NASA TECHNICAL NOTE

NASA TN D-6719

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NASA TN D-6719

APOLLO EXPERIENCE REPORT - STRUCTURAL LOADS DUE TO MANEUVERS OF THE COMMAND AND SERVICE MODULE/LUNAR MODULE

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • MARCH 1972

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TN D-6719		

4. Title and Subtitle	5. Report Date
APOLLO EXPERIENCE REPORT STRUCTURAL LOADS DUE TO MANEUVERS OF THE COMMAND AND SERVICE MODULE/LUNAR MODULE	March 1972
	6. Performing Organization Code
7. Author(s) Michael J. Rutkowski, MSC	8. Performing Organization Report No. MSC S-280
	10. Work Unit No. 914-50-20-14-72
9. Performing Organization Name and Address Manned Spacecraft Center Houston, Texas 77058	11. Contract or Grant No.
	13. Type of Report and Period Covered Technical Note
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546	14. Sponsoring Agency Code

15. Supplementary Notes

The MSC Director waived the use of the International System of Units (SI) for this Apollo Experience Report, because, in his judgment, use of SI Units would impair the usefulness of the report or result in excessive cost.

16. Abstract

Analyses were performed to determine the structural loads caused by maneuvers of the docked Apollo command and service module/lunar module (CSM/LM). Results of CSM/LM docked interface loads analyses and service-propulsion-system engine support structure load analyses are compared with the structural allowable loads of the CSM/LM docked interface and the service-propulsion-system engine thrust mount, respectively, for different phases of space-flight operations. An analysis also was performed to investigate the loads that resulted from the failure case in which the LM descent propulsion system is started in the full-throttle position.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
· Apollo · Command Module · Lunar Module · Structural Loads · Thrust Overshoot · Docked Interface Loads	

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
None	None	19	$3.00

*For sale by the National Technical Information Service, Springfield, Virginia 22151

APOLLO EXPERIENCE REPORT

STRUCTURAL LOADS DUE TO MANEUVERS OF THE COMMAND AND SERVICE MODULE/LUNAR MODULE

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SUMMARY

Analyses were performed to determine the structural loads caused by maneuvers of the docked Apollo command and service module/lunar module (CSM/LM). Results of the CSM/LM docked interface load analyses and the service-propulsion-system (SPS) engine support structure load analyses were compared with the structural allowable loads of the CSM/LM docked interface and the SPS engine thrust mount, respectively, for different phases of space-flight operations.

The analyses showed that some SPS engine starts yielded loads that were greater than the structural allowable loads at the CSM/LM docked interface and at the SPS engine support structure. However, further study indicated that an operational change in the SPS engine start could reduce these loads to acceptable levels; this study produced a recommendation which was incorporated successfully into the operational procedures.

An analysis was also performed to investigate the loads that resulted from the failure case in which the LM descent propulsion system (DPS) was started in the full-throttle position (FTP). All loads for a DPS FTP start were within the structural allowable load limits of the spacecraft. As an outgrowth of these studies, some recommendations were made for future programs.

INTRODUCTION

During the space-flight phases of an Apollo lunar mission, the docked command and service module/lunar module (CSM/LM) configuration undergoes midcourse-correction and lunar-orbit-insertion maneuvers by using the reaction control system (RCS) and the service propulsion system (SPS). In addition, the descent propulsion system (DPS) can be used in the docked configuration for aborts as a backup system to the SPS.

An analysis was required to evaluate the structural loads on the spacecraft for firings of the propulsion systems. However, because the CSM/LM docked interface is the most critical section (structurally) of the docked CSM/LM structure, the calculation of the loads at this interface was considered of prime importance. A load survey for the SPS and DPS engine support structure also was considered necessary.

This report describes the studies by the Structures and Mechanics Division (SMD) at the NASA Manned Spacecraft Center (MSC) to evaluate the structural loads for the docked CSM/LM spacecraft. Loads for different space-flight operations and propulsion characteristics are presented and compared with the structural allowable loads for the CSM/LM docked interface and the SPS and DPS thrust structure. The results of CSM/LM docked modal, structural, and flight tests which were used to verify analytical results are also presented.

SYMBOLS

C	damping
FI(N)	force
K	stiffness
M	mass
P_c	chamber pressure
Q(N)	displacement
$\dot{Q}(N)$	velocity
$\ddot{Q}(N)$	acceleration
R(J)	load vector matrix
β	gimbal angle
$\eta(J, N)$	load coefficient matrix
σ	standard deviation

Subscripts:

y	y-axis of the body axis system
z	z-axis of the body axis system

ANALYTICAL APPROACH

The analyses which were performed to evaluate the CSM/LM docked interface load criteria required definitions for the following parameters: rigid-body characteristics (mass, inertia, and center of gravity), elastic-body characteristics (generalized mass, modal frequencies and displacements, stiffnesses, and damping coefficients), and thrust characteristics (buildup rate, overshoot, steady-state thrust, and gimbal angles).

