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EFFECTS OF SYSTEM INTERACTIONS ON SPACE SHUTTLE LOADS AND DYNAMICS

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ABSTRACT

This paper describes how the unique configuration of the Space Shuttle during ascent causes a sensitivity to interactions among certain vehicle parameters. The paper discusses the balanced solutions that have been developed among factors that affect the structure, propulsion systems, aerodynamics, computer software, and other systems. The winged vehicle configuration with parallel external tank (ET) and solid rocket boosters (SRB's) results in a sensitivity to parameters such as wind azimuth and thrust dispersions. Examples are presented from the dynamic loads analysis of the lift-off and high dynamic pressure portions of flight that show how system solutions have been applied to interdisciplinary problems. The complexity of the Shuttle has resulted in the need for a close, interactive relationship among the technical disciplines. Some unique computational methods are also described.

INTRODUCTION

In developing the Space Shuttle, a balance had to be maintained between an assured structural integrity, minimum weight, and optimized operational flexibility as a launch vehicle. The ten years it has taken to develop the Space Shuttle, with ground and flight tests, have included unforeseen problems and setbacks; however, whenever complex interdisciplinary problems have occurred, balanced solutions have been found that have minimized any impacts in designing the Space Shuttle systems.

In dealing with these problems, certain capabilities in both technical and organizational areas have evolved. In technical areas, emphasis has been placed on the ability to deal with variables that affect vehicle dynamics and structural loads. These variables, such as propulsion characteristics, aerodynamics, and wind shears and gusts, have been defined to have nominal values and ranges of dispersion. Analysis methods and computer programs have been developed to rapidly assess the significance of changes to the data base. During the Shuttle development, some data matured early (e.g., Space Shuttle main engine [SSME] thrust build-up characteristics); some data matured in the middle of the development cycle (e.g., structural dynamics characteristics); and some data matured late (e.g., ignition overpressure from SRB's).

The principal interactions among vehicle systems and environmental parameters are shown schematically in Figure 1. The arrows show the directions of normal flow of design data. (When interdisciplinary problems occur, these data paths become interactive.)

The Shuttle program organization includes the NASA development centers, i.e., Johnson Space Center (JSC) and the Marshall Space Flight Center (MSFC) as well as the industrial contractors for the major vehicle elements and for system integration. These organizations took steps to deal with the interdisciplinary issues that surfaced during Shuttle development. Technical panels and ad hoc working groups were established to quickly identify problems that crossed technical disciplines. These panels proved effective in focusing resources on the problem areas and in rapidly bringing recommended solutions to the attention of program management. It was generally true that these solutions were not just aerodynamic solutions or structure solutions, but balanced vehicle system solutions.

In the sections that follow, three examples of dynamic interactions and the systems approach that was used to deal with them will be described. Two examples are taken from the lift-off event, which consists of interactions among propulsion characteristics, structural dynamics, and avionics software. The third example is taken from the high dynamic pressure event that occurs during boost (high q), with interactions among propulsion, aerodynamics, wind shears and gusts, flight control responses, and structural loads.

LIFT-OFF DYNAMIC LOADS - GENERAL COMMENTS

The lift-off dynamic loads event begins with the start signal to the three SSME's, and includes the occurrence of winds and gusts, the ignition of the two SRB's, and the sudden release of large forces and moments at the base of the vehicle. The dynamic loads at lift-off have resulted in design requirements for orbiter internal mass items, portions of the large ET, and the interface hardware between the orbiter and ET, and between the SRB's and ET.

The principal variables that must be considered in the analytical simulation of lift-off are:

1. Structural dynamic mathematical model
    - General model pedigree
    - SRB propellant stiffness (hot or cold)
    - Effects of ET cryogenic-induced shrinkage (preloads at base)

