7% and ion thermal motion by 8%. Thus, the effect of ion thermal motion and photoelectric effect on satellite potential are of the same order.

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Computerized Process for Calculation of Discrete Test Loads

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Introduction

A STRUCTURAL test is a process of imposing applicably distributed loads to a structure and recording the structure response. Most activities associated with testing evolve around the subject of loads – what type, how much, when, and where. The success of a structural test is contingent on the timely, accurate determination of the test loads data.

An extensive structural test program of a full-scale production Space Shuttle Orbiter was recently completed. This program was conducted to supplement and validate the stress analysis and to demonstrate the structural integrity of the vehicle when subjected to design loads.

This multifaceted test program was initiated in 1974 and was completed in late 1979. A total of 388 hydraulic actuators (jacks), strategically located over the external airframe surface were required to apply the design loads. In addition, over 5000 sensors (strain gages, deflectometers, load transducers, and thermocouples) were used to measure the structure's response. Closed loop servo systems were controlled by computers to apply precise synchronous loading of the jacks.

The test article, which is the scheduled second flight vehicle, consisted of a structurally complete full-scale orbiter less certain items of functional hardware, such as landing gears, crew module, and control surface actuators. Substitute hardware was designed and fabricated for these missing items as well as substitute payload which distributed applied loads into test.

The Test Program encompassed four sequences: influence coefficient tests; 120% limit load tests; aft fuselage pressure test; and forward fuselage thermal test.

The second sequence and major portion of the test program was the limit-load testing. A total of 38 loading applications were imposed on the airframe to simulate the critical design conditions in the launch, re-entry, and landing modes. The number of test conditions and complexity of the test setup required the implementation of a discrete test-loads computer program.

Structural Test Requirements

The computerized technique of deriving discrete test-loads began simultaneously in two areas. One area was the development of an acceptable test-load matrix. The second area was the development of the loading systems concepts.

The test-load matrix originated from the vehicle stress analysis load description. The stress-load description was presented in a 21,500 node point matrix. Each node point had three degrees of freedom; shear, x, y, and z, for a total of 64,500 degrees of freedom. This matrix was much too large and detailed a comprehensive loads input for a static structural test. To provide an applicable load description, the loads from this matrix were operated on by transform equations to provide the fixed test-grid matrix of 836 node points and 2,400 degrees of freedom.

The next step was to consolidate all of the 38 test-loading applications. These data, plus the test node grid geometry, the position of the movable surfaces, and a brief description of the loading application were recorded on a magnetic tape. This tape was then made accessible to both the main jack loads program and the interactive fixture design and verification programs.

The loading system concepts for most substructures were evaluated and refined using interactive computer programs which directly access the external test-load data. The development of acceptable loading concepts is an iterative process. A preliminary concept is first established and then analyzed for the critical design loads. The loading concept is then refined and the process is repeated. The results of each iteration is used to modify or validate the concept. The evaluation of these concepts was a coordinated effort involving the vehicle structural analysis and test organizations.

Program Description

The discrete jack loads program provides mechanisms to use the detailed knowledge of local conditions, while matching the gross external load distributions and maintaining test load within the mechanical capability of the test equipment.

The jack-loads program required, in addition to the external test-load matrix, three data sets: jack, ratio, and group.

The jack data set is the definition of the test geometry. This data set includes: jack and static test support locations; jack and static test support orientation; jack train definition; and jack piston areas.

A ratio is defined as a group of jacks which are loaded in a constant relationship designed to produce a required load vector. Ratios are developed and used in conjunction with specific jacks to produce a desired loading effect. The ratio data set includes: location; vector identification; jack orientation; and jack weightings.

The group data set is a model of the loading system over a specific portion of a structure. The group data set defines the relationship of jacks and ratios to the individual degrees of freedom of the test-loads matrix. In a given group, specific jacks and ratios are used to satisfy the shears and moments developed by unit loads in the degrees of freedom (DOF)

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assigned to that group. The loads program uses these groups to develop a transformation matrix from unit degrees of freedom of the test-load matrix to the discrete test loads. This transformation matrix is then used with the test-load matrix to calculate the jack loads.

Specifically, the method used to determine the discrete jack loads $\{S\}$ is based on the forming of a matrix $[T]$ which gives the discrete test loads due to a unit load in each DOF of the test-load matrix. The transformation matrix $[T]$ is computed one column $\{Ti\}$ at a time. The method used to determine $\{Ti\}$ is based on maintaining the static balance of a unit load $\{Li\}$ in DOF i of the test-load matrix $\{P\}$. In addition, redundancy in jack-loading capability is resolved by employing a weighted rigid-body transformation. The variables in this method are the independent jack variables, and the ratio variables. The jack-independent variables $\{Ss\}$ can be characterized by the load in the master servo load cell which is used by the computer to maintain jack train loads. The ratio variable $\{R\}$ is an artifice used to symbolize an equivalent jack train which is made up of a linear combination of real jack trains. The relationship between the ratio variables $\{R\}$ and the dependent jack variables $\{Sr\}$, are expressed by the equation

$$\{Sr\} = [Br]\{R\} \tag{1}$$

where $[Br]$ is the matrix of constraints which express the dependency of the jack variables in terms of the ratio variables.

