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EXTRACTING A REPRESENTATIVE LOADING SPECTRUM FROM RECORDED FLIGHT DATA

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ABSTRACT

One of the more important ingredients when computing the life of a structure is the loading environment. This paper describes the development of an aircraft loading spectrum that closely matches the service experience, thus allowing a more accurate assessment of the structural life. The paper outlines the flight loads data collection system, the procedures developed to compile and interpret the service records and the techniques used to define a spectrum suitable for structural life analysis. The areas where the procedures were tailored to suit the special situation of the USAF B-1B bomber are also discussed. The results of the methodology verification, achieved by comparing the generated spectra with the results of strain gage monitoring during service operations, are also presented.

INTRODUCTION

The high cost of structural maintenance and the desire for a high rate of operational readiness place great emphasis on improving the analytic tools used to project the economic life of the structure and the inspection intervals necessary to ensure structural integrity. All the analytic models currently used for structural life assessment have a common ingredient, that of the loading environment. The importance of the load spectrum is evident when considering that a life variation of a factor of two (2) or more is not uncommon when the load magnitude varies by 10%.

Rockwell International has produced a spectrum generation procedure for the USAF B-1B Bomber. The B-1B, which entered service in 1984, is a variable swept wing aircraft designed to operate at low altitude and having terrain following capability in both automatic and manual modes. Each aircraft is equipped with a flight loads data recorder, built by Electrodynamics Inc., and designed to collect sufficient flight parameters to enable the construction of fatigue loads spectra representative of the service experience of the aircraft. By 1991 some 10,000 hours of data had been collected and compiled in a data base utilizing the specially written Loads / Environment Spectra Survey (L/ESS) program. This database was used in 1992 to provide stress spectra for a structural life assessment of the B-1B under service operations and to compare the service experience with the design criteria. The basis for representative spectrum generation was that the lifetime usage can be represented by a repeated application of a 100 flight spectrum in order to include all mission types that occur at least 1% of the time while eliminating very infrequent events. The spectrum was produced in terms of occurrences of aircraft center of gravity load factors (Nz) which were translated to local stresses in the structure utilizing the NASTRAN finite element program. The spectrum approach is based on the assumption that the external structural loads and the internal stresses are linear with respect to aircraft center of gravity load factor. Validation of the methodology was achieved by comparing the final stress spectrum at six structural locations with stress spectra compiled directly from the L/ESS strain gage records.

Spectra generated for the B-1B wing and fuselage included only symmetric flight maneuvers, vertical gusts and ground loads. Control of the B-1B in the roll axis is by means of differential movement of the horizontal stabilizers requiring the inclusion of both symmetric and roll maneuvers and vertical and lateral gusts in the empennage spectrum. For the purposes of simplicity and brevity the descriptions and tables in this paper reflect only the symmetric loads.

FLIGHT LOADS DATA RECORDER

On Aircraft Monitoring and Recording

The collecting of operational data is performed by a microprocessor based solid state data collection and storage device, known as the Structural Data Collector (SDC), linked to multiple dedicated L/ESS sensors and with connections to non L/ESS aircraft sub systems. The SDC accepts both analog and digital inputs, and performs parameter sampling, real time data validation, data compression and archival storage of time history data received from a variety of sensors. The SDC receives analog inputs from three linear accelerometers for aircraft acceleration data, structural strain data from six strain gages, and control surface position data. The majority of the signals received by the SDC are provided via the Central Integrated Test System (CITS) serial digital link. CITS monitors various aircraft systems, including the Central Air Data Computer, Fuel CG Management System, Stability and Control Augmentation System and the Engine Monitoring System, for parameters required by the SDC. TABLE 1 defines the list of parameters monitored and processed by the SDC. The CITS Control and Display Panel allows the manual entry of the necessary mission documentation to the SDC. This is also defined in TABLE 1.

Each parameter is sampled at rates appropriate to that parameter. Sample rates range from once (1) per second to forty (40) times per second. Analog parameters are initially digitized using an eight (8) bit analog to digital conversion. Each parameter is then validated to protect the SDC memory from erroneous information. Validation testing includes a maximum and minimum allowable value test, a maximum allowable rate of change test and an excessive activity test. After validation each parameter is processed through one of three data compression algorithms. These algorithms significantly increase the number of flight hours of data that can be stored in the SDC memory by systematically eliminating insignificant or redundant information.

The following is a general description of the three data compression algorithms:

1) Parameters that are cyclic in nature such as strain gages records are compressed using a peak valley search routine. The procedure locates and saves only local maxima and minima that represent cycles greater than a specified threshold criterion. All intermediate data points are discarded.
2) Smoothly varying parameters such as altitude are compressed by a moving window technique called time history compression. This procedure saves a value whenever its current value has changed by at least a predetermined amount from the last recorded value. Some parameters are time hacked to a time history parameter, that is they are recorded whenever the primary time history parameter is recorded. An example of this is the center of gravity position which is recorded when the gross weight is recorded.
3) Engine parameters are processed through a special compression algorithm which combines aspects of both peak valley and time history compression with special logic tailored to the unique inter-relationship of the engine parameters.

The data compression methods and the necessary numeric threshold constants are also shown in TABLE 1.

Validated, compressed data is stored in the SDC memory for later extraction and ground processing. Depending on the relative severity of flight activity, data compression allows the SDC to hold 40 to 80 flight hours of recording between data extractions.

Data Extraction Procedures

At scheduled intervals, or when the post flight CITS output indicates that the SDC memory is filled to capacity, the stored flight information is extracted from the SDC memory and transcribed to floppy disks at a ground transcribing station.