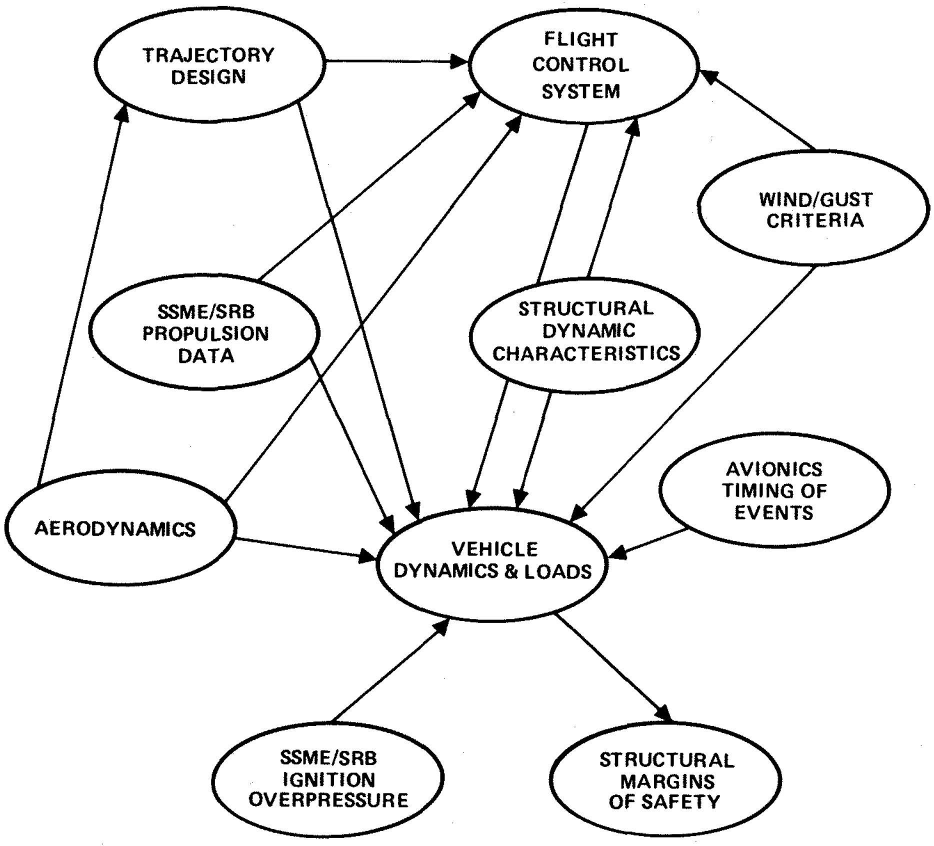


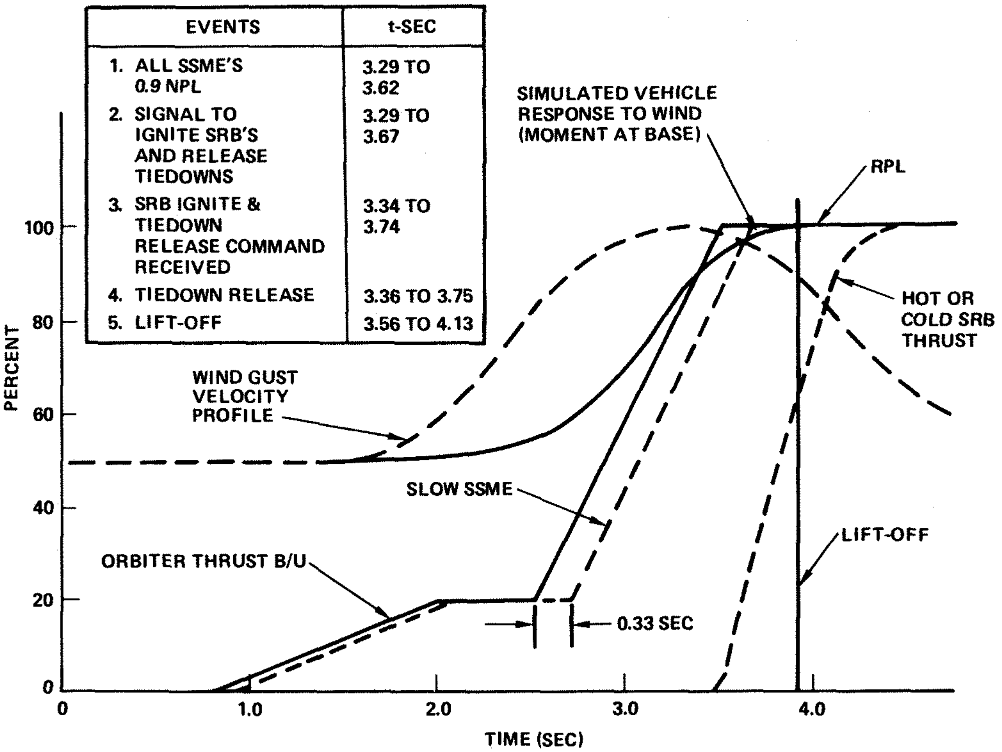
Figure 1. Vehicle Systems and Environment Interactions

