Evaluation of a Cost-Effective Loads Approach

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A shock spectra/impedance method for loads prediction is used to estimate member loads for the Viking Orbiter, a 7800-lb interplanetary spacecraft that has been designed using transient loads analysis techniques. The transient loads analysis approach leads to a lightweight structure but requires complex and costly analyses. To reduce complexity and cost, a shock spectra/impedence method is currently being used to design the Mariner Jupiter Saturn spacecraft. This method has the advantage of using low-cost in-house loads analysis techniques and typically results in more conservative structural loads. The method is evaluated by comparing the increase in Viking member loads to the loads obtained by the transient loads analysis approach. An estimate of the weight penalty incurred by using this method is presented. The paper also compares the calculated flight loads from the transient loads analyses and the shock spectra/impedance method to measured flight data.

I. Introduction

THE methodology for the establishment of spacecraft design loads is strongly influenced by project requirements which include cost, schedule, and weight. Historically, spacecraft structures have been designed to a variety of criteria. The criteria were based upon the availability and reliability of flight data at the inception of the various projects. Early spacecraft systems were typically designed to survive a sinusoidal vibration environment, which was conservatively estimated using flight data of similar space vehicles. Later shock spectra[1] and Fourier transform techniques[2,3] were utilized to improve both the prediction of the flight environment and the loads.

Recently the method of transient loads analysis was used to design the Viking Orbiter (VO)¶[4,5] This method requires a composite mathematical model of the spacecraft and launch vehicle as well as the availability of forcing functions that are applied to the composite model to compute member loads for the entire composite structure. The method of transient loads analysis is analytically the most rigorous and ideally leads to a lightweight design. The main objections to this approach are that it is costly, it leads to complex interfaces especially where many organizations are involved, and the results tend to be sensitive to changes in the structure. The method also tends to be ineffective in the support of internal design changes, since the updating and loads iterations require a long turnaround time.

The approach currently used on the Mariner Jupiter Saturn (MJS)** project utilizes an improved shock spectra technique.[6,7] This method utilizes shock spectra of launch vehicle accelerations and introduces the relative impedance of the spacecraft and launch vehicle. The objectives of this method are low-cost analyses within design schedule limitations with high reliability at only a moderate expense of structural weight as compared to a transient analysis design. The cost savings, estimated at between 30 to 60%, are not only a result of savings in computer expenditure and manpower to estimate loads but more significantly in providing good load estimates early in the program. These loads can be rapidly updated as the design evolves. It is estimated that the updating using the shock spectra method is 10 to 30 times faster than the transient analysis method. Good timely load values eliminate design delays and tend to prevent costly hardware modifications later in the program.

The shock spectra method used herein also provides for fabrication tolerances otherwise not accounted for in the analytical model. The method substantially decreases cost and improves schedule at the expense of weight. The data are valuable to future projects in the selection of the loads estimation approach.

To choose a method for obtaining spacecraft loads for the MJS, different approaches were evaluated within the Project requirements. The purpose of this paper is to evaluate the shock spectra method[6,7] as used for MJS by applying it to the VO. Member loads are estimated using a one cycle iteration on the existing design. The updated member loads are then used to estimate the weight penalty that would have been incurred if shock spectra techniques had been used to design Viking rather than transient analyses, as were used for the actual design. In addition, this paper compares the calculated flight loads from the transient loads analyses and the shock spectra/impedance method to measured flight data. Note that the shock spectra approach could not initially have been used for Viking, because estimates of the shock spectra at the base of the payload were not available.

II. Launch Vehicle

Both the Viking and MJS missions utilize the Titan IIIE/Improved Centaur D-IT Launch Vehicle with a new Centaur Standard Shroud (CSS). The events for loads analyses are: 1) Stage 0 ignition (also referred to as launch or liftoff, 2) max aerodynamic pressure (max αq), 3) Forward bearing reaction (FBR) release, 4) Stage I ignition, 5) Stage 0 jettison, 6) Stage I burn, 7) Stage I burnout, 8) Stage II ignition, 9) Shroud jettison, 10) Stage II burnout, 11) Centaur main engine start 1 (MES 1), 12) Centaur burn 1, 13) Centaur main engine cutoff 1 (MECO 1), 14) Centaur main engine start 2 (MES 2), 15) Centaur burn 2, 16) Centaur main engine cutoff 2 (MECO 2).

To date, a total of 4 Titan III E/Centaur vehicles have flown. The payloads and launch times were as follows: 1)

Received Aug. 16, 1976. This paper presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology under Contract NAS 7-100, sponsored by the National Aeronautics and Space Administration.

Index categories: Structural Dynamic Analysis; Spacecraft Configurational and Structural Design (Including Loads); LV/M Structural Design (Including Loads).

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¶The Jet Propulsion Lab. is responsible for the Viking Orbiter System which is part of the overall Viking Project managed by the Viking Project Office at Langley Research Center for NASA. The Proof Flight was flown in Feb. 1974, and two spacecraft were flown in the fall of 1975.