Parameter	Unit	Signal Type	Data Compression Method	Sample Rate /sec	Compression Constants	
					Threshold	Delta
Strain Gages						
Stabilizer Support Fitting Left Hand Side	ksi	Analog	PV	40	None	6.19
Stabilizer Support Fitting Right Hand Side	ksi	Analog	PV	40	None	6.19
Stabilizer Support Fitting Side Plate	ksi	Analog	PV	40	None	8.25
Wing Sweep Actuator	k lb	Analog	PV	40	None	42.70
Wing Lower Skin	ksi	Analog	PV	40	None	4.00
Forward Fuselage Dorsal Longeron	ksi	Analog	PV	40	None	8.29
Vertical Acceleration (Nz) (Air)	g	Analog	PV+A	40	0.77/1.2	0.14
Vertical Acceleration (Nz) (Ground)	g	Analog	PV+A	40	0.84/1.13	0.14
Lateral Acceleration (Ny) (Air)	g	Analog	PV+A	20	+/- 0.101	0.10
Lateral Acceleration (Ny) (Ground)	g	Analog	PV+A	20	+/- 0.047	0.05
Longitudinal Acceleration (Nx) (Air)	g	Analog	PV+A	20	+/- 0.094	0.09
Longitudinal Acceleration (Nx) (Ground)	g	Analog	PV+A	20	+/- 0.062	0.06
Pitch Rate	deg/sec	Digital	PV+A	8	+/- 2.10	2.10
Yaw Rate (Air)	deg/sec	Digital	PV+A	8	+/- 4.88	4.88
Yaw Rate (Ground)	deg/sec	Digital	PV+A	8	+/- 2.10	2.10
Roll Rate	deg/sec	Digital	PV+A	8	+/- 1.05	1.05
Pitch Acceleration	deg/sec^2	Digital	PV+A	8	+/- 25.2	5.60
Roll Acceleration	deg/sec^2	Digital	PV+A	8	+/- 46.8	15.62
Yaw Acceleration	deg/sec^2	Digital	PV+A	8	+/- 16.8	5.60
Wing Sweep Angle	degrees	Analog	TH+C	1	None	2.05
Flap Position	degrees	Digital	TH	1	None	4.03
Left Horizontal Stabilizer Position	degrees	Analog	THKA	20	None	None
Right Horizontal Stabilizer Position	degrees	Analog	THKA	20	None	None
Left Inboard Spoiler Position	degrees	Analog	THKA	20	None	None
Right Inboard Spoiler Position	degrees	Analog	THKA	20	None	None
Upper Rudder Position	degrees	Analog	THKA	20	None	None
Gross Weight	lbs	Analog	TH+C+D	1	None	4600.00
Center of Gravity	%MAC	Digital	THKC	1	None	None
Fuel Weight	lbs	Digital	THKD	1	None	None
Mach Number		Digital	TH	1	None	0.02
Airspeed	kts	Digital	TH	1	None	7.66
Altitude (Pressure)	ft	Digital	TH+E	1	None	237.00
Altitude (Radar)	ft	Digital	THKE	1	None	None
Wheel Speed (Main Gear)	kts	Digital	TH	1	None	None
Engine No. 2 Fan Speed	%	Digital	EPV	1	None	None
Engine No. 2 Core Speed	%	Digital	EPV	1	None	None
Engine No. 2 Power Lever Angle	degrees	Digital	EPV	1	None	4.80
Weight on Wheels (on/off)		Digital	disc	1	None	None
Main Gear Down		Digital	disc	1	None	None
Refuel Nozzle Latch (connect/unconnect)		Digital	disc	1	None	None
Structural Mode Control System (on/off)		Digital	disc	1	None	None
Terrain Following Status		Digital	disc	1	None	None
On/Off		Digital	disc	1	None	None
Manual/Auto		Digital	disc	1	None	None
Ride (soft/medium/hard)		Digital	disc	1	None	None
Engine Number 1 Stop		Digital	disc	1	None	None
Engine Number 2 Stop		Digital	disc	1	None	None
Engine Number 3 Stop		Digital	disc	1	None	None
Engine Number 4 Stop		Digital	disc	1	None	None

Disc - Discrete Signal
PV - Peak-Valley Compression Algorithm
EPV - Engine Compression
TH - Time History Compression
TH+C - Time History with group C time hack (typical)
PV+A - Peak Valley with group A time hack (typical)
THK A - Time Hack Parameter Group A (Typical)

DOCUMENTORY ITEMS
Aircraft Serial Number
Mission Date
Take Off Gross Weight
Stores Weight
Mission Type Code
Base Code

TABLE 1 - SDC Parameter List

GROUND BASED PROCESSING PROGRAMS

A software package, shown in FIGURE 1 and consisting of three major programs, performs the task of accumulating the flight loads data received from the field and processing the data through validation programs and compiling the L/ESS database. The L/ESS database contains three major sections, namely USAGE STATISTICS containing the information necessary to reconstruct the B-1B mission profiles, LOAD FACTOR RECORDS compiled from accelerometer data and STRAIN GAGE RECORDS containing the data from the six strain gages.