With these parameters defined, the following linear equation of motion was solved to obtain the responses for a damped N-degree-of-freedom system.

$$(M)[\ddot{Q}(N)] + (C)[\dot{Q}(N)] + (K)[Q(N)] = [FI(N)] \tag{1}$$

where M = mass

C = damping

K = stiffness

$Q(N)$ = displacement

$\dot{Q}(N)$ = velocity

$\ddot{Q}(N)$ = acceleration

$FI(N)$ = force

The loads at the CSM/LM docking interface can then be calculated from the responses by using the load equation

$$R(J) = [\eta(J, N)][\ddot{Q}(N)] \tag{2}$$

where $R(J)$ = load vector matrix (axial loads, shears, torsions, bending moments)

$\eta(J, N)$ = load coefficient matrix

Initially, SMD used the Spacecraft Maneuver Engine Transients (SMET) Program (ref. 1) to integrate equation (1) and to calculate loads by using equation (2). The SMET Program is a sophisticated computer program that was developed for SMD. This computer program contains a guidance and control loop for SPS thrust vector control (TVC), various RCS operational modes, engine dynamic characteristics, and propellant slosh.

A simpler dynamic response program, which yielded results that agreed with those from the SMET Program, was used for the bulk of the SMD analyses; the degree of sophistication offered by the SMET Program was not required.

ANALYSES

The design loads for the CSM/LM docked interface (table I) were calculated initially by the CSM contractor using a rigid-body planar model of the spacecraft. The load criteria for this design analysis used a dynamic factor to account for elastic-body responses, and a factor of 1.25 to account for thrust overshoot. The critical load condition for this design analysis included an SPS gimbal hardover failure at engine ignition.

TABLE I. - THE CSM/LM DOCKED INTERFACE DESIGN LOADS

Conditions		Axial load, lb	Shear, lb	Torsion, in-lb	Bending moment, in-lb	Vehicle weight, lb	Gimbal angles, deg	
							β_y	β_z
Nominal SPS thrust buildup	Minimum axial	-4 000	390	-3 960	144 000	76 000	0.78	6.50
	Maximum axial	-19 350	230	-13 800	52 800	65 000	0.41	6.50
	Maximum moment shear and torsion	-15 400	[a]940	-15 200	[a]174 000	76 000	0.78	6.50
Maximum SPS thrust buildup	Minimum axial	[a]19 900	110	0	13 100	65 000	0.41	0.32
	Maximum axial	[a]-24 600	66	0	8 320	65 000	0.41	0.32
	Maximum moment	-13 800	320	0	46 400	94 465	0.94	0.92
RCS (roll operation)	Maximum RCS torsion	--	--	[a]±26 100	--	65 000	--	--

[a]Denotes maximum.

Another contractor was directed by the SMD to investigate the degree of lateral-longitudinal dynamic coupling in the docked CSM/LM configuration. The study was based on Block I structural data, because the Block II drawings had not been released at the time of this study. However, major structural differences between the Block I and Block II spacecraft precluded the acquisition of loads that were considered to be sufficiently representative of those that would occur in Block II structures. Nevertheless, the study confirmed that a three-dimensional representation of the spacecraft structure which included mass eccentricity and stiffness asymmetry was required for an adequate determination of the dynamic responses and loads of the CSM/LM.

First-Generation SMD Study

The original SMD CSM/LM structural loads study was based on a detailed, 218-mass-point, 596-degree-of-freedom model. Fifteen three-dimensional elastic modes were generated for each of three service module (SM) propellant loading conditions: quarter full, half full, and full. To obtain conservative loads at the CSM/LM docked interface, the values of the modal frequencies were decreased by 20 percent, and a 20-percent increase in modal displacements was approximated by increasing the modal displacements at the engine gimbal point.

The SPS thrust time-history data were updated continuously during the SMD analysis. The initial thrust data, which were generated in June 1967 (ref. 2), did not exhibit a start transient overshoot and had a nominal steady-state thrust of 20 000 pounds (fig. 1). However, the flight data from the Apollo 4 mission (November 1967) indicated a 56-percent thrust overshoot for the start transient of the first SPS burn (fig. 1). A similar thrust overshoot was obtained from the flight data for the first SPS burn of the Apollo 6 mission.

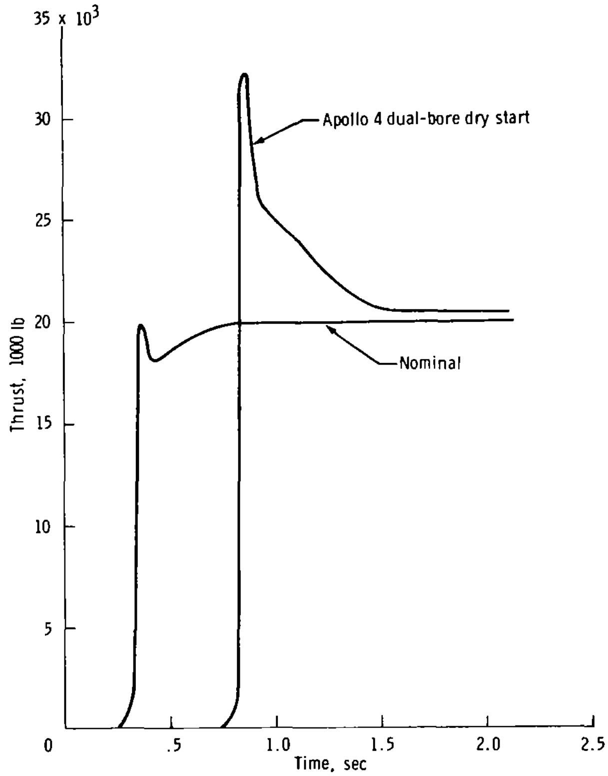

Figure 1. - The Apollo SPS engine start transient.