2. SSME thrust characteristics
    - Build-up rate (fast or slow)
    - Thrust misalignment (± pitch, ± yaw, and ± roll)
    - Dispersions on start time (simultaneous or 333-millisecond delay)
    - Ignition overpressure
    - Failure case (loss of thrust on one engine)
3. SRB thrust characteristics
    - Build-up rate
    - Thrust level (high performance or low performance)
    - Mismatch (symmetric or unsymmetric thrust build-up)
    - Thrust misalignment (inboard, outboard, ± pitch, ± yaw, and ± roll)
    - Ignition overpressure (magnitude, frequency, and timing)
4. Winds
    - Wind speed and direction
    - Gust wave length and timing
    - Asymmetric vortex-shedding
5. Timing of events
    - Nominal timing and dispersions
6. Sudden release of reaction forces at base of vehicle

These factors, including appropriate nominal values and dispersions, are combined to yield an engineering approximation to a 3-sigma structural loads solution. The combination of effects is shown schematically in Figure 2.

SSME IGNITION OVERPRESSURE

The first example of dynamic interactions pertains to the ignition of the SSME's. A series of single engine static firings was conducted early in the development of the SSME's. From some very limited external pressure and acoustic measurements, it was observed that a blast wave type of phenomenon existed concurrent with the ignition of the



EVENTS	t-SEC
1. ALL SSME'S 0.9 NPL	3.29 TO 3.62
2. SIGNAL TO IGNITE SRB'S AND RELEASE TIEDOWNS	3.29 TO 3.67
3. SRB IGNITE & TIEDOWN RELEASE COMMAND RECEIVED	3.34 TO 3.74
4. TIEDOWN RELEASE	3.36 TO 3.75
5. LIFT-OFF	3.56 TO 4.13

Figure 2. Lift-Off Sequence

engines; however, the magnitude of this wave varied greatly from test to test. In this period of testing, the ignition characteristics of the engine were being changed as part of the development process. Using the limited available overpressure data, estimates were made of the loads on the orbiter base heat shield considering the simultaneous ignition of three engines. A potential overload of the orbiter structure was indicated. An extrapolation of the pressure loads on to the orbiter base heat shield is shown in Figure 3. Other structural areas were evaluated such as the vertical tail, the body flap, and the orbital maneuvering system (OMS) pods.

A review of the data from the static firings resulted in the theory, which was later verified, that the overpressure wave was caused by the ignition of an external cloud of gaseous hydrogen. This cloud was formed by the venting of hydrogen through the engines prior to ignition.

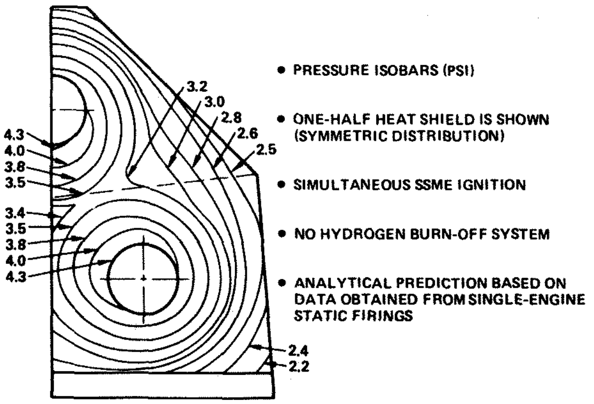


Figure 3. Pressure Map on Orbiter Base Heat Shield

Among the measures considered to lessen the impact of this potential problem were to

1. Change the ignition characteristics of the SSME's
2. Make a structural improvement in the affected areas
3. Stagger the ignition timing of the three SSME's to avoid the superposition of three overpressure waves
4. Provide a system to remove the cloud of free hydrogen prior to SSME ignition

These options were considered with the intention of minimizing the impact in time, cost, and complexity. The impact of any significant change to the SSME's was considered prohibitive at this stage of the program. Similarly, redesigning portions of the structure was to be avoided if possible. Fortunately, a combination of Items 3 and 4 provided the necessary solution with a minimum impact to the vehicle systems. The efficacy of these measures was demonstrated during the static firings of the clustered three SSME's as part of the main propulsion test (MPT) series conducted at the National Space Technology Laboratory in Mississippi in 1980.

