices such as explosive bolts or swiftly withdrawing pins. Another type of holddown launcher uses a restrained release, restraining the vehicle vertical motion during the first few inches of rise. Figure 1 shows a typical restraining type of holddown launcher.

The free type of launcher presents no restriction to vehicle vertical movement. The vehicle is free to rise when thrust exceeds weight. For solid propellant vehicles

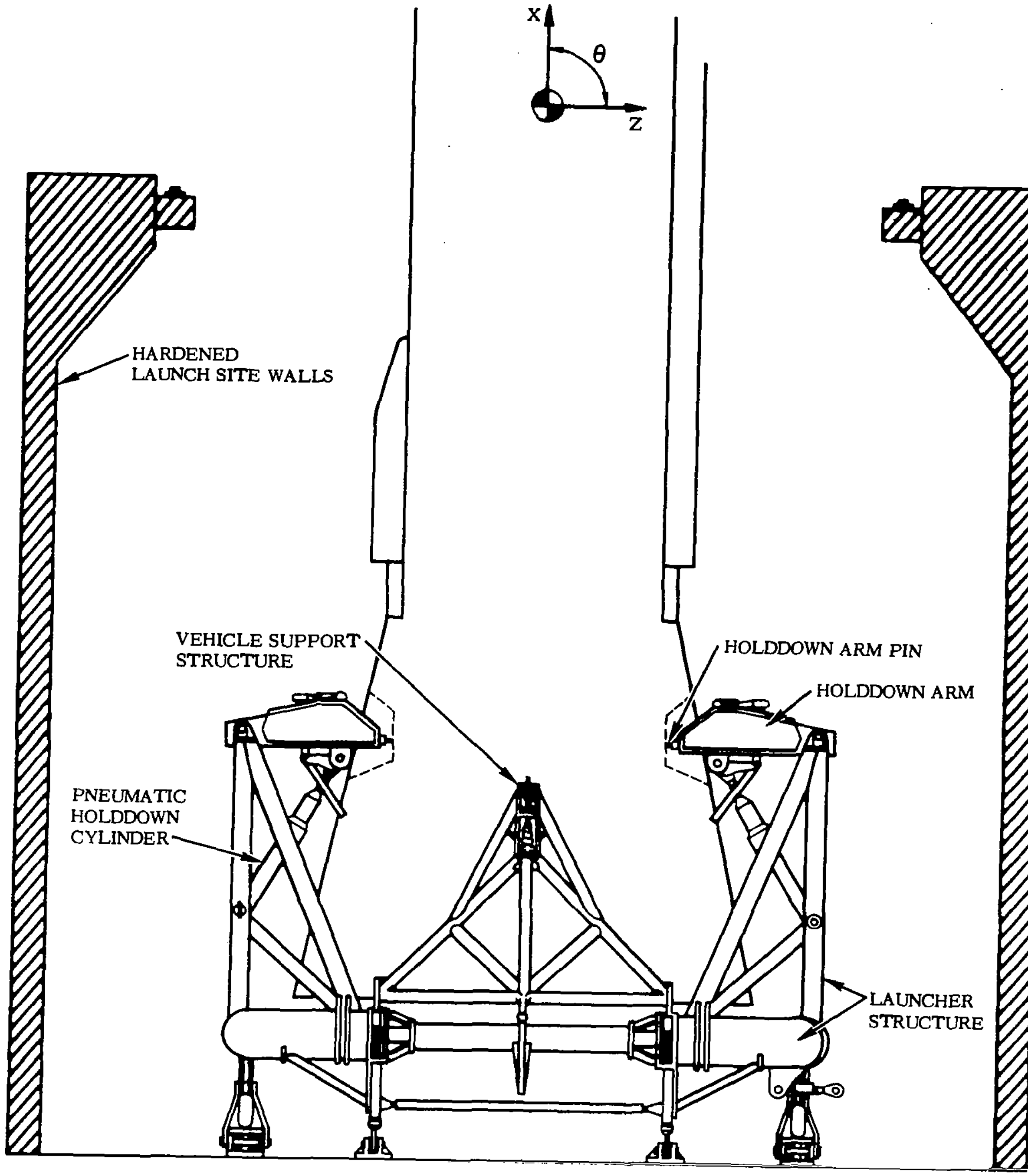


Figure 1. Restraining Type of Holddown Launcher

and single-engine liquid propellant vehicles this is acceptable. However, for multi-engine liquid propellant vehicles this free type of launch is usually not acceptable except in the case of a military weapon system.

Multiengine boosters often will not have sufficient thrust to rise when one engine fails. The resulting forces, however, may be sufficient to rotate the vehicle off the launcher. This results in destruction of the vehicle as well as considerable site damage. In the case of solid propellant vehicles, engine shutdown is achieved by rupturing the engine case and "considerable damage" to the pad is unavoidable.

4.1.1.2 Utility Structures. The utility structures at a launch site comprise the basic systems for handling, positioning, and servicing the vehicle. Such structures that cannot be removed from the immediate launch area before liftoff are built low and as far away from the launcher as practical. Some services, however, must be maintained even as the vehicle rises. Since these services often are required for the upper stages, they are delivered by means of umbilicals supported by towers and booms. These umbilical towers and booms offer the most critical flight path constraints.

4.1.2 LAUNCH VEHICLE REQUIREMENTS. In addition to the type of propellant, the number of first-stage engines, and the number of stages, there are other vehicle characteristics that may be important to liftoff analysis. These characteristics, which should be examined early in the analysis, include: 1) aerodynamics, 2) maneuvers, 3) thrust, and 4) inertia properties.