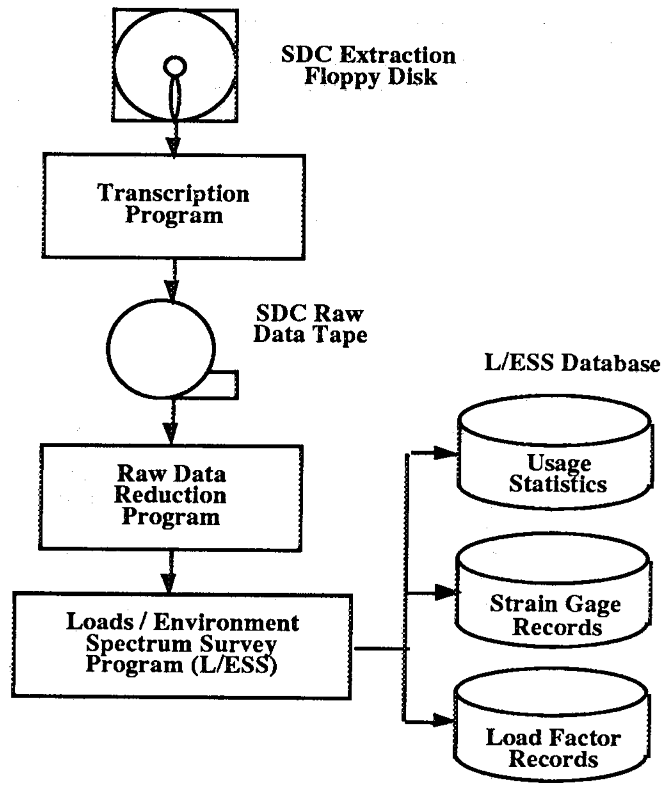

FIGURE 1 - Flow Chart for L/ESS Program

Transcription Micro-computer Program

The first program in chain is the Transcription Micro-computer Program which provides the micro-computer to main frame interface. This program was developed by the USAF at the Aircraft Structural Integrity Management Information Systems (ASIMIS) facility and was specifically tailored to the USAF hardware/ software environment. The floppy disks as received from the field are copied onto mainframe compatible storage media (disk files or magnetic tape). The data contained therein is copied, byte by byte, without reformatting onto a mainframe accessible storage device. The output file provides the input to the raw data reduction mainframe software.

Raw Data Reduction (RADAR) Program

The RADAR program converts the recorded SDC information into sequenced time histories of each recorded parameter in engineering units. The program is equipped with sort routines to separate the data by aircraft and sort in date sequence, based on the dates provided in the SDC documentary data. The output of the program is passed to the L/ESS program.

A 'VALIDATION' module evaluates the SDC records for validity and suitability for further processing. If key aspects are missing, clearly invalid or inconsistent with other data, an entire flight may be declared invalid. Flights are declared invalid, for example, if the aircraft serial number identification has been omitted from all documentary records on a particular data extraction from the SDC. Another cause of invalid data is those flights for which the data is incomplete (flights appear to end in the air) due to saturation of the SDC memory or loss of communication between the SDC and CITS. Individual parameters are also evaluated and may be declared invalid. Validity checks include monitoring coincident values of various parameters such as Mach number and altitude for combinations outside the aircraft envelope. A not infrequent occurrence is 'drop out' where a parameter records an extreme value and returns to normal. These are detected and corrected. Extensive printed diagnostics allow the analyst to monitor automated validation decisions made by the program.

The L/ESS program performs additional validation analysis and interprets the raw recorded data into convenient statistical parameters that can be stored in the L/ESS database. The approach is to block the mission data into discrete periods or mission segments characteristic of a particular type of flying or ground taxi operation, and categorize the information into the three relational databases.

The time history records of aircraft weight, wing sweep, altitude and Mach number, simplified samples of which are shown in FIGURE 2, together with the documentary data, are used to classify each flight profile using a pattern recognition procedure.

A description of the current 34 mission type classifications is shown in TABLE 2. Once the mission profile has been classified, the mission data is broken down into discrete mission segments for which the selection criteria are shown in TABLE 3. Engineering review of plots of selected mission profile parameters ensures correct classification assignments and the addition of new profile or segment classes as necessary. Extensive statistics, shown in TABLE 4, are stored for each segment of each mission type. These statistics, which maintain the frequency of occurrence of the segment and running average values for each