The ignition sequence for the SSME's was originally intended to provide a near-simultaneous ignition of the three engines. Analysis of the overpressure data from the early single engine tests led to the conclusion that a 120-millisecond stagger time between engine ignitions would effectively uncouple the overpressure waves from the three engines and result in pressures no greater than that from a single engine. The 120-millisecond stagger time was implemented in the MPT series, with the ignition sequence becoming SSME 3 (lower right), SSME 2 (lower left), and finally SSME 1 (upper centerline).

The second measure that was adopted was to devise a burn-off system to remove the cloud of free hydrogen prior to engine ignition. The burn-off system consists of pyrotechnic sparklers attached to the launch pad structure, which are positioned such that they would harmlessly burn-off any stray hydrogen in the vicinity of the three nozzles. The burn-off system is activated approximately 7 seconds prior to the ignition of the SSME's. The concept of the burn-off system is illustrated in Figure 4.

The staggered ignition sequence and the burn-off system were implemented in the MPT series beginning with Static Firing 7 in February, 1980. Dedicated pressure instrumentation was added to the simulated aft fuselage and base heat shield. As illustrated in Figure 5, these measures had a dramatic effect in eliminating the overpressure wave. Analysis of the staggered engine ignition established that the effects on propellant usage (payload capability) and on acoustic life of the structure were negligible. Pressure measurements obtained from the first three Shuttle flights confirm the elimination of the SSME ignition overpressure wave phenomenon.

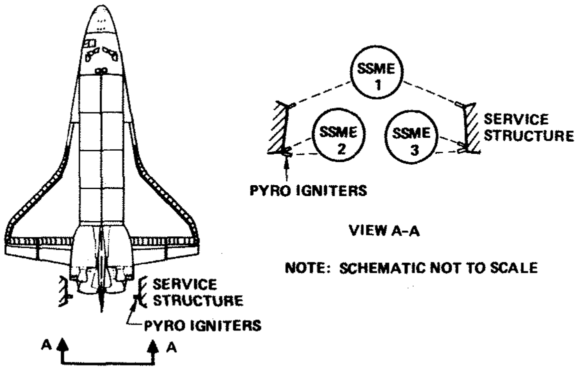


Figure 4. Free Hydrogen Burn-Off System

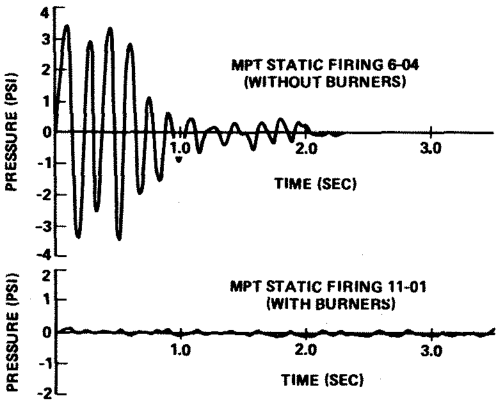


Figure 5. Overpressure Measurements From MPT With and Without Burn-Off System

LIFT-OFF DYNAMIC TWANG LOADS

The second example of balanced system solutions to interdisciplinary problems is also taken from the lift-off dynamic loads event. Whereas the first example pertained to local dynamic loads on the base of the vehicle, this second example involves the more general dynamic response of the entire vehicle to the transient forces at lift-off.

The Shuttle lift-off configuration and the external forces acting on it just prior to SRB ignition and release are shown in Figure 6. The SSME engines are ignited and build-up to 100 percent of rated power level. The design-level winds, including gusts, are applied. When all three engines are at 90 percent thrust or greater, a signal is given to ignite the SRB's and release the vehicle. Prior to release, the horizontal forces and overturning moments are reacted at the base of the vehicle by the launch pad. At the time of release, a significant moment has built up at the base of each SRB to counteract the wind and SSME forces. In Figure 7, the left side shows the deflected shape of the SRB's just prior to release, and the middle shows the deflected shape just after lift-off. The forces at the base of the SRB's decay rapidly to zero at the time of lift-off since there are no reacting forces once the vehicle leaves the pad. This rapid decay of base forces and change in deflected shape represents a shock input to the structure. The shock excites or twangs the vehicle, which causes it to vibrate significantly, mainly in its lower frequency structural modes. The right side of Figure 7 shows a time history of the base moment.