**The Jet Propulsion Lab. is responsible for the Mariner Jupiter Saturn system. Two NASA spacecraft will be flown in 1977.

Viking Dynamic Simulator (VDS), Feb. 1974, 2) Helios A, Dec. 1974, 3) Viking A, Aug. 1975, 4) Viking B, Sept. 1975.

Data obtained from earlier Titan launch vehicle systems indicated that Stage I burnout and State 0 ignition produced the highest payload loadings. The above four Titan/Centaur flights have confirmed these two events to be critical. Three other events which produced lower, but substantial loadings were: maximum aerodynamic pressure (max. αq), Stage I ignition and Stage I burn. The remaining 11 events did not significantly contribute to the spacecraft design loads.

III. Viking Design Experience

Background

The Viking Project started in 1968. This spacecraft system was the heaviest interplanetary probe launched by NASA to date. The Viking spacecraft configuration is shown in Fig. 1. The spacecraft weighs 7800 lb.

The design of the Viking structure used transient loads analysis. This method utilizes an analysis process to define design loads and flight loads to qualify the structure. Design loads are obtained using mathematical models of the Viking spacecraft (V-S/C) not verified by test. Flight loads are obtained using mathematical models of the new hardware that are verified by a test program. The final VO mathematical model consisted of a total of 32,000 degrees of freedom.

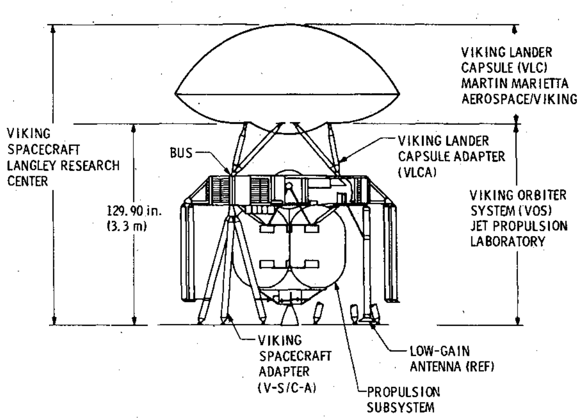

Fig. 1 Viking spacecraft configuration.

The approach selected at the time was based upon the following considerations: 1) Requirement for a lightweight structure, 2) High reliability for two V-S/C missions, 3) A new, not previously flown, launch vehicle system, 4) Availability of launch vehicle engine forcing function data from previous Titan and Centaur flights.

Primary Structure

Any structural element whose failure would result directly in an overall spacecraft structural failure was classified as primary structure. Early in the Viking program specific hardware items were established to be designed by transient loads analysis. Engineering judgment was used to select hardware with design loads in the low frequency (0 to 30 Hz) range.

Many of the structural elements are symmetric. The design loads for any group of elements was chosen as the maximum tension and compression load for identical members.

Load Analysis Cycles

Several transient load analysis cycles were performed during the course of the Viking Project. These analyses were complex, since many organizations were included. Figure 2 shows a flow diagram of a typical loads analysis cycle. The output for the VO part of the analysis cycle consisted of 550 member loads, 120 accelerations, and 70 displacements. An event for a loads analysis cycle may consist of up to 29 separate time history solutions. The results of these are combined to obtain statistical estimates of loads.

Schedule

Four major loads analysis cycles were required. Three of these occurred before the final mathematical model, verified by modal test, was developed. The first Viking loads cycle was the most comprehensive as far as the flight events were concerned. This loads analysis cycle considered 11 of 16 events. In the final loads cycle, four events that were deemed critical were considered: Stage 0 ignition, maximum aerodynamic pressure (max αq), Stage I burn, and Stage I burnout.

Two mini-loads analysis were performed, one by Martin Marietta Aerospace (MMA) and another by JPL. Mini-loads analyses employ a simplified launch vehicle model wherein ac-