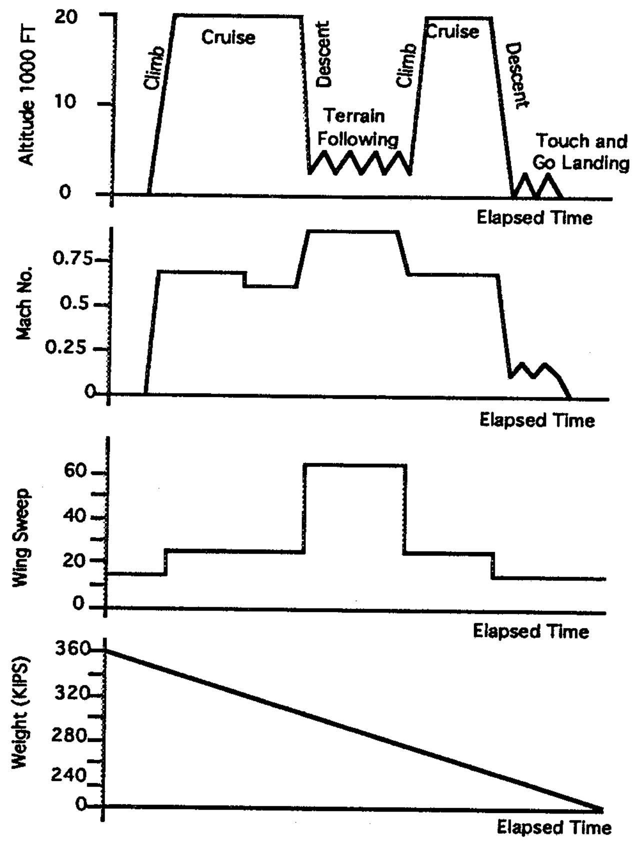

FIGURE 2 - Typical Profile Parameters

Mission Code		Mission Definition
Normal Weight	Heavy Weight	
1	1H	Training mission with at least 1 low altitude / high speed segment flown with terrain following system ON and with wings in aft position
2	2H	Training mission with at least 1 low altitude / high speed segment flown with terrain following system OFF and wing in aft position
3	3H	High altitude training mission with NO low altitude / high speed segment
4	4H	Ferry flight
5	5H	Functional check flight
6	6H	Ground alert - NO take off
7	7H	Airborne alert
8	8H	Operational mission similar to mission 1
9	9H	Operational mission similar to mission 2
10	10H	Operational mission similar to mission 3
11	11H	Pilot proficiency training
12	12H	Aircraft flight test mission
13	13H	General test support
14	14H	Training mission with at least 1 low altitude / high speed segment flo· n wit· terrain following system ON and at least 1 LHAS segment with wings less than 30 degrees
15	15H	Training mission with at least 1 low altitude / high speed segment flown with terrain following system OFF and at least 1 LHAS segment with wings less than 30 degrees
16	16H	Operational mission similar to mission 14
17	17H	Operational mission similar to mission 15

NOTE Normal weight missions have maximum in flight gross weight less than 375000 lbs
Heavy weight missions have maximum in flight gross weight greater than 375000 lbs

TABLE 2 - Mission Types

Segment Label	Definition
Take off run	Ground operations taken from 40 kt wheel speed to lift off
Touch and go taxi	Ground operations following a TAG touchdown and preceding a TAG liftoff
Landing runout	Ground operations taken from touch down to full stop
Miscellaneous taxi	Ground operations not otherwise defined
Full stop	Static ground time
Post take off climb	Rapid increase in altitude from lift off to flaps/gear retraction
Other climb	Any rapid significant increase in altitude not otherwise defined
Low cruise	Extended flight with no significant change in altitude. Average altitude less than 15000 ft and Mach/altitude combination that does not classify as LAHS segment
High cruise	Extended flight with no significant change in altitude. Average altitude greater than 15000 ft
Low refuel	In flight refuel operations with average altitude less than 15000 ft
High refuel	In flight refuel operations with average altitude greater than 15000 ft
Other descent	Any rapid significant decrease in altitude not otherwise defined
Pre Terrain following descent	Rapid decrease in altitude immediately preceding low altitude /high speed or terrain following segment
Post Terrain following climb	Rapid increase in altitude immediately following low altitude /high speed or terrain following segment
Low altitude/high speed	Low altitude / high speed flight performed with terrain following system off
Terrain Following (manual-soft)	Low altitude / high speed flight performed with terrain following system in manual mode and ride set to soft ride
Terrain following (manual-medium)	Low altitude / high speed flight performed with terrain following system in manual mode and ride set to medium ride
Terrain following (manual-hard)	Low altitude / high speed flight performed with terrain following system in manual mode and ride set to hard ride
Terrain following (auto-soft)	Low altitude / high speed flight performed with terrain following system in automatic mode and ride set to soft ride
Terrain following (auto-medium)	Low altitude / high speed flight performed with terrain following system in automatic mode and ride set to medium ride
Terrain following (auto-hard)	Low altitude / high speed flight performed with terrain following system in automatic mode and ride set to hard ride
Airwork - low altitude	Flight operations characterized by large numbers of maneuvers and changes in altitude with an average altitude less than 15000 ft
Airwork - high altitude	Flight operations characterized by large numbers of maneuvers and changes in altitude with an average altitude above 15000 ft
Go around (pattern flying)	Local landing pattern flight associated with touch and go landings and low approaches
Pre landing descent	Rapid decrease in altitude immediately preceding a TAG or full stop landing - from flaps/gear down to landing
Supersonic dash - low	Supersonic flight operations with average altitude below 15000 ft
Supersonic dash - high	Supersonic flight operations with average altitude above 15000 ft

TABLE 3 - Mission Segment Types

parameter, will be the basis for the compilation of the flight profiles for analysis. In addition, records are maintained for selected mission events, notably take offs, full stop and touch and go landings, landing gear extensions, flap and wing sweep operations and terrain following conditions.

The take off and landing statistics include the total number of the occurrences of the event, and the average condition defined by aircraft weight, c.g position, wing sweep and flap angles, velocity and thrust. The wing and flap movement events are defined in terms of the number of events and distributions of the degrees of movement. The terrain following statistics include distributions by time of aircraft weight, Mach number, altitude as well as the time operating in the manual or automatic modes and under various ride severity modes.

Number of times the segment recorded
Total time
Average Mach number
Average altitude
Average weight
Average c.g. position
Average fuel quantity
Average wing sweep
Average velocity
Average thrust
Average radar altitude
Total Structural Mode Control System (SMCS) time
Average segment start time (from mission start)
Total gear down time
Number of engine after burner operations
Number of gear extensions
Number of flap extensions (closed to partial)
Number of flap extensions (closed to open)
Total engine idle time
Total engine intermediate power time
Total engine MIL power time
Total engine afterburner time.