4.1.2.1 Aerodynamics. A stationary or slowly rising vehicle presents a large projected area to a wind acting horizontally to the ground. Generally this aerodynamic or wind force produces the largest flight path dispersion encountered in liftoff dynamics studies. The aerodynamic moment acting on the airborne vehicle at any instant is:

$$M_{aero} = \frac{1}{2} \rho V_W^2 S C_{N/\alpha} \alpha \ell_{aero} \tag{1}$$

where

ρ = air density, $slugs/ft^3$

V_W = equivalent wind velocity applied at the center of pressure, ft/sec

S = vehicle reference area, ft^2

$C_{N/\alpha}$ = aerodynamic normal force coefficient for a given angle of attack, rad^{-1}

α = instantaneous angle of attack, rad

ℓ_{aero} = aerodynamic moment arm, ft

For the altitude range of interest the air density (ρ) can be considered a constant with a magnitude on the order of 2.38×10^{-3} slug/ft^3. The angle of attack (α) for a 40-knot horizontal wind would vary from 90 degrees at ignition to about 55 degrees for the liftoff analysis of a vertically rising Saturn V. For this particular vehicle this change in angle of attack reduces the aerodynamic normal force coefficient ($C_{N/\alpha}\, \alpha$) from 0.8 at ignition to 0.6 after 6 seconds of flight. Since the value of the aerodynamic normal force for these large values of angle of attack is not very accurate, $C_{N/\alpha}\, \alpha$ is usually treated as a constant.

Because surrounding structures shield some of the vehicle from the wind, the entire side area is not the true vehicle reference area (S). This same shielding invalidates the use of the centroid of the side area in determining the center of pressure of the wind force and hence the aerodynamic moment arm (ℓ_{aero}). To complicate this problem further, the shield effect varies with wind direction and vehicle height. Usually the analyst will ignore the effect of a surrounding structure unless it is very close to the vehicle, such as the protective walls of a hardened launch site (see Figure 1).

Another aerodynamic consideration is the wind profile, the variation of wind velocity with respect to height above a flat ground. Some factors that affect this profile are the terrain, vegetation, and thermal gradient. As explained in the Handbook of Geophysics (Reference 2), the analyst has a choice of expressions that approximate this change in wind velocity with altitude for the first 300 feet. These expressions vary from a Simple Power-Law Wind Profile to an extremely complex Extended Logarithmic-Law Wind Profile. The Simple Power-Law Wind Profile shown in Figure 2 usually is sufficiently accurate for liftoff dynamics studies. For simplicity the normalization height is customarily chosen as the height of the site anemometer. The wind profile and the wind shielding of the surrounding structure tend to raise the center of pressure, thus decreasing the vehicle aerodynamic stability.

The third aerodynamic consideration is the handling of wind gusts. For most launch vehicles the period of interest is short (6 seconds). Thus long-duration ground wind gusts conservatively can be handled by using the actual peak wind speed (steady-state plus gust) as a steady-state wind velocity in the analysis. If this is not practical, such as for the analysis of large, slow rising vehicles, a wedge-shaped gust should be added to the measured steady-state wind velocity. This gust should have a rise and decay time of about 2 seconds and a maximum velocity of a three-sigma gust for the launch site at a scheduled launch time of year. This superimposed gust complicates the mathematical model and all but eliminates hand calculations for solving associated liftoff problems.

The final aerodynamic characteristic to be examined is a peculiarity of anemometers. Anemometers measure wind velocity; however, their output is somewhat filtered since they cannot respond to short-period wind peaks. In the case of the Bendix AN/GMQ-11 anemometer, a multiplication factor of 1.2 is used to convert recorded peak wind velocity to actual peak wind velocity.