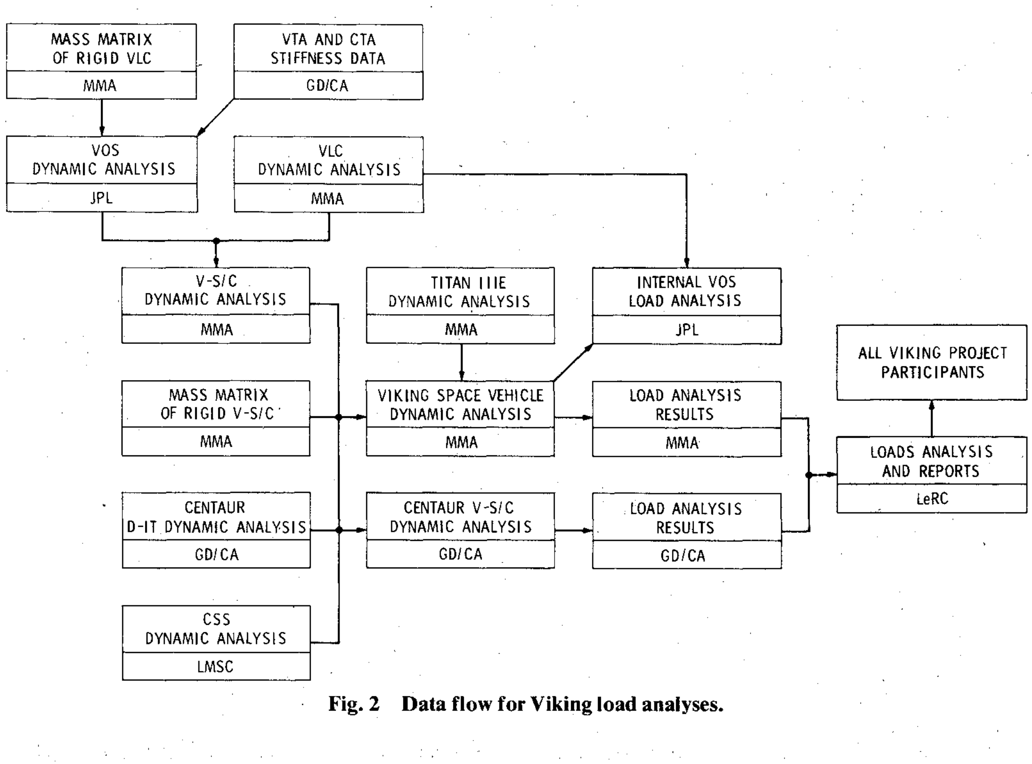

Fig. 2 Data flow for Viking load analyses.

celeration time histories determined from previous analyses are imposed at an intermediate location on the launch vehicle to generate loads for an updated spacecraft model. The objective was to obtain quick, relatively inexpensive estimates of loads to support the design schedules of the individual organizations.

Proof-Test Payload

The main objective of the first Titan IIIE/Centaur flight was the checkout of the new launch vehicle system. This proof flight provided an unusual opportunity of flying a dynamic simulation of the Viking, the Viking Dynamic Simulator (VDS). The main objectives of the VDS were to verify the mathematical modeling techniques, the methodology employed in coupling the spacecraft and launch vehicle models, the loads prediction techniques, the Viking flight instrumentation and the forcing functions used to force the composite vehicle. To best meet the objectives the VDS instrumentation consisted of a total of 8 strain gauges, 7 accelerometers, and 1 microphone. Six of the eight strain gauges were used to fully instrument the six members of the simulated VLCA, such that each strut acted as a load cell.[8]

A thorough modal survey was performed on the VDS to fully understand the dynamic characteristics of the payload. These test data then were used in a system transient loads analysis to predict loads for the major launch vehicle events. Table 1 compares the preflight analytical predictions to the actual flight measurements for three major events.

Viking Flight Instrumentation

Due to limits in the available telemetry channels the Viking spacecraft carried only 6 strain gauges, 4 accelerometers, and 1 microphone.[9] The six strain gauges were placed on the 6 members of the VLCA (Fig. 1).

The objectives of the Viking instrumentation were to maximize the return of engineering and diagnostic data. The six strain gauge channels for both the VDS and the Viking spacecraft were placed on the VLCA to obtain a complete force time history across the statically determinate interface.

Viking Vlight Results

Two Viking spacecraft, Viking A and Viking B, were launched in August and September 1975, respectively. The flight measurements of both spacecraft are compared to analytical preflight predictions for a total of five events. See Table 2.

Summary of Viking Experience

The ratios of flight loads measurements to the preflight predictions are an indication of the conservativeness of the transient loads analysis approach. It is seen that, in general, the higher loading conditions show larger margins between the prediction and the flight load. This is true of the max αq loadings and Stage I burn. The larger margin is related, as it should be, to larger uncertainties in the prediction of these events. Thus the max αq condition contains a conservative wind loading estimate which was probably not encountered in the flights. The Stage I burn loading was calculated using earlier Titan flights which did not employ propulsion feedline accumulators. The accumulators flown on Viking for the first time, have apparently reduced the Stage I burn forcing function.

For Viking, the flight loads compared very well with the predicted loads since the design requirement was to consider anticipated 3σ loads. This approach leads to moderately conservative design loads.

IV. Design Approach for the Mariner Jupiter Saturn Spacecraft

Background

During the planning phase of the MJS project a thorough review of available alternatives for determining spacecraft structural loads was conducted at JPL. The MJS spacecraft weights 4300 lb. The configuration is shown in Fig. 3. The object of this review was to utilize analytical and/or flight data from previous spacecrafts using the Titan IIIE/Centaur launch vehicle to formulate a cost-effective load analysis approach. A complete systematic transient loads approach such as was used for Viking, was considered too costly, not timely, and complex. The mini-loads approach did not save on computer time significantly but did decrease the time required for a loads cycle.