Subsequent analysis of the Apollo 4 and Apollo 6 flight instrumentation, along with a comparison of the flight data with ground test data, indicated that until additional ground test firings of the SPS engine could be performed, the Apollo 4 first SPS burn start transient was the best available representation of the SPS thrust. The Apollo 4 flight data were used for the first SMD study.

Initially, several different TVC conditions were investigated, including SPS gimbal hardover during engine ignition and SPS gimbal hardover during thrusting. The hardover start case was eliminated as a design condition because of its low probability of occurrence and because of crew visual displays. Subsequently, an SPS thrust vector mistrim angle of 1°, with the Apollo 4 first SPS burn start transient, was determined to be the critical load condition. Loads that were calculated at the CSM/LM docked interface for the Apollo 4 thrust data with a 1° mistrim of the thrust vector are presented in table II. Table III presents the loads for different thrust time histories and the design loads for the CSM/LM docked interface.

TABLE II. - THE CSM/LM DOCKED INTERFACE LOADS USING MEASURED

APOLLO 4 SPS THRUST DATA[a]

Condition	Axial load, lb	Shear, lb	Torsion, in-lb	Bending moment, in-lb	Fuel condition
Minimum axial load	10 640	390	-9 090	78 800	Quarter-full SM tanks
Maximum axial load	-27 300	240	-350	156 600	Quarter-full SM tanks
Maximum shear	-11 000 0	3707	31 000	85 300	Quarter-full SM tanks
Maximum torsion	+1 600 -2 500	1080	102 000	13 400	Half-full SM tanks
Maximum moment	16 300	1240	-12 200	254 600	Full-full SM tanks

[a]Analysis conditions:
1. Apollo 4 SPS thrust data
2. Initial modal data — deflections increased 20 percent, frequencies decreased 20 percent
3. Thrust vector mistrimmed 1°

TABLE III. - A COMPARISON BETWEEN STRUCTURAL LOAD CASES

FOR THE CSM/LM DOCKED INTERFACE

Condition	Apollo 4 measured thrust data	20 000-lb nominal thrust (ref. 2)	Design loads
Maximum tension, lb	10 640	4 970	19 900
Maximum compression, lb	-27 300	-17 055	-24 600
Maximum shear, lb	3 710	2 090	940
Maximum bending moment, in-lb	254 600	147 500	174 000
Maximum torsion, in-lb	102 000	48 320	26 100

Some CSM/LM docked interface loads exceeded the LM structural allowable loads and resulted in reduced factors of safety; in this original analysis, however, several limitations existed which caused doubt as to the validity of the calculated loads. An error was found in the loads calculations that increased the bending moments, and several inaccuracies in the modal data were discovered. The validity of the Apollo 4 and Apollo 6 flight data was also doubted. Although they were indicative of high thrust overshoots, these data were considered to be conservative because the flight transducer which measured SPS engine chamber pressure was presumed to overheat and provide erroneous thrust overshoot data. The foregoing limitations led to a second generation of tests and analyses, which established that large thrust overshoots did indeed occur.

Second-Generation SMD Study

A revised SMD analysis was performed by using an updated CSM/LM dynamic model, which was generated by SMD. The model was a better representation of the CSM/LM spacecraft and was later verified by the CSM/LM docked modal test. Twenty three-dimensional elastic modes were generated for each of four SM propellant loading conditions: quarter full, half full, three-quarters full, and full.

The dispersions used were 0 to 15 percent for the modal frequencies and approximately ± 10 percent for the maximum modal displacements. Again, dispersions were taken to give conservative loads. The frequencies were unchanged, but the SPS gimbal point deflections were increased by 10 percent.

Because the instrumentation in earlier tests was inadequate to determine thrust overshoots, a significant effort was made to define the SPS start transient thrust characteristics more accurately for the second-generation SMD study. A series of SPS start transient tests was therefore conducted at Arnold Engineering and Development Center (AEDC) during May and June 1968, with improved instrumentation, to define the magnitude and duration of SPS engine chamber pressure P_c overshoot. The preliminary data from these tests indicated a worst-case peak P_c of 169 psia that was equivalent to a peak thrust of 34 375 pounds (nominal thrust, 20 000 pounds), if direct proportionality of thrust and P_c were assumed.

The evaluation of these AEDC tests (ref. 3) contained a series of composite P_c time histories which were constructed from test data by combining the most adverse results experienced for each start condition. Figure 2 presents composite dual-bore start time histories with dry and wet starts and nominal and off-nominal high P_c. (A dry start is the initial engine start condition, whereas a wet start is the normal subsequent engine start condition.)