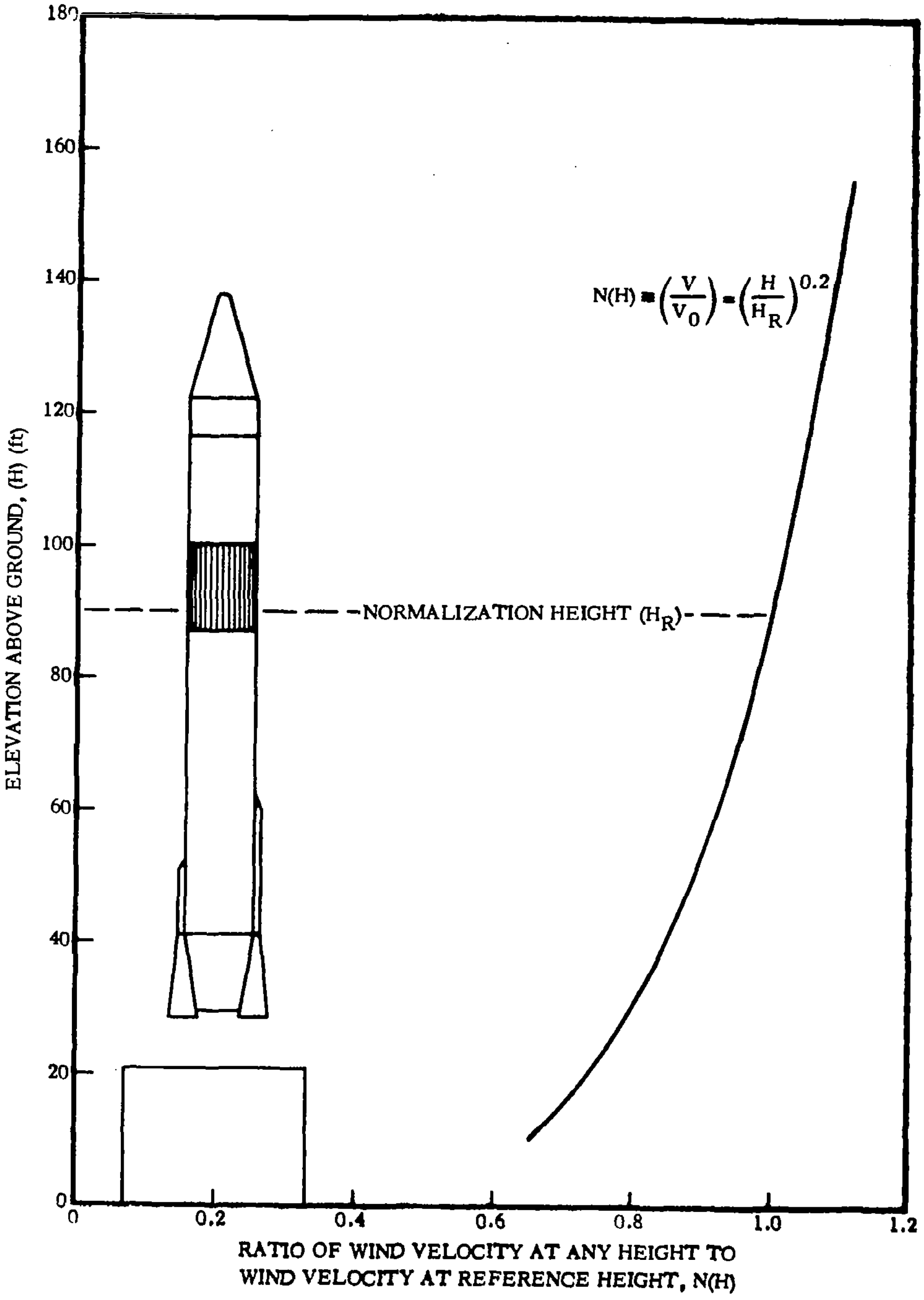


Figure 2. Simple Power-Law Wind Profile

4.1.2.2 Maneuvering. It is usually advantageous to make any necessary programmed pitch, yaw, and roll maneuvers as early in flight as possible. The low values of vehicle velocity make large attitude changes possible without producing destructive aerodynamic loads. Early pitch and yaw maneuvers also protect the launch site should the vehicle be destroyed shortly after liftoff. Low-level pitch-yaw movements, however, can cause considerable site damage due to flame impingement. They can also produce liftoff clearance problems. Therefore pitch or yaw maneuvers are not performed near the launch site.

While on the launch pad the vehicle major axis ordinarily does not coincide with the final flight path. Therefore a roll maneuver is required. It is possible that this roll reorientation could provide additional clearance problems for a vehicle with fins, pods, or other protrusions. If this maneuver in itself creates such problems it should be delayed until the vehicle is above all utility structures.

Even in the absence of programmed reorientations a certain amount of vehicle attitude changes will occur during liftoff. Most vehicles are aerodynamically unstable, requiring attitude control using a flight control system. This control system or autopilot must be activated before the vehicle attitude and rate errors become large. Activation before the vehicle leaves the launcher, especially a restraining type of holddown launcher, is usually not practical because launcher/vehicle interaction may result in an instability and large loads. As a consequence, autopilot activation normally takes place during the liftoff phase of flight.

When the autopilot is activated it produces control torques that eliminate the vehicle attitude and rate errors. Thus the autopilot produces vehicle maneuvers and also potential liftoff dynamics problems. (See Reference 3 for a thorough discussion of stability.) Normally these control torques are generated by angular changes in the engine thrust vectors. Jetivators, vanes, secondary gas injection, gimbaled engines, and gimbaled nozzles are the most common methods of changing the thrust vector. Except for secondary gas injection, each of these methods requires motion of vehicle hardware and could create additional liftoff clearance problems.

4.1.2.3 Thrust. Small variations in engine thrust produce large disturbing forces on the vehicle. The first of these perturbations occurs at ignition. A rocket engine does not produce full thrust instantaneously. This time history of thrust increase as well as the ignition sequence, in the case of multiengine boosters, is termed thrust buildup. Figure 3 is the thrust buildup for two extreme MA-3 booster engines, B1 and B2, and a more nominal sustainer engine. For the case presented, liftoff occurs between 1.4 and 1.6 seconds when the overturning moment due to booster engine thrust unbalance is greatest. Note the 200-millisecond ignition delay between any two engines. While this delay increases the magnitude of the overturning moment, it reduces the longitudinal loading on the vehicle due to ignition shock. The 200 milliseconds is not a nominal value; however, some delay should be applied to the start-up sequence for clustered engines. The variations in thrust can also cause longitudinal