The method was to be used in design load cycles at JPL with minimum turnaround time and cost. The dependence on outside organizations was to be minimized, realizing that some

Table 1 Comparison of preflight predictions to flight measurements for the six members of the VLCA Viking dynamic simulator

		Ratio[a] Flight/Transient Analysis		
Member No.	Type of Load	Stage 0 Ignition	Maximum Aerodynamic Pressure (Max αq)	Stage I Burnout
750	C	1.59	0.60	0.76
	T			
751	C	1.59	0.55	0.97
	T		0.47	0.70
752	C	1.33	0.65	0.82
	T			0.36
753	C	1.56	0.58	0.71
	T			0.47
754	C	0.66	0.41	0.80
	T			0.44
755	C	0.83	0.60	0.77
	T			0.43

[a] The only ratio shown is for loads which approach the member design load. The ratio for small loadings is meaningless. C = Compression, negative (-). T = Tension, positive (+).

minimum number of composite transient analysis cycles might be required for the verification of the chosen approach and for final design verification.

The chosen method was to produce reliable upper-bound member loads at a moderate increase of structural weight. Finally, the method had to be relatively insensitive to the details of the mathematical model of the structure, to damping estimates, and to minor structural changes.

While the composite transient loads analysis was considered too costly, the conventional shock spectra approach was considered to be too conservative. To satisfy the MJS requirements a method was developed wherein the shock spectra approach is modified to account for the relative impedance of the spacecraft and launch vehicle, and potential changes in the frequencies of the MJS spacecraft.

Shock Spectra and Impedance Method

The method used to obtain design loads for the MJS spacecraft will only be summarized here. A complete mathematical development is contained in Refs. 6 and 7.

The major features of the method are as follows: 1) The shock spectra envelope is related to the maximum reaction force at the launch vehicle/spacecraft interface using the effective mass[10,11] of the spacecraft and spacecraft damping. This is a significant improvement over the traditional method of relating loads to a static or sinusoidal acceleration equivalent to the shock spectra envelope. 2) A shock spectrum reduction factor is introduced which accounts for the shape of the shock spectra peaks as well as the relative impedance of the spacecraft and launch vehicle. 3) The method utilizes shock spectra from analyses performed on VDS, Helios, and Viking to obtain an envelope of the ensemble of analytical shock spectra. These data are updated and modified as flight data become available. 4) In matching the interface impedances of the spacecraft to launch vehicle an allowance for frequency errors within a prescribed tolerance band is provided for. In the implementation the modal member loads are allowed to decrease as the frequency mismatch increases, allowing for a smooth transition from one design to the next.

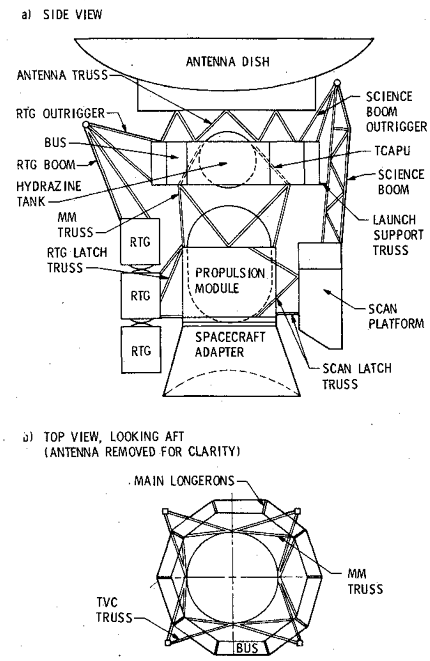

Fig. 3 MJS spacecraft schematic shock spectra for Stage 0 ignition.

The most important assumptions made in the derivation are as follows: 1) The spacecraft and launch vehicle are adequately represented by linear mathematical models. This is also required for the transient analysis. 2) The shock spectra of the interface acceleration of previous flights are available from which an envelope can be constructed. Although the

Table 2 Comparison of preflight predictions to flight measurements for the six members of the VLCA, Viking A and Viking B compression only

Member No.	Ratio Viking A/ Prediction	Ratio Viking B/ Prediction	Ratio Viking A/ Prediction	Ratio Viking B/ Prediction	Ratio Viking A/ Prediction	Ratio Viking B/ Prediction
	Stage 0 Ignition		Maximum Aerodynamic Pressure (Max αq)		Stage I Ignition	
750	0.68	0.79	0.63	0.59	0.88	1.13
751	0.59	0.48	0.52	0.41	1.00	1.00
752	0.87	0.96	0.62	0.62	0.85	1.00
753	0.87	0.97	0.53	0.56	0.86	0.86
754	0.78	0.53	0.50	0.47	0.67	0.67
755	0.78	0.82	0.56	0.65	0.95	0.95
	Stage I Burn		Stage I Burnout			
750	0.45	0.45	0.84	0.81		
751	0.44	0.44	0.65	0.65		
752	0.41	0.41	0.87	0.81		
753	0.51	0.51	0.81	0.81		
754	0.41	0.41	0.64	0.59		
755	0.51	0.53	0.90	0.87		