TABLE 4 - Data Stored for each Mission Type/Mission Segment/Wing Sweep Condition

The load parameters provided by the accelerometers and the strain gages are recorded by the SDC as load traces defined as a sequence of peaks and valleys with time tags. Each peak and valley from the strain gage trace is assigned to the mission classification and mission segment based on the time tag correlation with the flight profile records. Each load cycle is stored in a 'range/mean' matrix in a cell defined by the load range and mean value of the cycle as shown in FIGURE 3. The load factor data is dealt with in a similar manner except that each cycle is first designated as being due to a gust or a pilot induced maneuver. High frequency cycles are determined to be gusts and the remainder defined as maneuvers. The maneuver load cycles are classified by mission type, mission segment, wing sweep angle and flap position, while the gust load cycles are classified by wing sweep, altitude, Mach number and weight. TABLE 5 shows the list of eighty one (81) gust, maneuver or ground classifications extracted from more than 10000 classifications collected by the L/ESS program. Selection was based on those classes for which the maximum amount of data was recorded. Range/mean tables provide a better definition of a random load spectrum than does the more commonly used cumulative occurrence data of peaks and valleys especially when the spectrum contains significant variation of mean loads. This is particularly important for the B-1B due to the variable wing sweep causing significant variation in mean load. Furthermore, the terrain following requirement results in the aircraft being subjected to gust loads while experiencing significant maneuver loads. Small cycles are accurately placed about elevated means and the collected data can be readily reconstructed.

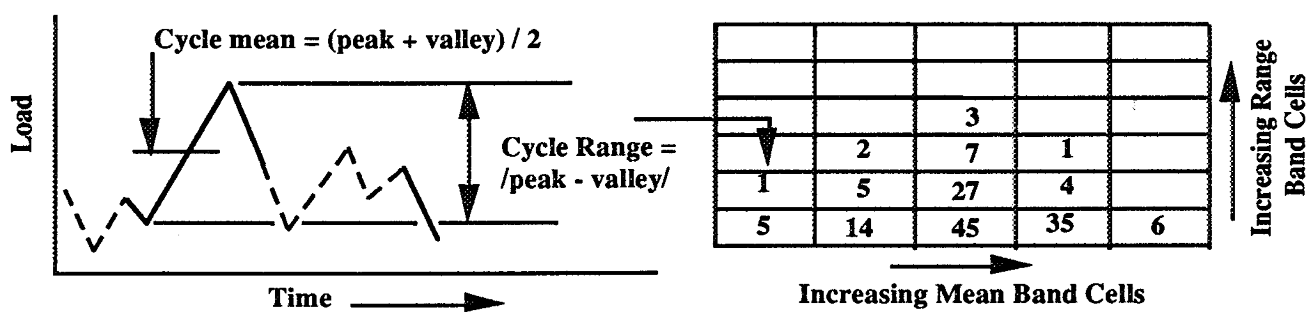

FIGURE 3 - Range/mean Table Defintiion

Load Type	Data ID	Mission Segment	Wing Angle	Flap Position	Altitude	Weight	Mach No.
Maneuver	1	Post Take Off Climb	< 22.5	Extend			
	2	Climb	< 22.5	Extend			
	3		< 22.5	Up			
	4		22.5 - 30				
	5		> 60				
	6	Cruise	< 22.5	Extend	< 15000		
	7		< 22.5	Extend	> 15000		
	8		< 22.5	Up	< 15000		
	9		< 22.5		> 15000		
	10		22.5 - 30		< 15000		
	11		22.5 - 30		> 15000		
	12		50 - 60				
	13		> 60		< 15000		
	14		> 60		> 15000		
	15	Refuel	22.5 - 30				
	16	Descent	< 22.5	Extend			
	17		< 22.5	Up			
	18		22.5 - 30				
	19		> 60				
	20	Pre Terrain Following Descent	22.5 - 30				
	21		> 60			<315	
	22					> 315	
	23	Post Terrain Following Climb	22.5 - 30			< 310	
	24					> 310	
	25		> 60			< 310	
	26					> 310	
	27	Low Alt (Terrain Following System Off)				< 310	
	28					> 310	
	29	Terrain Following Automatic- Hard Ride				< 310	
	30					< 310	
	31	Terrain Following - Automatic - Med Ride					
	32	Terrain Following - Automatic- Soft Ride				< 310	
	33					> 310	
	34	Airwork	22.5 - 30				
	35		> 60				
	36	Go Around & Pattern Flying	< 22.5	Extend			
	37		< 22.5	Up			
	38	Pre-landing Descent	< 22.5	Extend			
	39		< 22.5	Up			
Vertical Gust	40	All	< 22.5	Extend	< 1 AGL	200 - 250	< 0.4
	41				2.5 - 5		
	42				< 1 AGL	250 - 300	
	43				2.5 - 5		
	44				15 - 20		
	45				< 1 AGL	300 - 350	
	46				2.5 - 5		
	47	All	< 22.5	Up	2.5 - 5	200 - 250	0.4 - 0.6
	48				2.5 - 5	250 - 300	
	49				5 - 7.5		
	50				7.5 - 10		
	51				10 - 15		
	52	All	22.5 - 30		10 - 15	250 - 300	0.6 - 0.8
	53				15 - 20		
	54				20 -30		
	55				10 - 15	300 - 350	
	56				15 - 20		
	57				20 - 30		
	58	Refuel	22.5 - 30		15 - 20	250 - 300	
	59				20 - 30		
	60	All	50 - 60		15 - 20	250 - 300	0.8 - 0.9
	61				20 - 30		
	62				15 - 20	300 - 350	
	63				20 - 30		
	64	All	> 60		< 1 AGL	250 - 300	0.8 - 0.9
	65				2.5 - 5		
	66				5 - 7.5		
	65				7.5 - 10		
	68				10 - 15		
	69				15 - 20		
	70	All	> 60		< 1 AGL	300 - 350	
	71				2.5 - 5		
	72				5 - 7.5		
	73				7.5 - 10		
	74				10 - 15		
	75				15 - 20		
Ground	76	Taxi				200 - 250	
	77					250 - 300	
	78					300 -350	
	79					> 350	
	80	Pre-Flight Braking					
	81	Post Flight Braking					