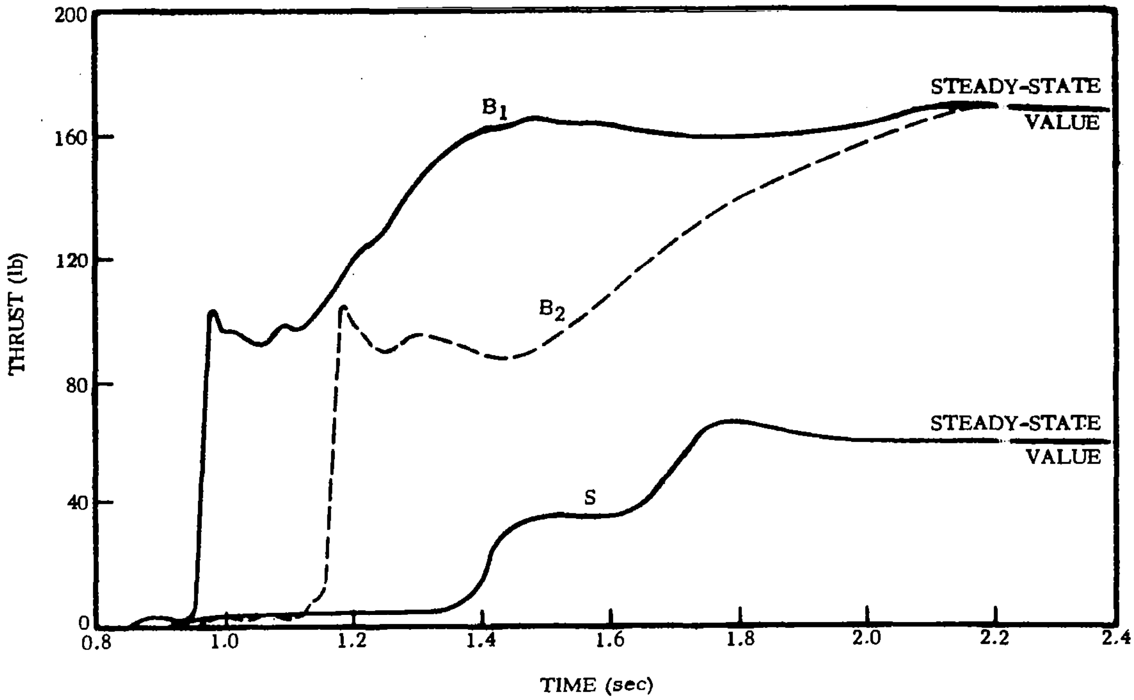


Figure 3. MA-3 Rocket Engine Thrust Buildup Characteristics

oscillations that may couple with the launcher. These oscillations may also be caused by other systems such as the tank pressurization or ground stabilization. These oscillations are discussed in detail in Reference 4.

After the thrust buildup transients have died out, the full-thrust level for rocket engines still may have some variation. When engines are used in clusters this thrust level variation can produce a disturbing moment if each engine thrust vector does not pass through the vehicle center of mass. The specification for engine thrust tolerance for the MA-5 propulsion system is ±3%.

In addition to the disturbing forces caused by unequal engine thrust, the engine thrust vector could produce additional perturbations due to misalignment. Engine fabrication tolerances, mounting tolerances, changes in temperature after ignition, and material compliance under load can produce this thrust vector misalignment. For the MA-5 propulsion system the total thrust vector misalignment could be nearly 0.75 degree.

4.1.2.4 Inertia Properties. During liftoff propellants are consumed, changing the vehicle mass and moments of inertia. Holddown launchers accentuate these changes because of the delay between engine ignition and vehicle liftoff. However, changes in mass moments of inertia and centers of mass seldom reach magnitudes where they must be included in liftoff dynamics analyses. On the other hand, the high propellant flow rates for large vehicles such as Saturn V produce changes in total mass that cannot be ignored. Figure 4 shows the change in vertical acceleration due to propellant consumption for a Saturn V vehicle. Except for those analyses concerned with short liftoff times, a significant change in vehicle mass cannot be ignored.

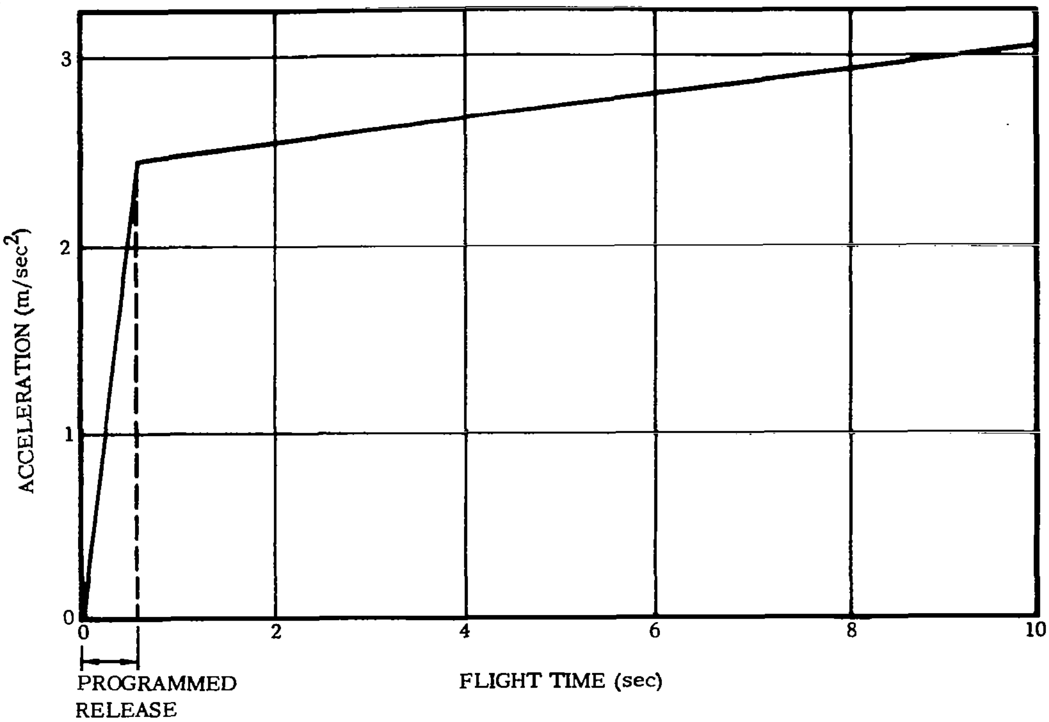


Figure 4. Liftoff Acceleration, Saturn V

4.1.2.5 Other Disturbances. In addition to aerodynamic characteristics, low-level maneuvers, engine thrust anomalies, and mass changes, the airborne vehicle is subject to other self-generating disturbances. Each should be examined. Many will produce effects so small that they can be considered negligible.

During erection in the launcher the vehicle is usually aligned with the local vertical. However, the vehicle is subjected to many environmental changes between the times of this alignment and actual launch. Chief among these changes is the material deformation due to propellant loading (for liquid propellant boosters) and wind loads. A 0.5-degree misalignment at liftoff is not impossible. This vertical alignment at liftoff establishes the flight path reference while the vehicle is in the vicinity of the launch site.