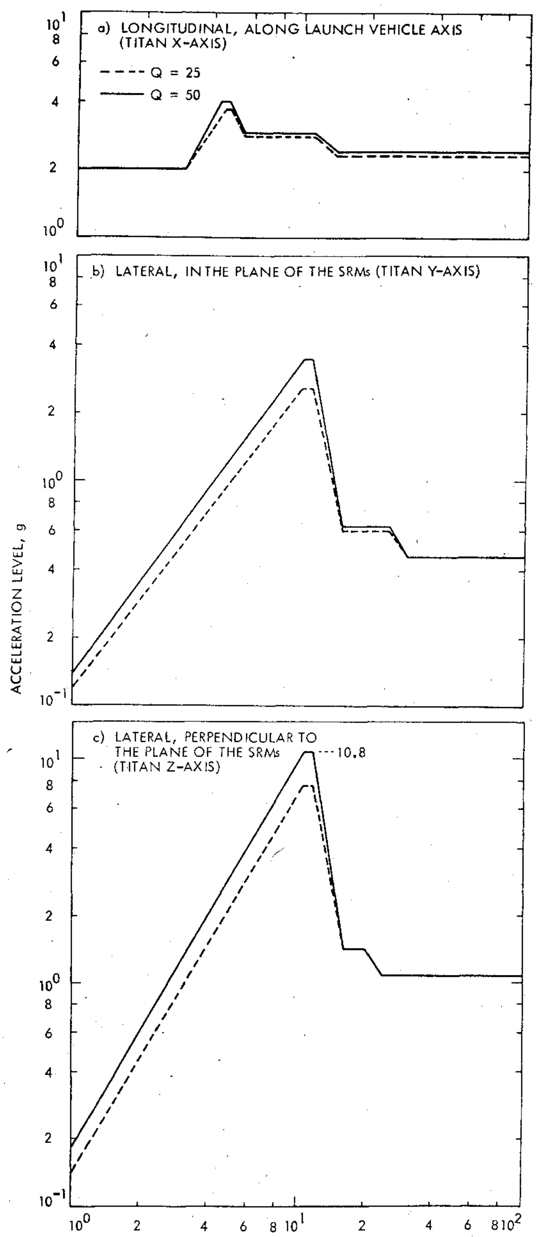

Fig. 4 Shock spectra for Stage 0 ignition.

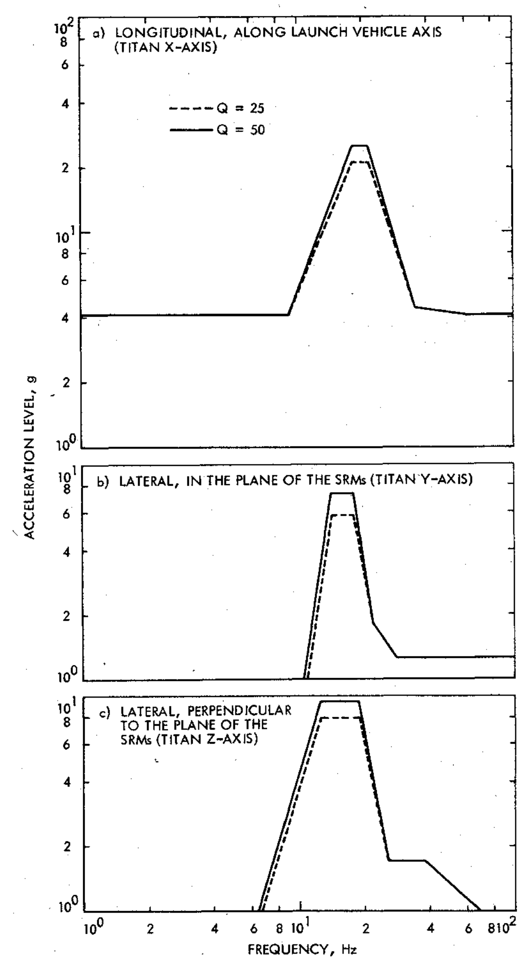

Fig. 5 Shock spectra for Stage I burnout.

method assumes an unloaded interface, it is shown[6,7] that shock spectra for an unloaded interface are within the envelope based on the existing loaded interface data. 3) Only translational shock spectra and impedances at the interface are considered; rotations are neglected. 4) Response shock spectra of future flights will be within a conservative envelope of those from prior flights. 5) The frequency distribution of the source of the disturbance is relatively flat compared to that of the interface accleration response.

Procedure

Internal Load Cycles

The spacecraft and launch vehicle are represented by normal modes. The spacecraft is cantilevered at its interface to the launch vehicle. The launch vehicle free-free modes are used. For the purpose of this paper, the launch vehicle normal modes include the Viking spacecraft. Launch vehicle normal modes including Helios or VDS could have also been used. The launch vehicle damping used is supplied by MMA and is based on flight experience. Typically the launch vehicle damping varies from $c/c_c = 0.015$ to $c/c_c = 0.030$. A damping of $c/c_c = 0.010$ and $c/c_c = 0.020$ was used for the spacecraft. Of the two values the one that gave the most conservative results was chosen.