In addition to the evaluation, a statistical analysis of the AEDC test data was performed to predict a worst-case overshoot with corresponding 3σ limits (ref. 4). Figures 3 and 4 present statistically derived 3σ thrust and chamber pressure time histories from this analysis. Figure 3 shows time histories for operation in the dual-bore mode, and figure 4 shows time histories for the single-bore mode. (A dual-bore start uses two redundant oxidizer paths and two redundant fuel paths, and a single-bore start uses only one oxidizer path and one fuel path.)

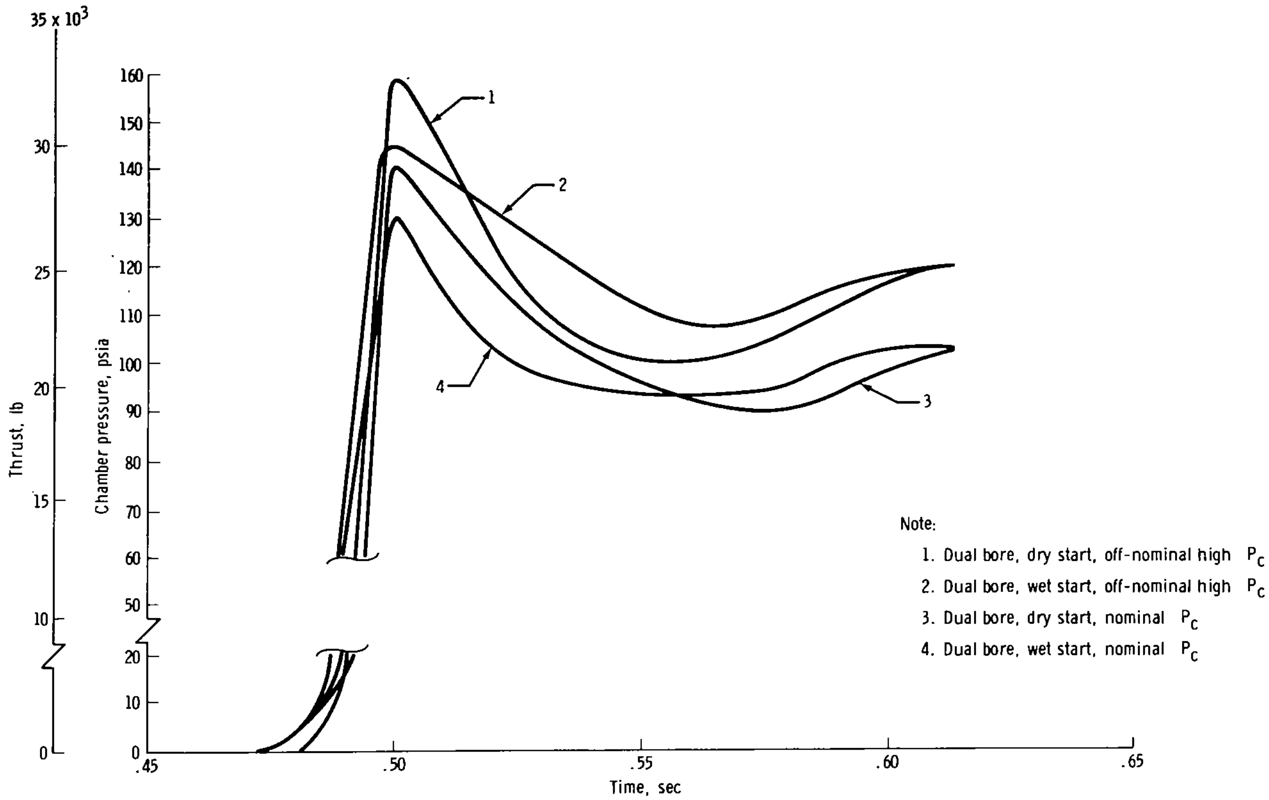

Figure 2. - The Apollo SPS engine start transients, based on data from AEDC tests.

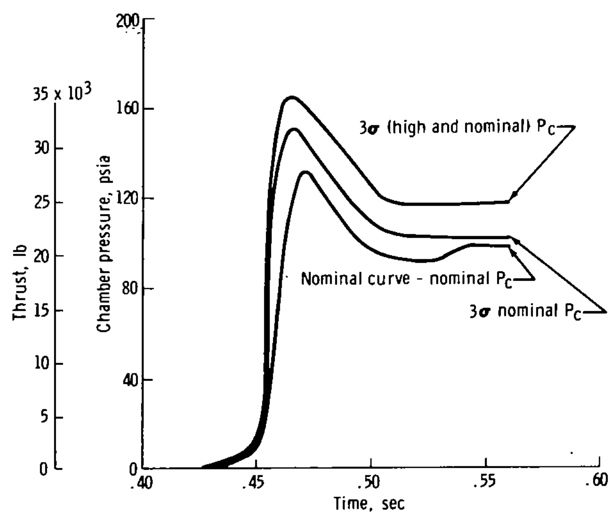

Figure 3. - The 3σ dual-bore SPS start transients, based on statistical analysis of AEDC test data.