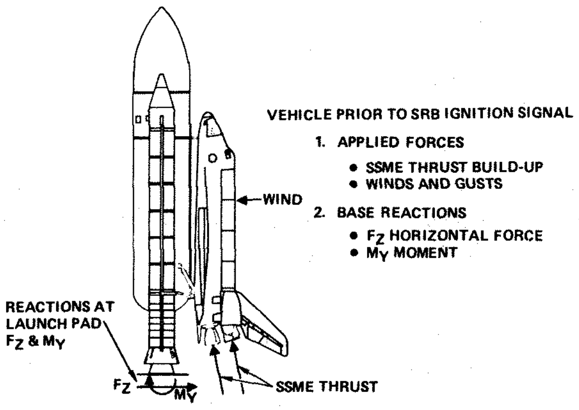


Figure 6. Lift-Off Configuration and Applied Forces

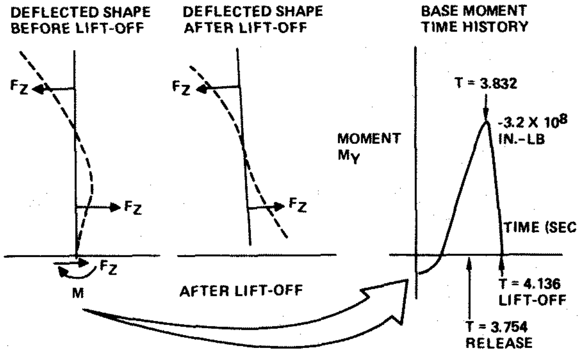


Figure 7. Lift-Off Twang Effect

An update to the lift-off analysis data base was conducted in 1977 in support of the Shuttle critical design review. This analysis resulted in a marked increase in dynamic loads, notably in the region of the orbiter/ET forward attachment structure. While the analysis included updates to all areas of the data base, the increase in dynamic loads was primarily attributed to refinements in the stiffness characterization of the SRB's. Changes were made in the treatment of the stiffness properties of the solid propellant and in the stiffening effect of internal pressure.

Among the measures considered to alleviate the loads were:

1. Lift-off with a lower thrust level on the SSME's
2. Lift-off with one engine out
3. Tilt the vehicle on the launch pad
4. Devise a controlled release for the base restraints
5. Introduce a time delay for SRB ignition and vehicle release

A study of these options showed that most of them were either ineffective, unfeasible, or introduced undesired risks. Option 5 proved to be both effective and easy to implement.

A time history of the base-bending moment of the vehicle and the time of nominal release are shown in Figure 8. It is known that if the magnitude of the base-bending moment at the time of release could be reduced, the subsequent twang loads would also be reduced; thus, it was proposed that the time of lift-off be delayed past the time of peak moment until the vehicle has rebounded and the moment is in the trough. The delay chosen was 2.7 seconds. The effect of this time delay is to reduce the critical twang load in the forward attachment structure by 25 percent. The effect of the SRB ignition delay on payload capability (a loss of 600 pounds) is considered acceptable, and the effect on the acoustic life of the structure is negligible.

The implementation of the 2.7-second SRB ignition delay required assurance of the ability to accurately predict the cantilevered dynamic characteristics of the vehicle, i.e., the time and extent of the rebound. Full-scale dynamic testing was conducted using SRB's bolted to the launch pad. Final verification was obtained from the flight readiness firing of the Shuttle engines prior to STS-1. This is illustrated in Figure 9. This figure shows a time history of the strain in the tiedown bolts between the SRB's and the launch pad. This is a measure of base-bending moment. The predicted optimum time for lift-off coincided precisely with the time of minimum strain in the bolts. The 2.7-second SRB ignition delay is now the baseline procedure in the Shuttle lift-off sequence.