Each spacecraft cantilever mode and launch vehicle mode having resonant frequencies in the same range are paired to account for differences in spacecraft frequencies between the analytical model and the flight hardware. Then the largest possible spacecraft modal response of this pairing is determined by allowing an artificial shift of the resonant frequency ration to produce the most adverse "tuning" between two modes.

Based on the experience gained from VDS, Helios, and Viking analysis and flight only two events are being considered for the MJS internal loads cycle: Stage 0 ignition and Stage I burnout.

The directional shock spectra for $Q = 25$ ($c/c_c = 0.02$) and $Q = 50$ ($c/c_c = 0.01$) which were used in evaluating the Viking loads are shown in Figs. 4 and 5. The shock spectra shown are based on VDS, Helios, and Viking analyses and Helios flight data.

Having determined the modal responses the member forces for each mode p^i can be determined by multiplying the modal force coefficients by the modal response. The total dynamic loading for each member is then determined by a root sum square (rss) technique, thus

$$F_D = \sqrt{\sum_i (p^i)^2} \qquad (1)$$

where F_D is the dynamic loading, and i are the spacecraft normal modes. The acceleration, or quasistatic, load component F_q is then added to obtain the total loading F_T

$$F_T = F_q \pm F_D \qquad (2)$$

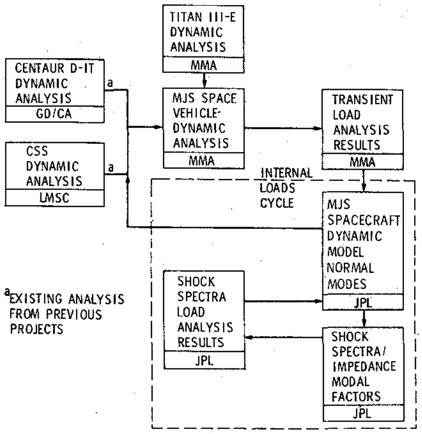

Fig. 6 Data flow for MJS internal and external loads analyses.

Once the eigenvalue solution of a new spacecraft is obtained the individual loads are calculated within two to three working days. It is estimated that the shock spectra method is 10 to 30 times faster and 30 to 60% less expensive than the transient loads analysis method. It should also be noted that the number of required eigenvalue solutions is reduced since the influence of shifts in frequencies due to design changes are considered in the impedance matching.

External Loads Cycles

The purpose of the external loads cycles using a composite space vehicle transient analysis was to verify the shock spectra approach, estimate its conservatism and verify the final flight loads. Figure 6 gives the flow diagram for the overall loads analysis process. A comparison of Fig. 2 with Fig. 6 shows the relative complexity of the Viking design procedure as compared to the MJS design approach.

The first cycle included the following events: Stage 0 ignition, maximum aerodynamic pressure, Stage I burnout, and Centaur main engine cutoff. The second cycle was an update of Stage 0 ignition. The last cycle will consist of verifying the MJS design for Stage 0 ignition, maximum aerodynamic pressure, and Stage I burnout.

Comparison of MJS Shock Spectra/Impedance Member Loads to Transient Loads

Results of the first and second MJS transient load cycles were used to verify that the shock spectra/impedance method was a valid approach for obtaining spacecraft loads. Two significant conclusions were drawn after comparing the loads for all members of the primary structure: 1) the shock spectra loads were higher than the transient loads for all members types showing that the shock spectra approach was conservative, and 2) the Stage 0 ignition and Stage I burnout shock spectra adequately covered the max. αq loading condition as assumed.

Typical ratios for the individual members of the MJS mission module (MM) adapter are shown in Table 3. The first two transient loads cycles have confirmed that the shock spectra method gave moderately conservative loads for MJS and that it could be used with high confidence.

V. Application of the MJS Loads Approach to the Viking Orbiter

Objective

The MJS design approach for obtaining member loads previously described was applied to the VO primary structure. Viking was chosen because it was originally designed to transient loads analysis, and because member force measurements were available from two flights, Viking A and Viking B.

The objectives were: 1) to determine the conservatism of the method; and 2) to estimate the weight penalty as applied to the Viking primary structure. The intent was to generate quantitative data for future projects and to further validate the use of the approach for MJS.

Assumptions

In addition to the assumptions used earlier for MJS, the Viking loads estimates are based on only one loads cycle. The normal procedure in either the transient or shock spectra/impedance approach is to iterate on the member forces and properties until the changes in the member properties are negligible. For Viking, an existing design was used to calculate the member loads using the shock spectra procedure. The eigenvalue problem was not re-solved for another cycle. The member loads obtained from this one cycle were then used as a comparison to the loads obtained from a transient analysis. An increase in structural weight for the Viking Orbiter due to the increased loads was then estimated.