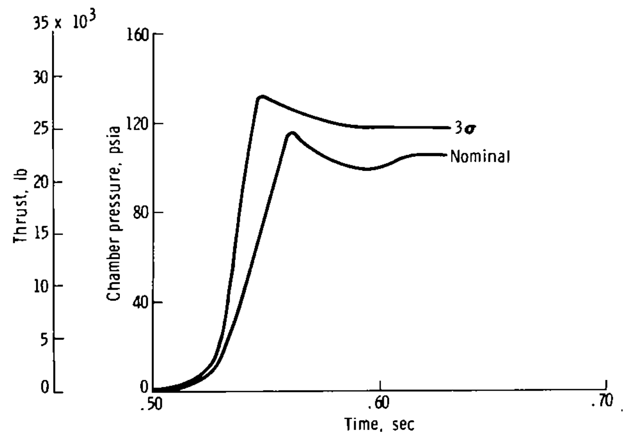

Figure 4. - The 3σ single-bore SPS start transients.

The loads at the CSM/LM docked interface for the preliminary AEDC test data were within the structural allowable load limits, as were the composite time histories for single-bore starts and the statistically derived time histories for single-bore starts. In contrast, the loads for the composite time histories for dual-bore starts and the statistically derived time histories for 3σ dual-bore starts were in some cases greater than the structural allowable load limits.

The CSM/LM docked interface loads for 3σ single-bore starts with a mistrim gimbal angle of 1° are presented in table IV. Figure 5 shows a comparison of the loads at the CSM/LM docked interface for various start conditions with the LM ultimate capability.

TABLE IV. - THE CSM/LM DOCKED INTERFACE LOADS FOR 3σ

SINGLE-BORE SPS STARTS WITH 1° MISTRIM[a]

Condition	Axial load, lb	Shear, lb	Torsion, in-lb	Bending moment, in-lb
Maximum axial load	-20 800	130	100	32 000
Maximum shear	-7 500	3100	9 000	58 000
Maximum torsion	-16 800	910	16 600	50 000
Maximum moment	-8 400	870	1 600	72 500

[a]Analysis conditions:

1. 3σ single bore SPS start (fig. 4)
2. 1° mistrim
3. SMD modal data — deflections, +10 percent; frequencies, -5 percent
4. Quarter-full SM tanks

The results of the analyses, which used the revised modal data, also indicated that the major portion of the calculated loads at the CSM/LM docked interface resulted from the use of rigid-body modes and the first four elastic modes (two orthogonal bending modes, a torsion mode, and an axial mode). This conclusion differs with the results of the earlier analyses, which indicated significant contributions to the loads from higher order modes.

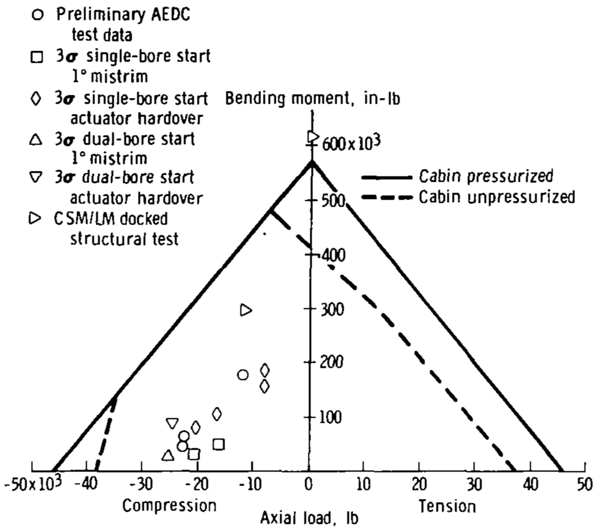

Figure 5. - The CSM/LM docked interface loads as a function of LM structural capability.

Contractor Studies

Although the SMD loads analyses were concerned primarily with evaluating the structure loads for the SPS start transient, other load conditions existed that had to be investigated for a complete systems analysis. The CSM contractor investigated the CSM/LM docked interface loads for some failure conditions by using modal data and load coefficients supplied by SMD. Loads were calculated in an analog computer simulation of manual takeover following an SPS gimbal hardover failure. The takeover was from both the automatic thrust vector control (ATVC) and the digital autopilot (DAP). The analog computer was linked to a guidance and control hardware evaluator (HE). The HE included the stability and control system, the guidance and navigation hardware, the TVC actuators, and a realistic mockup of the Block II command module with functional displays and switches. In these closed-loop simulations, the pilot would manually control the thrust vector in either the rate mode or the direct mode, when an SPS gimbal hardover failure occurred.

During the manual takeover, the pilot activates the roll control that pulses the RCS jets in roll and excites the torsion modes. Table V presents the worst-case loads from these simulations. Simulations were also conducted for RCS roll jet failures, which occurred during attitude hold maneuvers with a nonthrusting SPS engine. The maximum torsion load generated on the HE was ± 112 000 in-lb for four-quad control. For the normal two-quad control, the torsion load was ± 56 000 in-lb.