Flight control system sensor null offset errors produce flight path reference errors. For vehicles using rate integrating and rate gyroscopes, these errors are on the order of 0.015 degree and 0.12 degree per second, respectively. Often the effect of gyroscope null offset errors can be neglected.

Most vehicles are not entirely symmetrical, producing a center-of-mass offset from the vehicle centerline. For those vehicles with engines aligned along the vehicle centerline this center-of-mass offset will produce a small moment. During liftoff, when the vehicle is fully fueled, an offset greater than 0.5 inch is uncommon.

For those vehicles using liquid propellants the major portion of the total weight at liftoff is only partially restrained. Propellant sloshing motion sometimes results in vehicle behavior significantly different from what it would be if these masses were rigid. Propellant sloshing frequencies higher than the first mode are seldom considered. The popular methods of simulating propellant motions are through the use of the pendulum analogy and the spring-mass analogy. Because the flight regime of interest for liftoff dynamics problems is brief, the inertia properties of the sloshing masses are usually considered constant. The effects of propellant sloshing can often be ignored.

Many booster vehicles exhaust onboard gases while in flight. Notable in this category is the exhaust gas from an onboard turbine. These exhaust gases produce a disturbing force on the vehicle. For instance the turbine exhaust for the MA-5 booster engine system produces a force of 1200 pounds. Indiscriminate exhausting of this gas can produce large moments.

4.2 PROBLEM INVESTIGATION

Liftoff dynamics concerns itself with the stability and flight path of the vehicle starting at engine ignition and continuing until the vehicle is above all launch site structures. The early flight phases of this study (ignition and liftoff) are closely associated with the determination of structural loads. In actual practice a single study is often sufficient for evaluating vehicle loads as well as vehicle dynamics. Structural loading at engine ignition and while the vehicle is in the launcher is discussed in Reference 5.

Once the proper configuration of vehicle and launch site have been specified, the next analysis step is to determine what, if any, liftoff dynamics problems exist. Because liftoff dynamics usually does not produce prohibitive constraints on hardware design, most liftoff analyses consist of nothing more than a cursory examination showing that no problem could exist.

4.2.1 COMBINING DISTURBANCES. Ordinarily the disturbances that influence liftoff dynamics are mathematically combined by direct summation, especially for the initial examinations used to decide if a problem exists. When using direct summation to determine a worst case, each disturbance is applied so it produces its maximum influence in the most critical direction. If the "worst case" approach indicates that a problem could exist, it is often desirable to use statistical procedures to formally predict a probable worst value. If the disturbances are normally distributed, independent variables, then the statistical combination can be accomplished by root-sum-squaring. With the exception of disturbances due to the wind, and disturbances with known directions such as turbine exhaust, the assumption of independence and normal distribution for liftoff dynamics disturbances does not lead to serious errors. If the root-sum-squaring method is used the dynamics effects of the wind and other biases are added numerically to the combined total of the other disturbances.

A typical wind restriction determination would use a form of the preceding. For this, those disturbances that are basically normally distributed would be combined by statistical methods. Then those disturbances that have a normal direction would be added vectorially with the statistical values to give a worst-predicted vehicle motion, without winds. Then the wind necessary to cause a launch problem is determined, and the vehicle is restricted to wind velocities less than critical.

A third method of combining the effects of the disturbances is by Monte Carlo (see Reference 6). Using this method the disturbances do not have to have normal distribution. Any distribution can be managed. This method does, however, require numerous repetitive solutions of the liftoff dynamics equations. Therefore Monte Carlo requires the use of a high-speed digital computer.

4.2.2 METHOD OF SOLUTION. A detailed analysis of vehicle dynamics consists of a complete set of dynamics equations of motion with appropriate control loops. The equations of motion should be written referenced to the true vertical. These differential equations must then be solved as a function of time, recording time histories of all variables of interest. These equations may be written in three dimensions (roll, pitch, and yaw) although this does not generally improve the accuracy/complexity ratio over single-plane studies.

Seldom will the solutions to liftoff dynamics problems be enhanced by the inclusion of vehicle flexibility in the equations of motion. In the case of clearance studies a small arbitrary margin of clearance is maintained to account for the flexibility of the vehicle and launch structure. The only times that flexing is included in the analyses are: 1) when the interaction of a vehicle and a restraining type of holddown launcher is studied, or 2) when a control loop in the vehicle or launcher is suspected to be sensitive to vehicle or launcher modes.

The design engineer usually has three methods of simulating the dynamics of the vehicle system: analog, digital, or a hybrid combination of both. If all-analog is used, then since the disturbances are uncorrelated the equations of motion for each disturbance will have to be simulated, resulting in a rather large simulation. If it is impossible to simulate and record these equations simultaneously, multiple runs will be required. Each run will contain the effect of one or more disturbances. Care should be exercised in maintaining repeatability between runs. Utilizing recorded values, usually x-y plotter values, of each parameter, the total drift can be calculated as outlined in Section 4.2.1. Analog simulations may allow more human error to arise during processing of the data but will allow for more versatility and for choosing various parameters during the run. The repetitive operation feature of current analog equipment is also advantageous.

Use of a digital computer, although some accuracy may be lost in numerical integration techniques, eases the cumbersome task of processing the data. More equations could be required if the effects of the uncorrelated disturbances are solved simultaneously. For example, recording nominal-plus-eight disturbances for a single-plane analysis of translation, rotation, and control deflection requires that 27 differential equations be solved.

Of course, a hybrid simulation incorporates the advantages of both systems. Integration and problem solving are accomplished on the analog while simulation control, function generation, recording, and processing are performed by the digital.