VO Loads Using the Shock Spectra/Impedance Technique

The loads for Stage 0 ignition and Stage I burnout obtained using the MJS methodology for VLCA are given in Table 4. Table 5 gives the ratios of shock spectra loads to the

Table 3 Comparison of MJS mission module adapter loads shock spectra/impedance vs. transient loads analysis

		Stage 0 ignition	Stage I burnout	max αq
Member	Type of load	Ratio shock spectra/ transient	Ratio shock spectra/ transient	Ratio shock spectra/ transient
6801	C	1.46	3.22	1.91
	T	1.63	2.32	1.74
6802	C	1.35	2.91	1.64
	T	1.53	2.56	1.43
6803	C	3.38		1.50
	T	4.28		1.63
6804	C	3.27		1.75
	T	4.39		2.11
6805	C	1.38	4.39	1.70
	T	1.55	3.13	2.02
6806	C	1.39	3.59	1.55
	T	1.52	2.49	1.68
6807	C	3.57		1.41
	T	4.86		1.60
6808	C	3.32		1.78
	T	4.29		1.82

Table 4 Comparison of Viking shock spectra/impedance member loads to transient loads for the VLCA

		Stage 0 Ignition			Stage I Burnout		
Member No.	Type of Load	Shock Spectra lb	Transient, lb	Ratio Shock Spectra/ Transient	Shock Spectra lb	Transient, lb	Ratio Shock Spectra/ Transient
750	C	-7760	-2920	2.66	-7620	-3060	2.49
	T	6540	940		5400	2000	2.70
751	C	-7130	-2700	2.64	-4240	-1970	2.15
	T	6510	1790	3.64	3230	1790	1.80
752	C	-10650	-2290	4.65	-5160	-3100	1.66
	T	9450	390		3060	2110	1.45
753	C	-10210	-2890	3.53	-5780	-3050	1.90
	T	9010	930		3570	1900	1.88
754	C	-4400	-2820	1.56	-4890	-2170	2.25
	T	3830	1880	2.05	3970	1980	2.01
755	C	-8380	-2810	2.98	-6920	-3000	2.31
	T	7160	820		4870	2050	2.38

Table 5 Viking primary structure loads comparison of shock spectra vs transient analysis loads by groups

Structure	Member type	Type of load	Ratio Shock Spectra/ Transient Stage 0 Ignition & Stage I Burnout	Ratio Shock Spectra/ Transient Maximum αq
VLCA	750	C	2.74	2.44
		T	3.49	5.59
	751	C	2.53	2.35
		T	3.29	3.30
	752	C	3.44	2.94
		T	4.48	6.80
V-S/C-A	678	C	1.37	1.34
		T	4.14	1.79
	687	C	1.19	1.19
		T	1.50	1.43
	679	C	1.45	1.60
		T	1.72	2.00
Upper plane truss	726	C	1.23	1.47
		T	1.21	1.88
	728	C	1.14	3.08
		T	1.22	2.85
	730	C	2.20	2.66
		T	1.99	2.76
Propulsion Subsystem				
Top diagonals	3	C	2.10	3.21
		T	2.06	
Side diagonals	4	C	1.67	
		T	1.97	2.57
Bus Structure				
Main longerons	806	C	2.07	2.37
		T	3.18	
	810	C	2.23	
		T	2.11	2.58
	811	C	1.58	
		T	1.86	2.15
Lower ring moment, (in.-lb)	402	max	2.00	2.34
		min	2.08	2.39
Bedframe side	658	C	1.88	1.99
		T	1.54	4.01
Bedframe end	662	C	2.34	2.21
		T	1.92	2.44

Table 6 Estimated minimum increase in Viking orbiter structural weight using member loads obtained by the shock spectra/impedance method

Subsystem	Weight, lb	Weight Increase, lb	Percent of Increase
V-S/C-A	97.0	0.0	0.0
VLCA	20.3	2.6	12.8
Upper plane truss	9.5	0.1	0.0
Propulsion bipods	11.4	7.5	65.8
Bus bedframe	7.8	2.0	25.6
Bus longerons	47.8	0.7	0.0
Bus lower ring	31.6	2.6	8.2
Overall	225.4	15.5	6.9

maximum transient loads for the VO structure. Both maxima have been obtained from the same two launch vehicle events, and the members have been divided into groups using symmetry.

Before using the member loadings obtained from the shock spectra method to estimate a weight increase for the Viking Orbiter it is important to check the assumption that the MJS method does indeed envelop the loading for the maximum aerodynamic pressure (max αq). Table 5 shows that the maximum shock spectra loads are at least 19% above the transient loading for max. αq. The transient analysis for Viking, in turn, has been shown to be conservative by examining the flight data (Tables 1 and 2).

Estimates of Weight Increase for the Viking Orbiter

The Orbiter member loads shown in Table 5 were used to estimate a weight increase by resizing the individual members. Table 6 shows the minimum percent weight increase for the VO. Note that some subsystems, such as the spacecraft adapter, show no weight increase at all.

The weight increase of 6.9% shown in Table 6 is the minimum additional structural weight required as compared to the actual VO primary structure capability determined by the test program, not the analysis. In some cases the tested capability was much greater than the analytically predicted values. If analytically predicted capabilities were used as a reference, as would be done in designing the structure, the weight increase would be larger. Since the conservatism in structural design is dictated by factors such as manufacturing considerations, handling and design load conditions that changed in the course of the project, a weight increase of up to 50% might be possible. These considerations as they arose on Viking are reflected in Table 6 leading to an overall structural weight increase of only 6.9% for VO, using the shock spectra/impedance method rather than the transient loads analysis method.