The basic static equilibrium equation is

$$[Cs]\{Ss\} + [Cr]\{R\} = [Cl]\{Li\} \tag{2}$$

where $[Cs]$, $[Cr]$, and $[Cl]$ are the matrices of the static load results at the origin for each jack, ratio and DOF i in the external test-load matrix respectively.

Note $[Cr]$ can be determined by

$$[Cr] = [Cs]\,[Br] \tag{3}$$

Equation (2) in general is not adequate to determine the unknown variables $\{Ss\}$ and $\{R\}$. A second set of conditions, that of a weighted rigid-body transformation is necessary to uniquely determine the unknowns. The following equations express the variables in terms of six independent rigid-body accelerations $\{A\}$ at the origin:

$$\{Ss\} = [Ws]\,[Cs]^T\{A\} \tag{4}$$

$$\{R\} = [Wr]\,[Cr]^T\{A\} \tag{5}$$

where $[Ws]$ and $[Wr]$ are diagonal matrices of mass weighting associated with the jacks and ratios. $[Cs]^T$ and $[Cr]^T$ are the rigid-body motions of jacks and ratios due to unit motions at the origin.

Combining Eqs. (2), (4), and (5):

$$[Cs]\,[Ws]\,[Cs]^T\{A\} + [Cr]\,[Wr]\,[Cr]^T\{A\} = [Cl]\{Li\} \tag{6}$$

Rewriting Eq. (6):

$$[I]\{A\} = [Cl]\{Li\} \tag{7}$$

where

$$[I] - [Cs]\,[Ws]\,[Cs]^T + [Cr]\,[Wr]\,[Cr]^T \tag{8}$$

Solving Eq. (7) for $\{A\}$:

$$\{A\} = [I]^{-1}\,[Cl]\{Li\} \tag{9}$$

To recover the independent jack loads, $\{Ss\}$, and the independent ratio loads $\{R\}$ substitute $\{A\}$ from Eq. (9) into Eqs. (4) and (5) respectively. The jack loads $\{Sr\}$ are calculated by substituting the value of $\{R\}$ from Eq. (5) into Eq. (1).

The column vector $\{Ti\}$ corresponding to a test load DOF is

$$\{Ti\} = \{Ss\} + \{Sr\} \tag{10}$$

The transformation vectors $\{Ti\}$ are collected to form the complete transformation matrix $[T]$ used to determine the discrete jack loads $\{S\}$ for external test-load conditions $\{P\}$ by the equation

$$\{S\} = [T]\{P\} \tag{11}$$

Program Implementation

Group modeling is the key to successful implementation of the discrete test-loads program.

Modeling and the components of a model can best be understood by actual illustrations of sample structures. The crew module provides the most elementary example. The test-loading requirements were described by one node point possessing six degrees of freedom. The loading system concept incorporated three x-jacks, one y-jack, and two z-jacks. The model of the crew module group is shown in Fig. 1.

Group modeling for this structure simply required the assigning of six jacks to the six known degrees of freedom of the crew module node.

The loads program was confronted with six equations and six unknowns. The group is statically determinate, and only one unique set of loads can exist for this group for any given loading condition.

Most of the 150 groups used to mathematically model the Space Shuttle Structural Test were more subtle and included the use of weighting factors and ratios. The ratio is a convenient device to include side conditions which ensure the matching of critical test-loading criteria.

A rudder speed brake panel illustrates the implementation of the ratio. The loading criterion for this structure was to match the desired hinge moment developed by the speed brake panel node loads. The loading system consisted of one jack orientated normal to the panel reference plane. The jack

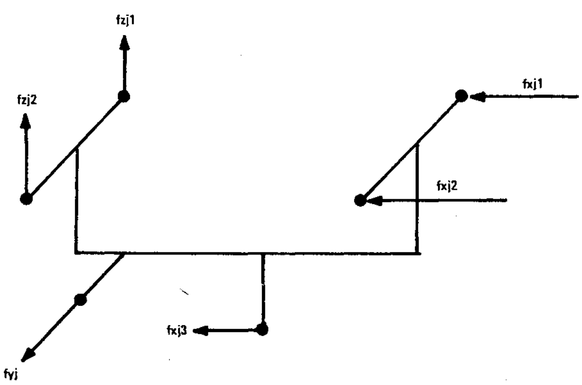

Fig. 1 Crew module group model.