The CSM contractor also calculated CSM/LM docked interface loads for SPS engine gimbal hardover failure without manual takeover. The loads were calculated for the case when the engine starts at a -0.707° mistrim in both pitch and yaw, and then gimbals at the maximum rate to 7° in pitch and to trim in yaw. The loads from this analysis are presented in table VI for the 3σ single-bore start transient (fig. 4).

The results of these studies indicated that for the failure cases that were investigated, the CSM/LM docked interface loads were within the structural allowable loads. These results, when they are combined with the results of the SMD analyses, formed a complete systems analysis of the CSM/LM docked interface loads that resulted from SPS and RCS thrusting.

TABLE V. - THE CSM/LM DOCKED INTERFACE LOADS FOR SPS GIMBAL HARDOVER WITH MANUAL TAKEOVER[a]

Axial load, lb	Shear, lb	Torsion, in-lb	Bending moment, in-lb	Failure condition
-12 000	640	-40 000	215 260	Direct mode takeover from ATVC yaw gimbal hardover
-12 000	250	-84 000	53 670	Direct mode takeover from ATVC yaw gimbal hardover
-12 000	660	-76 000	175 450	Direct mode takeover from ATVC pitch gimbal hardover
-19 000	410	-20 000	147 500	Rate mode takeover from ATVC yaw gimbal hardover
-12 000	320	-70 000	60 000	Rate mode takeover from DAP pitch gimbal hardover

[a]Analysis conditions:
1. Steady-state thrust
2. SMD modal data

TABLE VI. - THE CSM/LM DOCKED INTERFACE LOADS FOR SPS GIMBAL HARDOVER WITHOUT MANUAL TAKEOVER[a]

Condition	Axial load, lb	Shear, lb	Torsion, in-lb	Bending moment, in-lb	Fuel condition
Maximum axial load	-23 200	380	-3 370	21 400	Quarter-full SM tanks
Maximum shear	-7 570	3260	7 630	28 300	Quarter-full SM tanks
Maximum torsion	-7 380	2070	29 500	67 000	Quarter-full SM tanks
Maximum moment	-14 200	630	-750	98 100	Half-full SM tanks

[a]Analysis conditions:
1. 3σ single-bore SPS start (fig. 4)
2. SMD modal data
3. Initial gimbal angles mistrimmed -0.707° each; at start of thrust buildup gimbals at maximum rate to -7° pitch and to trim in yaw

The DPS Thrusting

In contrast to the SPS, which is a fixed-thrust engine, the DPS is a throttleable engine. In the normal mode of operation, the DPS is started at a 10-percent-thrust throttle position. However, a system failure may cause the DPS to be fired at the full-throttle position (FTP). Because the DPS is used as a backup for the SPS in the case of an abort, loads at the CSM/LM docked interface were investigated for DPS FTP starts. The DPS engine has a steady-state thrust level of about half that of the SPS (between 9800 and 10 500 pounds) and a maximum gimbal angle of ±6° in both pitch and yaw. The thrust curve used in this analysis (fig. 6) had an overshoot to 14 400 pounds and a steady-state thrust of 9880 pounds.

All loads at the CSM/LM docked interface for both a trimmed and a hardover DPS FTP start were considerably less than the loads for an SPS start and were well within the LM structural capability. In addition, the worst DPS thrust structure load produced by an FTP start was less than 18 000 pounds, compared with the structural allowable load limit of 19 500 pounds.

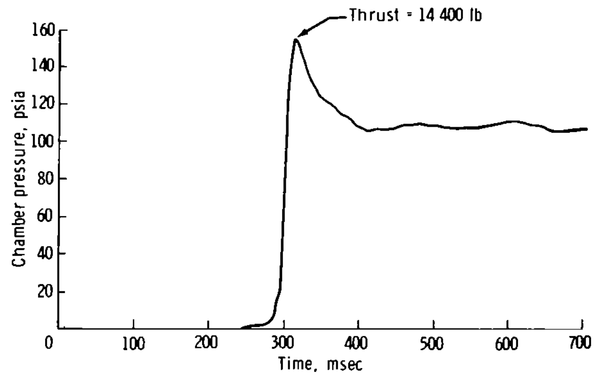

Figure 6. - The LM descent engine full-throttle-position start transient.

The SPS Engine Support Structure Loads

The SPS start transient thrust overshoots, which were measured in the AEDC tests, were also used to evaluate the SPS engine support structure loads. The SPS engine thrust mount has a test-verified minimum strength of 49 500 pounds in the axial direction. For the composite dual-bore dry starts for off-nominal and nominal SPS propellant tank pressures, SPS thrust structure loads of 55 000 and 49 300 pounds were computed. The SPS thrust structure loads of 60 200 pounds and 54 800 pounds, respectively, were calculated by using the 3σ dual-bore thrust time histories for high and nominal SPS propellant tank pressures. These results indicated the severity of the dual-bore mode of operation, and showed that the structure was unable to sustain off-nominal high dual-bore starts.