TABLE 5 - Load Factor Data Records

COMPILING FLIGHT BY FLIGHT SPECTRA FROM THE L/ESS DATABASE

The spectrum generation procedure, shown diagramatically in FIGURE 4, comprises the following tasks:

a) Extract the mix of flight profiles that comprise the 100 flight representative usage, from the L/ESS database to become input to the spectrum generation program
b) Reconstruct mission profiles from the L/ESS database to become input to the spectrum generation program. The flight profiles must be sufficiently detailed to describe the aircraft operational and loading environment.
c) Generate local stress spectra at desired locations in the airframe structure using the flight profiles data, the mission mix statistics and accessing the L/ESS load factor database and the database of structural internal loads solutions from NASTRAN covering the required flight conditions.

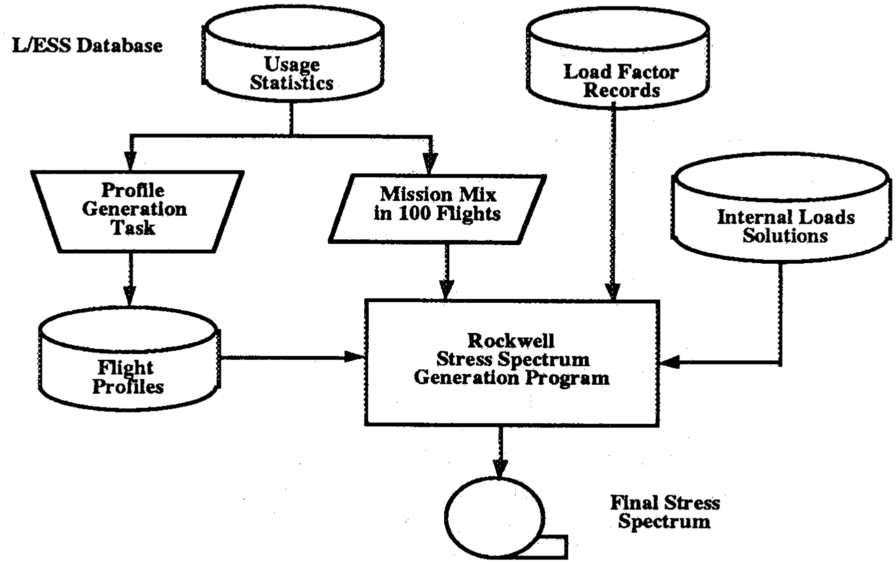

FIGURE 4 - Overview of Spectrum Generation Procedure

Mission Mix Representing Aircraft Service Usage

The first task is to establish the distribution of the available mission profiles that will represent the service experience of the B-1B. Interrogation of the L/ESS data base reflected that there were eight profiles that occurred at least once in 100 flights, the criteria chosen for a representative mission mix. That mix is shown in TABLE 6. It should be noted that mission type 1 is sub-divided into mission 1a and 1b. This was to accommodate the statistic that the number of terrain following segments approximated 1.5 per mission. Similarly mission types 2 and 3, where statistically air refueling occurs on every other flight, are subdivided.

Mission Code	Occurrences. per 100 flts	Mission Definition	Mission Flt Hours
		Training Missions	
1a	21	2 low altitude/high speed segments & terrain following ON	5.77
1b	21	1 low altitude/high speed segment &terrain following ON	3.91
2a	8	1 low altitude/high speed segment & terrain following OFF with air refuel	5
2b	7	1 low altitude high speed segment & terrain following OFF without refuel	5
3a	10	High Altitude with air refuel	3.65
3b	10	High Altitude without refuel	3.65
1H	2	Heavy weight mission 1	6.14
2H	2	Heavy weight mission 2	6.89
		Other	
4	6	Ferry flight	4.02
5	1	Functional check flight	2.25
11	12	Pilot proficiency flight	0.99
		Average for 100 flights	4.16

TABLE 6 - Mission Mix in 100 Flights

Detailed Mission Profiles

Considerable engineering judgment is applied to the task of reconstructing flight profiles from the L/ESS database statistics. The goal is to include all events that will cause changes in the structural loads and thus impact the computed fatigue life. The development of fracture mechanics analysis tools which account for loading sequence when computing crack growth rates has required attention to be paid to the sequence of mission segments and events as well as the magnitude of the loads. The detailed sequential flight profiles, a sample of which is presented in TABLE 7, are constructed with the following criteria to maintain consistency with the service records:

a) All mission segments that occurred, on average, in every mission are included and sequenced appropriately. The sequence is defined by a combination of logical segment sequence for a mission from take off to landing and a survey of many collected profiles plots such as those in FIGURE 2.
b) Mission segment times are consistent with the L/ESS statistical distribution adjusted to provide the recorded average flight length.
c) Average flight parameters of wing sweep, gross weight, altitude, and Mach number are taken from the L/ESS statistics with adjustments, applied if necessary, to ensure consistency with the mission segment sequence. Typical adjustments include those to the gross weight to reflect declining weight as fuel is used. Parameters such as wing sweep and flap position are refined to the normal available operating positions.
d) The spectrum profiles are then refined to match the number of significant events recorded in the L/ESS database. Among these are the number and degrees of wing sweep activities, the number of flap cycles, number of landings, distribution of terrain following situations such as automatic or manual flying, soft or hard ride setting and activation of the structural mode control system.