4.3 INDIVIDUAL STUDIES

4.3.1 THRUST BUILDUP. Vehicle loads due to engine ignition will not produce vehicle rigid body motions when holddown-type launchers are used. The vehicle is held from moving until thrust buildup is essentially complete.

The motion of a vehicle launched from a site employing a free launcher, however, begins with engine ignition. Engine-starting transients can produce vehicle rotation before the vehicle has developed sufficient thrust to rise. The magnitudes of these angular displacement and rate errors at liftoff become the initial conditions for the liftoff phase of flight. In addition to finding these initial conditions, thrust buildup analyses may be needed to determine if this prerise movement could cause the vehicle to fall off its support structure. Improper contact between the vehicle and launcher could cause considerable damage.

The disturbances that contribute to vehicle dynamics during thrust buildup are: 1) engine thrust differential, in the case of multiengine boosters, 2) engine thrust vector misalignment, 3) ground winds, 4) center-of-mass offset, 5) exhaust gases, and 6) vehicle alignment. The possibility exists that thrust buildup could produce a dynamics problem. One obvious but not too practical solution would be to replace the free launcher with a holddown launcher. Other, less costly solutions may exist. The angular alignment of an engine or engines could be altered to counter known moments such as those produced by the engine start sequence, center-of-mass offset, or turbine exhaust gases. The engine start sequence could be varied, however. As a rule all engines in a cluster should not be started simultaneously. Finally, the time histories of thrust buildup can be changed. The thrust buildup characteristics for a liquid propellant vehicle using an "inert lead" start are quite different from those using a dry start. An inert lead start is accomplished by injecting an inert compound like lithium cloride into the thrust chamber instead of fuel at engine ignition.

For an Atlas vehicle launched from a free launcher, rigid body attitude errors of 0.5 degree and rate errors of 1.0 degree per second at the start of the liftoff flight phase are not impossible.

4.3.2 LIFTOFF. Liftoff is defined as that flight phase beginning with first vertical motion and ending when all holddown mechanisms are released or when the vehicle is clear of the launcher. Both vehicle-to-launcher clearance and vehicle initial conditions for post-liftoff studies are products of liftoff analyses.

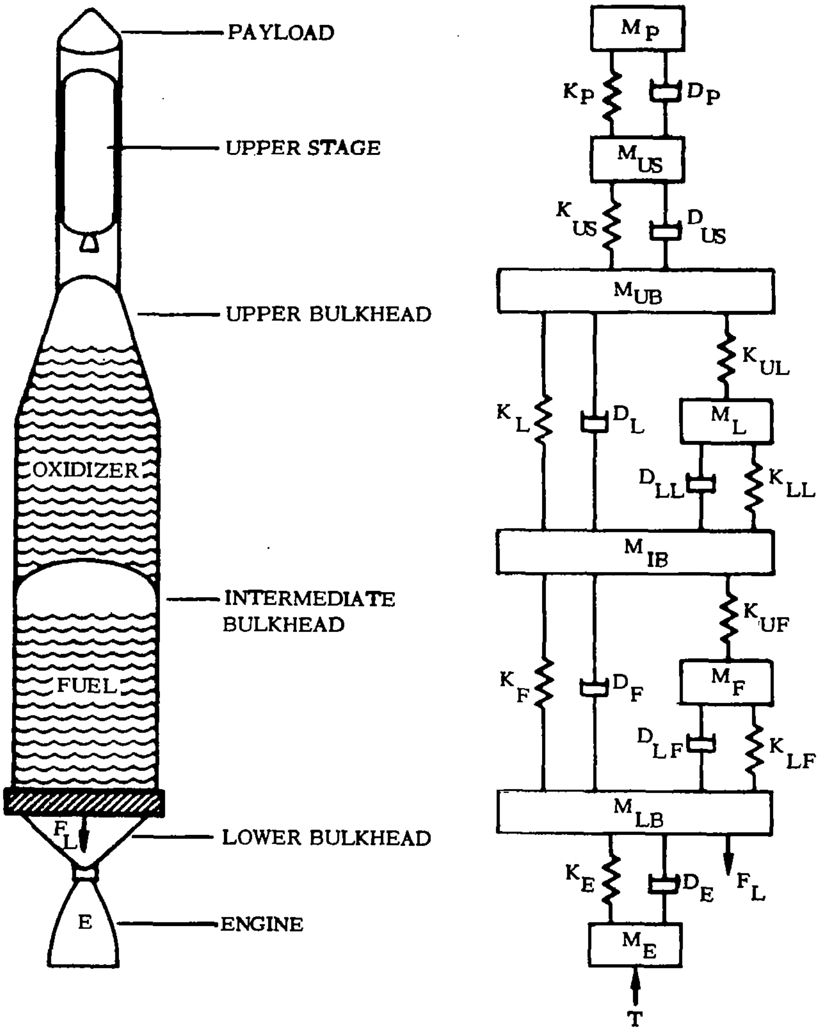
Vehicle dynamic analyses during liftoff include the effect of the launcher force in addition to all the usual disturbances: wind, thrust misalignment, etc. The launcher forces greatly complicate the analysis of liftoff from a restraining-type holddown launcher. In some cases the mathematical description of a flexible vehicle model, such as the one shown in Figure 5, is combined with the launcher dynamics equations to determine the forces between vehicle and launcher.

For the restraining type of holddown launcher the onboard flight control system or autopilot normally is not activated until after completion of the liftoff flight phase. Activating the autopilot while the vehicle is still partially restrained by the launcher could produce unnecessarily large vehicle-to-launcher loads. Since it is beneficial to activate the autopilot as early as practical, autopilot activation is often programmed to be simultaneous with the end of the liftoff phase. Thus liftoff analyses provide the initial conditions for the flight control system.