Because a better definition of the SPS engine support structure loads for a dual-bore start was needed, loads that were calculated for 52 starts from the AEDC tests were used to perform a statistical load analysis. As shown in table VII, this analysis indicated that the loads which resulted from dual-bore operation of the SPS exceeded the structural allowable load for the SPS engine support structure. In contrast, all loads that were calculated for single-bore starts (wet and dry, nominal and off-nominal, and worst measured) were within the structural allowable load limit except the 3σ start (fig. 4), which gave a 37 700-pound load.

TABLE VII. - THE SPS THRUST STRUCTURE LOADS[a]

Start conditions	Load, lb
Dual bore	
Mean dry start (including nominal and off-nominal conditions)	41 400
Worst-measured wet start	47 800
Worst-measured dry start	53 900
$+3\sigma$ start (wet or dry) with nominal propellant tank pressure	49 600
Single bore	
3σ start (fig. 4)	37 700
All other single-bore starts	<35 700

[a]Minimum structural capability, 49 500 pounds.

In view of the significant difference in the SPS engine support structure loads for dual-bore and single-bore start transients, the SMD recommended single-bore starts for all SPS burns. The Apollo mission rules were subsequently changed before the Apollo 8 flight, so that all SPS burns would be made in the single-bore mode.

VERIFICATION TESTS

The CSM/LM Docked Modal Test

A vibration modal survey was performed on an Apollo docked CSM/LM in the MSC Vibration and Acoustic Test Facility. One test objective was to determine the dynamic characteristics of the docked spacecraft. The experimental verification of the analytical description of the spacecraft increased the confidence in the validity of the computed loads.

A comparison of the experimental and analytical results for the CSM/LM docked modal test indicates that, in general, the analysis underestimated the natural modal frequencies by approximately 15 percent. However, the modal displacements compared more closely and are generally accurate to within ± 10 percent. In addition, the structural damping for the first two bending modes was found to be 1.5 percent, rather than the 1 percent which had been used in the load analyses.

The Apollo 9 Stroking Test

In addition to the CSM/LM docked modal test, a flight test was needed to verify the extrapolation of the analysis to the flight condition. A stroking test was performed during the Apollo 9 flight to investigate the dynamic response of the CSM/LM to a known forcing function. The SPS engine was gimbaled in the pitch plane, so that a lateral saw-toothed force history was applied to the spacecraft at the engine gimbal point (fig. 7). The pitch and yaw body rates for the full-amplitude stroking test during the third SPS burn of the Apollo 9 mission are shown in figure 8. Table VIII presents the first two bending-mode frequencies from the flight data as compared with the preflight test data. Although the measured frequencies agreed with the analytical frequencies, the amplitudes of the responses were less than the analytically predicted results.

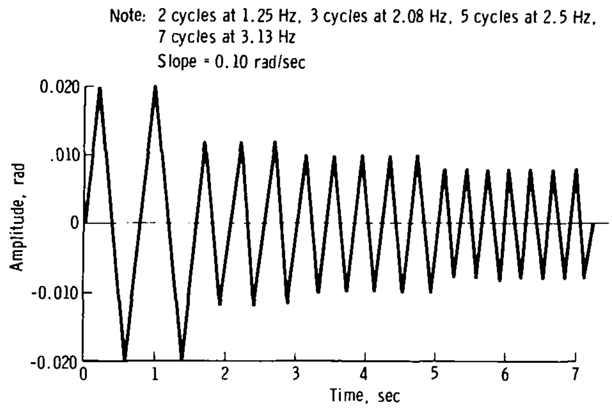

Figure 7. - The full-amplitude stroking signal performed on the Apollo 9 flight.

The flight stroking test resulted in pitch and yaw rates of approximately 0.1 deg/sec. These rates damped in