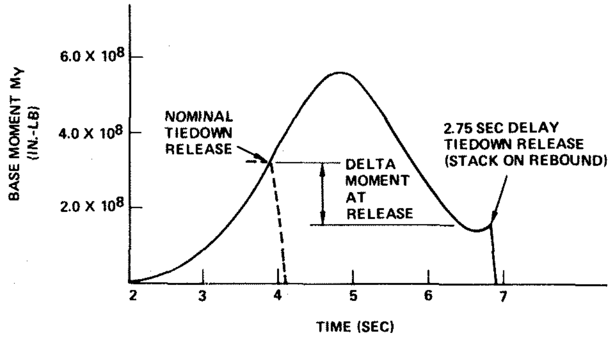


Figure 8. Delayed SRB Ignition Base My Versus Time

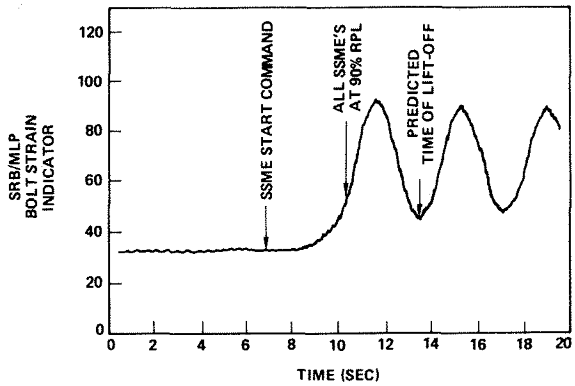


Figure 9. Flight Readiness Firing Tiedown Bolt Strain

HIGH-Q BOOST LOADS - GENERAL COMMENTS

The third example of interdisciplinary problems is taken from the portion of the ascent trajectory known as high dynamic pressure boost (high q). As shown in Figure 10, the time of high dynamic pressure (i.e., greater than 400 psf) is approximately 30 seconds to 90 seconds flight time, which corresponds to a Mach range of 0.6 to 2.7. These values will vary from flight to flight, being dependent upon specific trajectory design and dispersions such as winds. Some of the features of the high-q boost event are:

1. Vertical ascent through wind shears and gusts
2. Throttling of the three main engines to as low as 65 percent of rated power to limit the value of maximum q
3. Movement of the elevons through a predetermined deflection schedule to limit airloads on the elevons

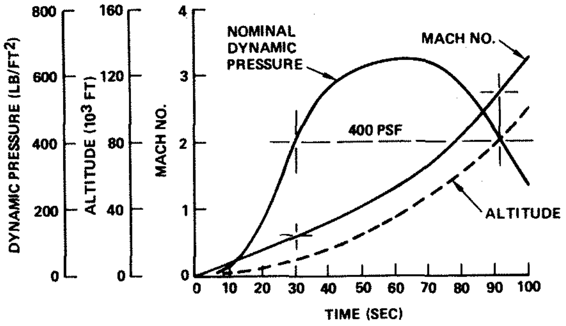


Figure 10. Typical High-Q Boost Trajectory Data

4. An active load-relief control system providing commands for gimballing the three SSME's and the two SRB's in response to wind shear and gust

HIGH-Q BOOST LOADS SURVEY

In early Shuttle load studies, full dynamic simulations were made of the elastic vehicle transient response. Approximately 20 cases were run in a typical loads survey; however, it was apparent that the Shuttle configuration (i.e., winged vehicle with parallel staging) made it more sensitive to wind azimuth and system dispersions than was an axisymmetric vehicle such as Apollo/Saturn. This is illustrated in Figure 11.

The structural loads survey considered dispersions on parameters such as

1. SSME thrust level and thrust vector alignment
2. SRB thrust level and thrust vector alignment

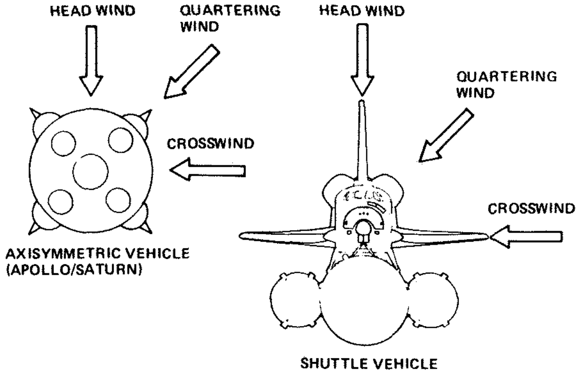


Figure 11. Configuration Differences

3. SRB thrust mismatch
4. Trajectory differences for the various design missions
5. Variations in rotational accelerations
6. Tolerances in aerodynamic coefficients
7. Loss of thrust of any one SSME

A calculation technique was required to provide a more rapid and cost-effective means of surveying all combination of flight time, wind azimuth, and system dispersions. Expanded use of full transient response simulations would be time-consuming and expensive; thus, a new technique was devised based on the use of weighting factors applied to unit sensitivity load cases (load partials) to identify the critical combinations of dispersions. These selected critical cases were then evaluated to obtain balanced distributed loads.