Table 1 Assignation of six jacks to six degrees of freedom

Unknowns	Knowns
fxj_1 fxj_2 fxj_3	Sx, My, Mz
fyj fyj	Sy
fzj_1 fzj_3	Sz, Mx

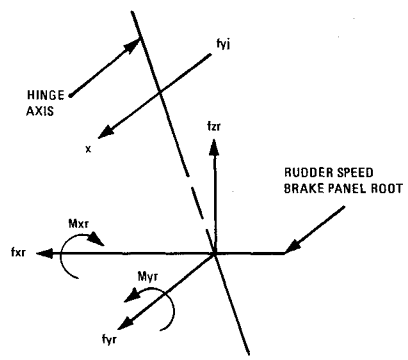

Fig. 2 Rudder speed brake model.

position for any given test condition was best fitted by an interactive program accessing the test-load matrix. All desired loading parameters with the exception of the hinge moment *Mz* were balanced by ratios developed by jacks from other noncritical substructures. The model of a rudder speed brake is shown in Fig. 2.

The strategic placement of the *x* and *y* ratios, *fxr* and *fyr*, at the speed brake panel hinge root assures that the hinge moment of the panel will be developed by the jack, properly located or not. The *z* ratio *fzr* and the moment ratios are supplied to complete the static balance of model.

Final Loads Processing

Derived test-loads data were stored on magnetic tape. These tapes were accessed by the test operation computers to apply the loads and by computers programmed to tabulate, in test report form, the jack data for all test applications. The external test-load matrix and the discrete test-load tape were accessed by computers programmed to provide the applied vs desired loading parameters. The loading parameter plots, produced by the computer, provided the verification of the quality of the discrete test loads.

Summary

The computerized process used to calculate the discrete test loads provided the capability to recompute quickly and efficiently a revised set of test loads caused by last minute changes in basic loading requirements. This capability was a major contributor to the success of the Space Shuttle Orbiter structural test program.

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Technology Status of a Liquid Fluorine-Hydrazine Rocket Engine

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Introduction

THE Space Storable Propulsion Systems Technology Program was initiated in the fall of 1976. Its objective is to demonstrate the technology readiness of a space storable liquid propulsion system so that this technology can be applied to planetary missions with start dates in fiscal 1982 and beyond. The primary element of the fluorine-hydrazine propulsion system is the rocket engine assembly (REA). The significant design criteria for the assembly are shown in Table 1. The REA incorporates the propellant valves and the thrust chamber assembly (TCA) which consists of the liquid propellant injector and the thrust chamber. Progress on the propellant valves and prior TCA progress has been detailed.[1,2]

Table 1 Rocket engine requirements

Thrust	3560 N (800 lbf)
Chamber pressure	690 kN/m^2 (100 psia)
Total firing duration	4000 s, minimum
Vacuum performance $I_{(sp,vac)}$	3626 N-s/kg (370 lbf-s/lbm)
Mixture ratio	1.5
Expansion ratio	60:1 or 80:1
Maximum weight (not including valves)	13.6 kg (30 lb)

Observations of the tests conducted with carbon/carbon composite thrust chambers showed that the film cooling on the chamber walls was at first effective. As time progressed, the film was destroyed by a combination of radial heat flux from the combustion gases and axial heat flux along the chamber wall from the hotter throat section. In addition, head-end combustion gas recirculation (sometimes referred to as radial winds) was adding to the problem of higher-than-predicted wall temperatures. Local corrosion of the inner wall was also experienced. The injector was modified to incorporate additional film cooling (36%) in an attempt to maintain the chamber wall below the ammonia-carbon reaction initiation temperature (the cause of the corrosion) and to block the "radial winds." An alternate like-doublet injector was also fabricated. This design incorporated 27% of the fuel as film cooling.

This Note presents the status of the efforts to develop a lightweight thrust chamber assembly capable of achieving the long-duration performance requirement.

Nickel Chamber Tests

Three tests were conducted at the JPL Edwards Test Station with the reworked propellant injector installed in a heavyweight nickel thrust chamber. Test durations of 5, 15, and 30 s were accomplished. Utilizing the simplified JANNAF[3] methodology, an average extrapolated performance value of 3549 N-s/kg (362 lbf-s/lbm) was achieved at an overall mixture ratio of 1.5 assuming an 80:1 expansion ratio. Post-test inspection showed that the fuel liquid film cooling length extended to the throat of the chamber during the first test. As the test duration was increased, the liquid length receded toward the forward end of the chamber. It was apparent that, as had been previously determined, the heat transfer characteristics could not be predicted through the use of short-duration nickel chamber tests and must be analyzed during long-duration carbon chamber tests. Three 5-s tests were conducted with the alternate injector installed. An average extrapolated performance value of 3578 N-s/kg (365 lbf-s/lbm) was achieved at an overall mixture ratio of 1.5 and an expansion ratio of 80:1. No further testing was conducted with this injector because of cost and schedule restraints.

Unlined Carbon/Carbon Composite Chamber Tests

Two 200-s tests were completed utilizing the reworked propellant injector. The first test incorporated a new chamber. It was found that the occurrence of corrosion just downstream of the injector had been eliminated by maintaining low head-end temperatures through increased film cooling. Substantial corrosion occurred in the convergent and

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