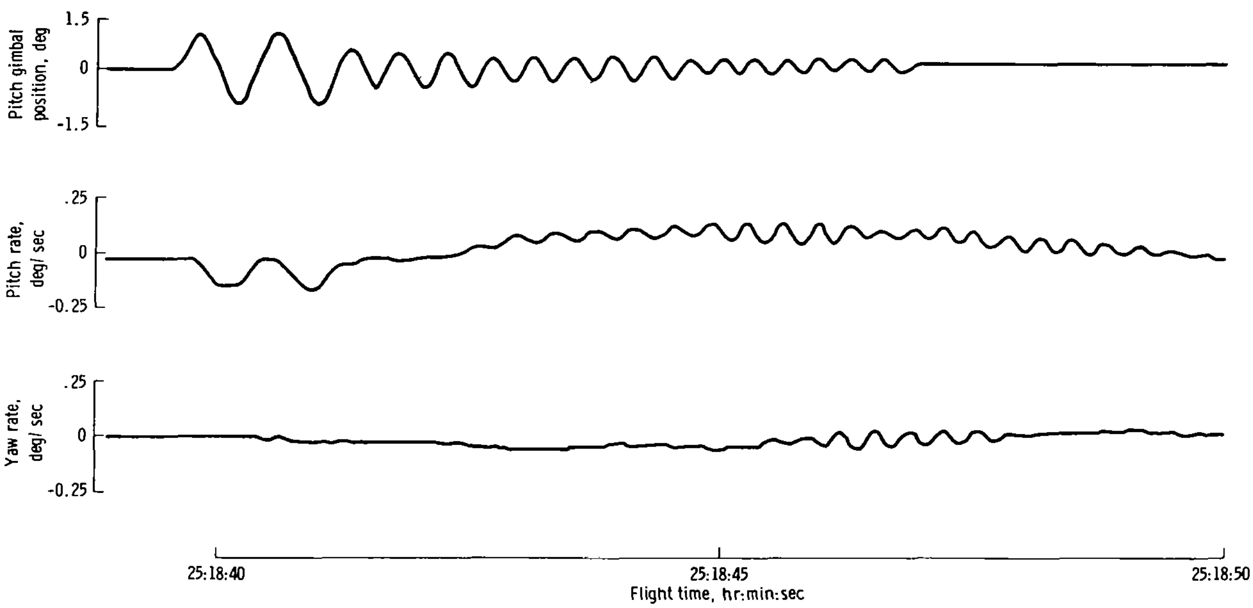

Figure 8. - The Apollo 9 spacecraft dynamic response during the full-amplitude stroking test.

TABLE VIII. - A COMPARISON OF EXPERIMENTALLY VERIFIED CSM/LM FREQUENCIES WITH APOLLO 9 FLIGHT DATA

Condition	Spacecraft weight, lb	First-mode frequency, Hz,	Second-mode frequency, Hz,
CSM/LM docked modal test condition DM1A	70 129	2.76	3.02
Apollo 9 flight	80 226	2.75	3.09
CSM/LM docked modal test condition DM2	82 430	2.65	2.93

approximately 10 seconds. The amplitude of these rates was less than one-half of the amplitude that was observed on the HE. The difference in rates was attributed in part to the difference between the fuel condition and the damping ratio that existed in flight and those used in the HE simulation.

The CSM/LM Docked Structural Test

A CSM/LM docked structural test was performed to identify the ultimate strength of the LM upper docking structure. Also demonstrated was the LM upper docking structure capability to withstand the structural loads that were anticipated for SPS thrust buildup. These test loads, which were applied successfully to a lunar module test article (LTA-3) docking structure, are plotted on the LM capability curve in figure 5.

CONCLUDING REMARKS AND RECOMMENDATIONS

The NASA Manned Spacecraft Center Structures and Mechanics Division initial analysis of the loads for the docked command and service module/lunar module (CSM/LM) spacecraft indicated that the service-propulsion-system (SPS) start transient could result in loads which exceeded the lunar module structural allowable loads. This analysis included uncertainties, however, especially in the modal representation of the CSM/LM and the SPS thrust buildup characteristics. Therefore, a revised analysis was initiated with improved dynamic characteristics and updated SPS thrust buildup characteristics.

The revised docked CSM/LM load analysis was performed by using a three-dimensional elastic model which was verified by the results of the CSM/LM docked modal test. Single- and dual-bore thrust data were obtained from the results of the SPS engine start transient overshoot tests, which were conducted at Arnold Engineering and Development Center. Initially, both SPS gimbal actuator hardover and 1° mistrim cases were investigated. However, the SPS gimbal actuator hardover case was subsequently eliminated as a design condition because of its low probability of occurrence.

The CSM/LM docked interface loads were compared with the interface capability, which was analytically defined and then later experimentally verified by the CSM/LM docked structural test. Results of this analysis indicated that the loads for single-bore SPS starts are within the structural allowable loads of the CSM/LM docked interface. However, the loads for dual-bore starts are significantly greater than those for single-bore starts. The loads for off-nominal high dual-bore starts exceed the structural allowable loads of the CSM/LM docked interface.

Similarly, the loads on the SPS engine support structure are considerably higher for dual-bore starts than for single-bore starts. The off-nominal high dual-bore cases exceed the structural capability of the SPS engine support structure. In contrast, the loads for descent-propulsion-system full-throttle-position starts are well within the structural allowable load limits of both the CSM/LM docked interface and the descent-propulsion-system engine support structure.

Because of the significant difference between the loads for single-bore starts and dual-bore starts, the Structures and Mechanics Division recommended that the Apollo mission rules be changed so that all SPS burns would be made in the single-bore mode. This recommendation was implemented before the Apollo 8 mission.

The Apollo 8 flight had four SPS single-bore starts. The Apollo 9 mission flight-tested a docked CSM/LM in earth orbit. The five docked CSM/LM and the three CSM SPS single-bore starts, as well as the one docked descent-propulsion-system start, were all performed successfully. Finally, the Apollo 10 and 11 missions were flown with complete success, and the structural reliability of the CSM/LM spacecraft was demonstrated for all phases of the Apollo lunar missions.

Based upon experience gained in the Apollo Program, the following two recommendations are made.

1. In ground propulsion testing for future programs, sufficient and appropriate instrumentation should be provided to ensure accurate definition of the magnitude, duration, and other important characteristics of thrust overshoots.

2. For the prediction of realistic and accurate spacecraft loads, the analysis should include a three-dimensional mathematical representation of the spacecraft, mass eccentricity, and stiffness asymmetry.

Manned Spacecraft Center
National Aeronautics and Space Administration
Houston, Texas, May 19, 1971
914-50-20-14-72

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