The focus of the load survey was the q alpha versus q beta flight envelopes, called squatcheloids. The squatcheloid provides a means of defining the pertinent flight dynamics parameters such as dynamic pressure (q), angle-of-attack (alpha), angle-of-sideslip (beta), and the rotational accelerations ($\dot{p}$, $\dot{q}$, and $\dot{r}$). An example is shown in Figure 12. The inner A squatcheloid is based on nominal wind criteria as noted. The B squatcheloid is based on the full design wind criteria, i.e., 99 percentile wind shear and 9 meters per second gust, reduced by a multiplying factor of 0.85 to account for a statistical combination of shears and gusts. The Al-squatcheloid includes the effects of system dispersions such as thrust variations and accelerometer alignments. The load increments between the B and A squatcheloids, and between the Al and A squatcheloids are treated as dispersions and are combined appropriately with other dispersions in the loads calculation process. Such a methodical treatment is necessary because of the sensitivity of the Shuttle configuration to dispersions in vehicle and environmental data.

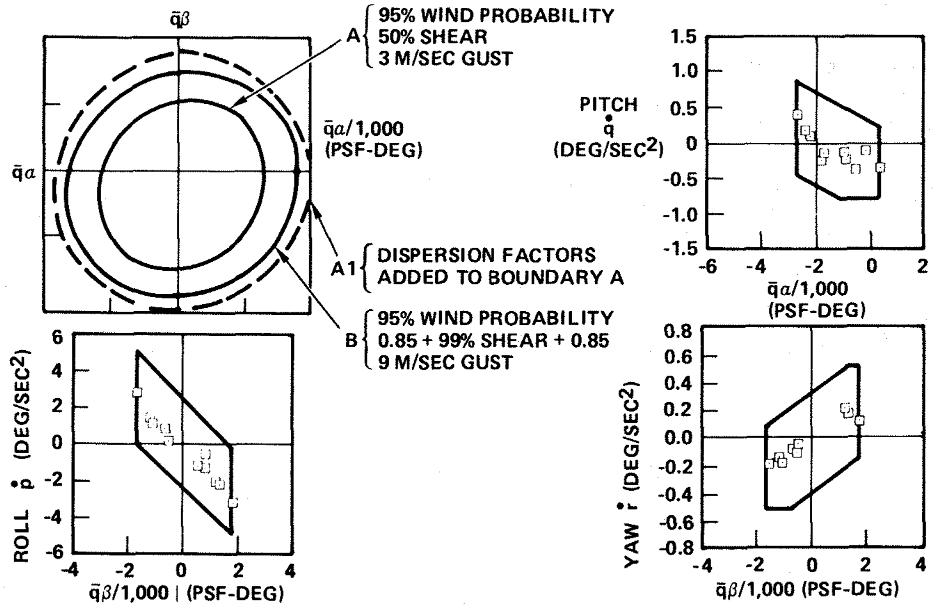


Figure 12. Example of Squatcheloid for Mach 1.05

Squatcheloids are developed for each of several Mach numbers of interest in the high-q regime for both no-failure and one-engine-out conditions. The high-q loads analysis then becomes the methodical survey of the squatcheloids, including consideration of all pertinent deterministic and random dispersions in the data base. The method for handling dispersions is

$$L_{max} = L_A + \sum \begin{pmatrix} \text{deterministic} \\ \text{load} \\ \text{increments} \end{pmatrix} + \text{RSS} \begin{pmatrix} \text{random} \\ \text{load} \\ \text{increments} \end{pmatrix}$$

Where: L_{max} = Maximum load from survey

L_A = Baseline load (Mission 3; A squatcheloid)

1. Deterministic load increments
   - Portion of SRB thrust dispersion
   - Effect of SSME throttling
   - Missions other than Mission 3
2. Random load increments
   - SRB thrust misalignments
   - SRB thrust mismatch
   - Rotational acceleration dispersions
   - Elevon deflection dispersion
   - Effect of maximum shear and gust (squatcheloid B minus squatcheloid A)
   - Effect of flight control dispersions (squatcheloid A1 minus squatcheloid A)
   - Aerodynamic tolerances
   - Portion of SRB thrust dispersion

Using the load partials, the effects of deterministic dispersions are combined directly, whereas the effects of random independent dispersions are combined by root-sum-square (RSS). The load survey is conducted by calculating loads for approximately 30 places on the vehicle including the wing, vertical tail, and the interface structure between orbiter and ET, and between the SRB's and ET.

Computer programs have been developed for the rapid and inexpensive survey of load cases using rigid body calculation techniques. When the critical cases have been identified, balanced distributed load cases are developed including the loads caused by elastic body response. The technique for handling the dispersions in the balanced load cases is as listed in the following.