For nonrestrictive holddown launchers and for free launchers, autopilot activation customarily is programmed to occur during the liftoff phase. Clearance between the launcher and the vehicle, particularly any movable controls such as engine bells or aerodynamic surfaces, becomes critical shortly after autopilot activation. There is no simple rule of thumb that can dictate the optimum autopilot activation time with respect to alleviating clearance problems. Table 1 is a list of the lateral displacements of an engine bell exit plane at three vehicle heights for three autopilot activation times, measured as vehicle altitude. Note that for clearing obstacles at one foot of rise a late autopilot activation (9 inches) would be preferred. If, however, critical clearance occurred at two or three feet of rise, then early activation would be advantageous. These preferable activation times would be completely different for another launch vehicle or even another configuration of the same basic vehicle.

It is possible that a dynamics problem could exist during liftoff which could not be corrected merely by changing the time of autopilot activation. Sometimes the angular alignment of the engines is purposely biased to produce forces that counter directional disturbances such as turbine exhaust or unsymmetrical launcher forces. Another method of eliminating dynamics problems during liftoff is to change the constraining force-time history for restraining launchers. Small changes in the release characteristics, for restraining launchers, can change vehicle motions during liftoff.

4.3.3 POST-LIFTOFF. Post-liftoff is defined as that flight phase beginning when the vehicle is clear of the launcher and ending when it is above all launch site structure that could offer flight path constraints. In many reports this flight phase is called launch drift.



1. F_L IS LAUNCHER RESTRAINING FORCE

2. T IS ENGINE THRUST

Figure 5. A Spring-Mass Model of a Launch Vehicle

Table 1. Rocket Engine Exit Plane Translation

	One Foot Of Rise			Two Feet Of Rise			Three Feet Of Rise		
	Autopilot Activated At			Autopilot Activated At			Autopilot Activated At		
	1 Inch	4 Inches	9 Inches	1 Inch	4 Inches	9 Inches	1 Inch	4 Inches	9 Inches
Engine Translation (ft)	0.1158	0.0772	0.0143	0.1487	0.1401	0.1044	0.1645	0.1673	0.1530
Vehicle Translation (ft)	0.1100	0.1500	0.1500	0.1800	0.2600	0.3100	0.1950	0.3200	0.4150
Total Translation (ft)	0.2258	0.2272	0.1643	0.3287	0.4001	0.4144	0.3595	0.4873	0.5680

Note: The translations shown here are calculated values for a typical launch vehicle during a free launch.

If autopilot activation has not already occurred it most assuredly will early in the post-liftoff phase of flight. The two major reasons for studying this flight phase are: 1) to confirm that the autopilot can gain control of the vehicle following activation, and 2) to evaluate the clearance between the vehicle and the launch site structures. The sooner in flight that the autopilot is activated the greater the assurance that an aerodynamically unstable vehicle can be controlled. Control of unstable vehicles is achieved by applying a moment equal in magnitude but opposite in direction to the sum of the disturbing moments. The largest single disturbing force is normally the ground wind. For an aerodynamically unstable vehicle this force produces a translation in the downwind direction and a rotation such that the nose points downwind. If an angular change in an engine thrust vector is used to correct this rotation, this engine force also produces a downwind translation. Under certain conditions early autopilot activation, with its increased vehicle downwind acceleration, will produce more severe clearance problems than would the uncontrolled vehicle. Under these conditions a determination of the optimum autopilot activation time requires a detailed post-liftoff dynamics analysis.

In addition to the aerodynamic forces due to horizontal winds and vehicle transients due to autopilot activation, other disturbances are present during this post-liftoff phase. These disturbances include: 1) vehicle misalignment, 2) thrust misalignment and unbalance, 3) center-of-mass offsets, 4) flight control sensor nulls, and 5) exhaust gases. Excluding the effects of ground winds, the disturbance that produces the largest amount of vehicle drift during the post-liftoff phase of flight is vehicle vertical alignment. This alignment is the vehicle flight path reference until guidance corrections are made later in flight.

Besides the variations in vehicle parameters the launch site parameters are often varied to assure vehicle clearance. Figure 6 shows the trajectory of the skirt of an Atlas/Centaur vehicle for a 29-knot wind blowing straight toward the umbilical tower boom. Also shown is the umbilical boom retraction trajectory. For these conditions a minimum clearance with this boom occurs at 5.3 seconds when the boom is nearly vertical.