Discussion of Results

The results presented in this paper show that the improved shock spectra/impedance method is an effective approach of obtaining spacecraft design loads for lower cost (30 to 60%) and improved schedule (10 to 30 times). The loads obtained for both Viking and MJS show a comfortable margin with some gain in weight. In applying the method to Viking, the following observations were made:

1) This method is only applicable for a launch vehicle system that has been previously flown or that has been the subject of transient loads analysis and/or where reliable flight data are available. The degree of confidence in the method is directly proportional to the quantity and quality of the flight or analytical data.

2) Some transient analyses for the verification of the method are recommended for any new spacecraft design. Ideally a transient loads verification would be made using a model verified by test. The results of such an analysis should be available before the static qualification test is conducted.

3) The weight estimates presented are min. increases and can be used as guidelines for future projects. The tradeoff of dollars/pounds of payload and dollars/transient analysis for each project will differ and will depend on payload weight limitation, fund limitation, and degree of confidence.

4) The method relies heavily on engineering judgment of the analyst, more so than the transient analysis. While both require judgement in structural modeling the shock spectra analysis requires a careful examination of the interface impedence matching. The following two areas of improvement are suggested: a) Expand the impedance matching to more than three interface translations, either by adding rotational shock spectra at the interface or by taking advantage of other translational degrees of freedom where flight measurements exist. b) Use unloaded launch vehicle normal modes rather than modes which contain a previously flown spacecraft. Reference 6 shows that the error of using a shock spectra derived from a loaded rather than an unloaded interface is acceptable. In the application of the method to VO it was found that some launch vehicle normal modes primarily consisting of spacecraft appendage local modes caused difficulty in the impedance matching leading to unrealistically high spacecraft loads. This problem might be eliminated by using unloaded launch vehicle normal modes. Launch vehicle modes loaded by a rigid rather than elastic spacecraft might also be considered.

References

[1]Howlett, J.T. and Raney, J.P., "New Approach for Evaluating Transient Loads for Environmental Testing of Spacecraft," *The Shock and Vibration Bulletin,* Bulletin 36, Part 2, Naval Research Lab., Washington, D.C., Jan. 1967, pp. 97-106.

[2]Trubert, M.R., "A Practical Approach to Spacecraft Structural Dynamics Problems," *Journal of Spacecraft and Rocket,* Vol. 9, No. 11, Nov. 1972, pp. 818-824.

[3]Trubert, M.R., Chisholm, J.R., and Gayman, W.H., "Use of Derived Forcing Functions at Centaur Main Engine Cutoff in Predicting Transient Loads on Mariner '71 and Viking Spacecraft," Jet Propulsion Laboratory, Pasadena, Calif., Technical Memorandum 33-486, June 28, 1971.

[4]Wada, B.K., "Viking Orbiter—Dynamics Overview," *The Shock and Vibration Bulletin,* Bulletin 44, Part 2, Naval Research Lab., Washington, D.C., Aug. 1974, pp. 25-39.

[5]Wada, B.K. and Garba, J.A., "Dynamic Analysis and Test Results of the Viking Orbiter," *ASME Winter Annual Meeting,* ASME Paper 75-WA/Aero 7, Houston, Texas, Nov. 30-Dec. 4, 1975.

[6]Bamford, R. and Trubert, M., "A Shock Spectra and Impedance Method to Determine a Bound for Spacecraft Structural Loads," Jet Propulsion Laboratory, Technical Memorandum 33-694, Pasadena, Calif., Sept. 1974.

[7]Bamford, R. and Trubert, M., "A Shock Spectra and Impedance Method to Determine a Bound for Spacecraft Structural Loads," AIAA Paper 75-811, Denver, Col., 1975.

[8]Day, F.D. and Wada, B.K., "Unique Flight Instrumentation/Data Reduction Techniques Employed on the Viking Dynamic Simulator," *presented at the 45th Shock and Vibration Symposium,* Dayton, Ohio, Oct. 1974.

[9]Day, F.D. and Wada, B.K., Strain Gaged Struts and Data Reduction Techniques to Maximize Quality Data from Spacecraft Flight Measurements," *presented at the 21st International Instrument Symposium, Instrument Society of America,* Phila., Penn., May 19 to 20, 1975.

[10]Bamford, R.M., Wada, B.K., and Gayman, W.H., "Equivalent Spring Mass System for Normal Modes," Jet Propulsion Laboratory, Pasadena, Calif., Technical Memorandum 33-380, Feb. 15, 1971.

[11]Wada, B.K., Bamford, R., and Garba, J.A., "Equivalent Spring-Mass System: A Physical Interpretation," *The Shock and Vibration Bulletin,* Bulletin 42, Part 5, Naval Research Lab., Washington, D.C., Jan. 1972, pp. 215-225.