- Load condition consists of
  - Applied forces caused by baseline load condition

    plus

  - Applied forces caused by deterministic load dispersions

    plus

  - Applied forces caused by random load dispersions modified by a K-factor

    Where:

$$\text{K-factor} = \frac{\text{RSS (random load increments)}}{\sum \text{(random load increments)}}$$

This shows how a K-factor is used as a weighting factor for the random dispersions. The resulting balanced load cases are then used to determine structural margins of safety.

At the time of the Shuttle critical design review, the methodology described was used to survey approximately 65,000 load cases in the high-q boost regime. Of these, approximately 50 cases were selected for final distributed loads. Figure 13 illustrates a typical distribution of critical cases on the squatcheloids where each of the data points represents a maximum load on the wings, vertical tail, or interface structure. The squatcheloid survey technique has proved to be an efficient method for the survey of all the Shuttle system dispersions.

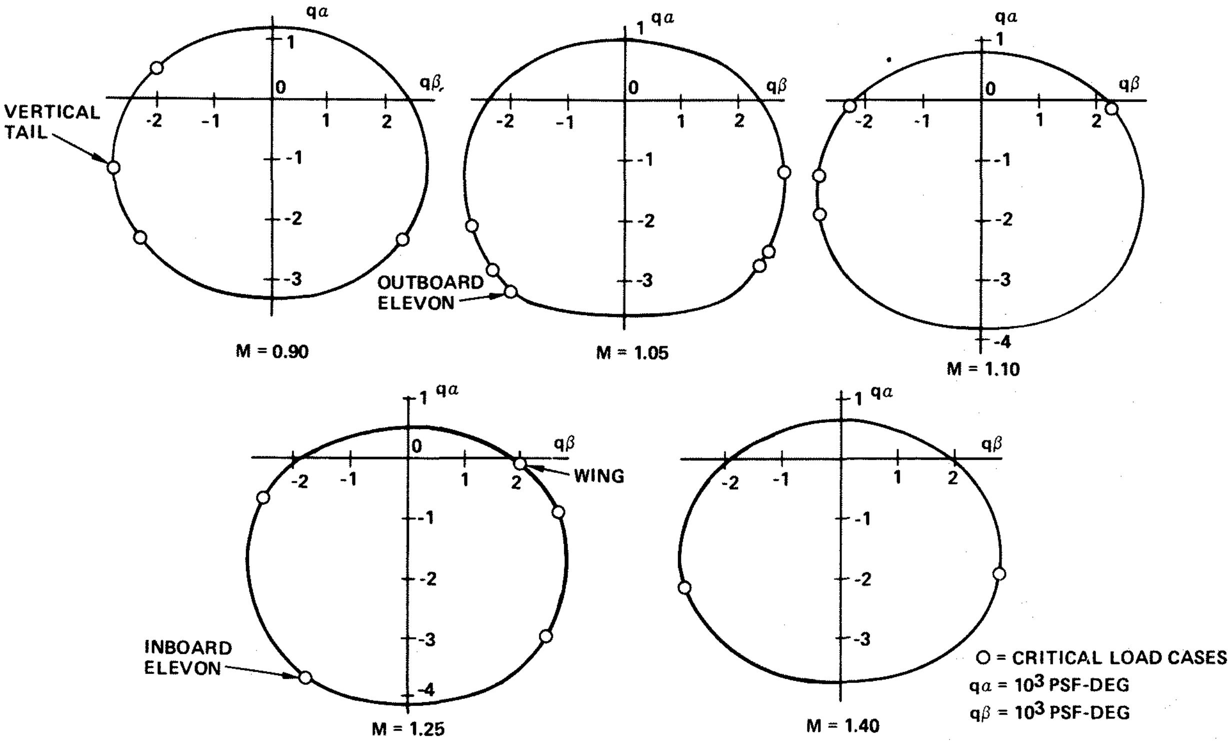


Figure 13. Squatcheloids With Critical Load Cases

CONCLUSIONS

The unique mated configuration of the Shuttle during ascent results in a sensitivity of structural loads and dynamics to relatively small changes in applied forces. The development cycle of the Shuttle vehicle has illustrated a sensitivity to interactions among lift-off parameters such as thrust build-up characteristics, the timing of lift-off, and the dynamic response of the structure. Also evident are interactions among high-q boost parameters such as wind azimuth, aerodynamic and trajectory dispersions, and structural loads. Close working relationships are required to develop balanced system solutions to interdisciplinary problems involving areas such as structures, aerodynamics, propulsion, trajectory design, and avionics. In the course of dealing with these problems, the required capabilities have evolved in both the technical and organizational domains.

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