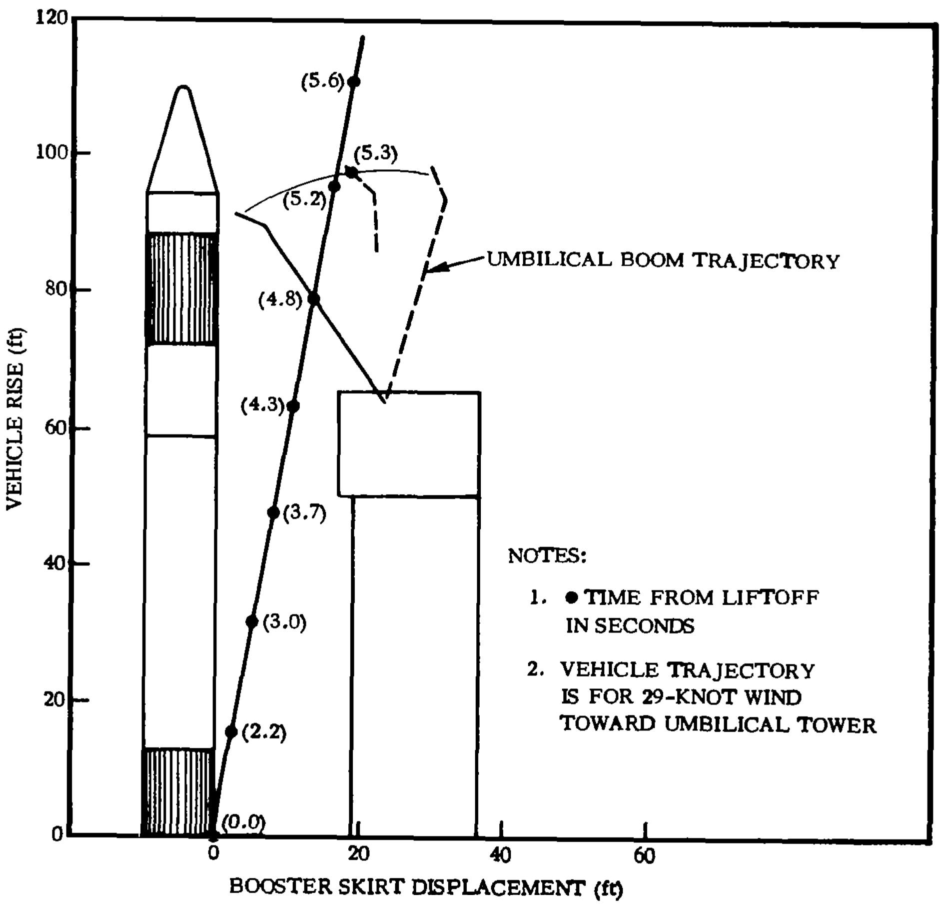
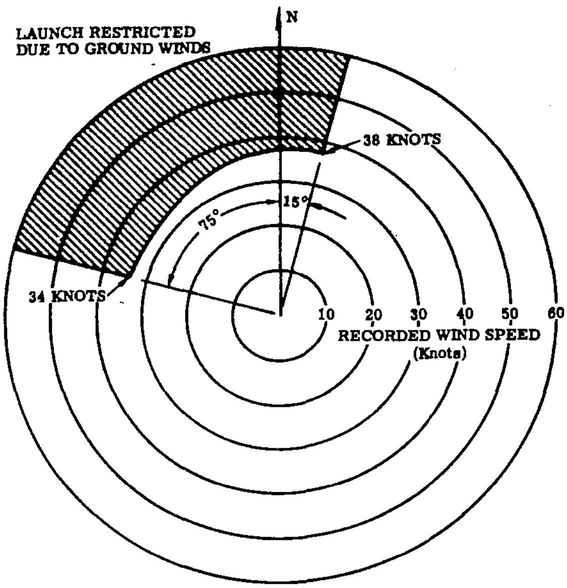
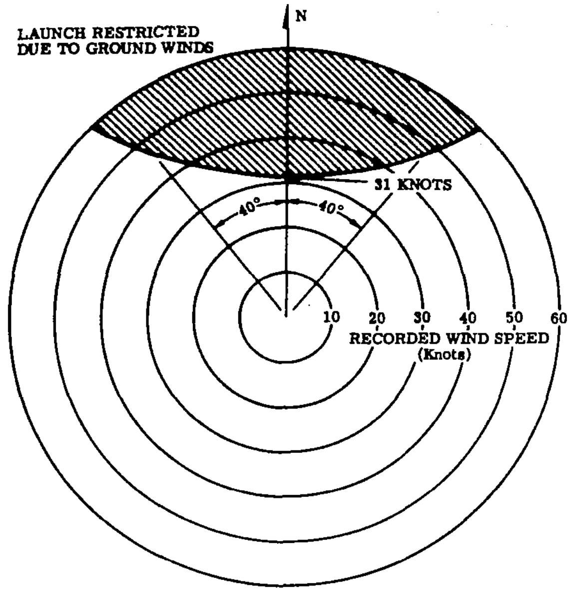


Figure 6. Clearance Between Launch Vehicle and Umbilical Boom

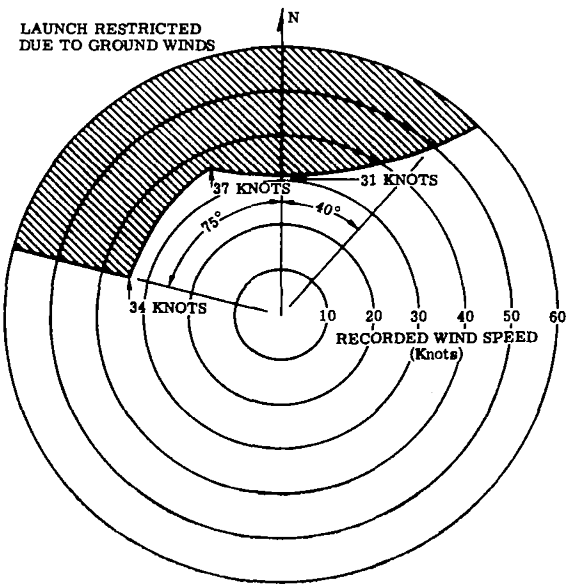
When all practical parameter changes for both vehicle and site facility have been analyzed clearance can be assured by imposing a ground wind restriction at launch. Figure 7 shows a typical wind restriction due to collision hazards. For this example the wind restrictions due the lower umbilical boom (7a) and the upper umbilical boom (7b) are combined to produce the total launcher/vehicle clearance (7c). Other



a. Lower Boom
Restriction



b. Upper Boom
Restriction



c. Total Restriction

Figure 7. Launcher/Vehicle Clearance Ground Wind Restriction

structures such as the tower were eliminated as potential collision hazards earlier in the study and are not included in this final wind restriction.

Launcher/vehicle clearance ground wind restrictions are combined with all other launch restrictions, such as those defined by vehicle loads, to determine the total launch availability for a given vehicle. As the launcher/vehicle clearance ground wind restrictions become more constraining the total launch availability is reduced. Low values of launch availability could eliminate the use of a vehicle for some missions. Therefore imposing a ground wind restriction should be avoided because of its effect on vehicle applicability.

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