The profiles are stored on a database for convenient accessing by the spectrum generation program.

Segment Title	Time (mins.)	Weight (kips)	cg position % mac	Altitude (1000 ft.) AGL	Mach No.	Thrust (kips)	Wing (degrees)	No. of Touch and Go Landings	Flap (degrees)	No. of Flap Ops	Flaps Down Time (mins.)
Pre-flight	5.0	342.	20.7	0.0	0.00	28.7	15.0		25	0	5.0
Post Take Off	0.4	342.	20.2	0.5	0.33	30.9	15.0		25	1	0.4
Climb	11.7	323.	29.2	12.0	0.66	15.2	25.0		0	0	0.0
Cruise - High	53.0	323.	29.2	20.0	0.69	8.0	25.0		0	0	0.0
Descent	4.8	315.	28.9	16.0	0.66	1.7	25.0		0	0	0.0
Cruise - Low	9.2	315.	28.9	12.0	0.62	6.8	25.0		0	0	0.0
Pre T F Descent	3.6	307.	31.4	9.0	0.85	4.2	67.5		0	0	0.0
T F Hard Ride (Auto TF)	9.1	294.	30.0	0.9	0.85	7.6	67.5		0	0	0.0
TF System Off (Manual)	9.7	294.	30.0	1.2	0.85	7.7	67.5		0	0	0.0
T F Soft Ride (Auto TF)	12.9	294.	30.0	0.9	0.85	7.6	67.5		0	0	0.0
Post T F Climb	2.8	292.	31.2	9.0	0.85	10.9	67.5		0	0	0.0
Cruise - Low	6.5	292.	31.2	11.0	0.85	8.2	67.5		0	0	0.0
Pre T F Descent	3.0	292.	31.2	8.0	0.85	4.2	67.5		0	0	0.0
T F Hard Ride (Auto TF)	9.1	281.	30.0	0.9	0.85	7.6	67.5		0	0	0.0
TF System Off (Manual)	9.7	281.	30.0	1.2	0.85	7.7	67.5		0	0	0.0
T F Soft Ride (Auto TF)	12.9	281.	30.0	0.9	0.85	7.6	67.5		0	0	0.0
Post T F Climb	3.0	281.	30.0	9.0	0.85	10.9	67.5		0	0	0.0
Post T F Climb	5.5	262.	29.2	18.0	0.66	13.2	25.0		0	0	0.0
Refuel - High	26.9	291.	30.1	20.0	0.69	8.0	25.0		0	0	0.0
Cruise - High	97.0	262.	29.2	20.0	0.69	8.0	25.0		0	0	0.0
Descent	7.9	255.	24.1	14.0	0.51	0.8	15.0		0	0	0.0
Pre-land Descent	12.4	245.	18.2	1.3	0.33	5.9	15.0		25	0	12.4
Go Around	35.0	245.	18.2	1.7	0.41	7.1	15.0	5	25	2	29.2
Post Flight	5.0	238.	18.9	0.0	0.00	2.2	15.0		25	0	5.0

TABLE 7 - Typical Mission Profile

Database of Load Factor Occurrence Data

A summary of the available records selected from L/ESS database of load factor occurrence data are shown in TABLE 5. The load factor occurrence data are stored in "range/mean format" in a database for use by the spectrum generation program. The number of flight hours and missions represented by each range/mean table are also stored.

Database of Internal Loads Solutions

On the basis of the defined flight profiles, a series of external load conditions was developed to cover all mission segments within the flight profiles. In general, for each flight condition - defined by gross weight, cg position, Mach number, altitude and aircraft configuration (wing angle and flap position) - the following load conditions were generated:

a) 1g conditions (42 conditions)
b) Conditions representing a delta 1g maneuver (42 conditions)
c) Conditions representing a delta 1g vertical gust (8 conditions)

In addition, ground loads were developed for a series of aircraft gross weights (6 conditions).

The basic approach that the external and internal loads are linear with respect to load factor allows the computation of loads for any load factor by combining the 1g loads with factors of the incremental gust and maneuver loads. The internal loads database was established to hold the internal forces and stresses for all members in B-1B complete airframe NASTRAN finite element model and to extract same by model member identification, type and load direction.

SPECTRUM GENERATION PROCEDURE

The stress spectrum generation task in FIGURE 4 is performed with a Rockwell written computer program, which incorporates the procedure shown in FIGURE 5. The spectrum program offers the following spectrum control options:

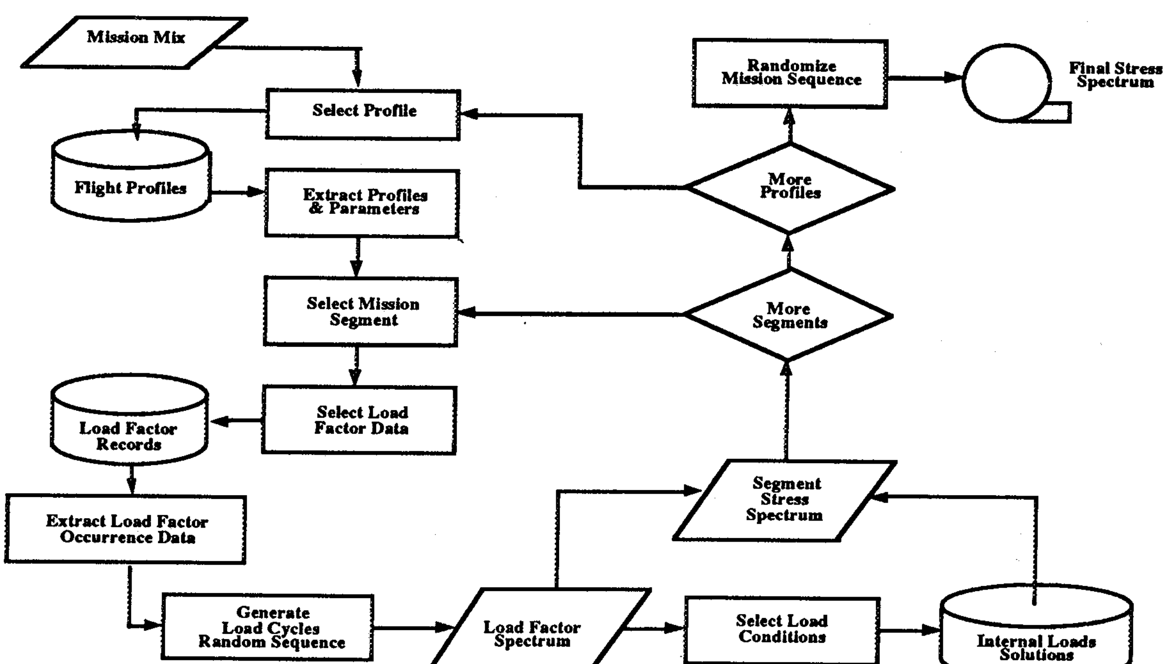

FIGURE 5 - Spectrum Generation Flow Chart

a) Sequencing of loads within a mission segment (high/low, low/high or random). Random sequencing selected for the B-1B spectrum.
b) Clipping of infrequent high loads - High loads that occurred less frequently than once in 100 flights were not included in the B-1B spectrum.
c) Truncation of low loads - Load cycles for which the range (maximum load factor - minimum load factor) was less than 0.2g were removed from the B-1B spectrum.

The FIGURE 5 flowchart shows how the program loops through all required mission profiles, flight segment by flight segment. The primary tasks are to select the load factor data and create a load factor spectrum. The load factor spectrum is then related to the NASTRAN conditions by means of a code defining the appropriate internal loads conditions and the applied factors to obtain the structural stresses corresponding to the load factor.

Selection and Interpretation of Load Factor Data

The program selects appropriate data from the list of available range/mean records (TABLE 5) and converts the data to a number of randomly sequenced discrete load factor cycles representing the flight segment time. The range/mean data selection from TABLE 5 is based on the mission segment title, the flight profile parameters and aircraft geometry parameters for that segment. Typically both maneuver and gust data are selected for flight segments. Ground segments will typically select taxi and braking data.

The number of cycles extracted for each flight segment is defined by:

$$\text{Flight segment time} \quad * \quad \frac{\text{total number of cycles in the range/mean table}}{\text{total time represented by the range/mean table}} \qquad (1)$$

Individual cycles are randomly selected using a select and not replace procedure to ensure the cyclic statistics are maintained. The range/mean file is re-supplied if the number of cycles in the table is less than the number required for the mission segment.

For range/mean data defined as maneuver data or taxi data the load cycle is defined as:

The mean load factor +/- 1/2 the range factor (2)

Range/mean data defined as gusts are interpreted as follows:

The magnitude of the gust is + /- 1/2 the range load factor
superimposed on a maneuver condition defined by the mean load factor. (3)

Range/mean data defined as braking conditions are defined as a cycle with:

Maximum load of the braking force (Nx) combined with a 1g taxi condition (4)
Minimum load equal to the 1g taxi load.

Load Factor and Stress Spectrum Generation

Load cycles defined in terms of mean load factor and range are selected from within the statistics of the range/mean data to represent the mission time defined in the flight profile. The load cycles which occur less than once per flight are distributed statistically to the various missions using this range mean table. Peak and valley load factors are computed from the range and mean load factor. Each peak and valley in the load factor spectrum carries an identification code defining the mission segment, the flight parameters such as weight, Mach number, altitude and geometry for which the load factor was derived. The code also reflects if the load factor was due to a gust, maneuver or ground condition.

Load factors are converted to stresses by relating the identification code to one or more of the NASTRAN solutions referred to above and applying the appropriate load factors. Stress spectra at any location in the airframe structure are available on demand by program operators by selecting the airframe component and the NASTRAN element numbers representing the structural location under consideration.

The forces or stresses from multiple NASTRAN elements can be combined using any arithmetic function to define the stress at the required structural detail.

SPECTRUM GENERATION METHODOLOGY VERIFICATION

The spectrum generation methodology was verified by comparing the stress spectra generated using the methodology outlined above with stress spectra compiled directly from strain gage records collected within the L/ESS program. Six strain gages are installed on every B-1B at the locations defined below.

- Strain gage 1 - Right hand arm of the stabilizer support fitting
- Strain gage 2 - Left hand arm of the stabilizer support fitting
- Strain gage 3 - Side plate of the stabilizer support fitting below the horizontal stabilizer
- Strain gage 4 - Wing sweep actuator rod end
- Strain gage 5 - Outboard wing lower skin
- Strain gage 6 - Forward fuselage dorsal longeron

The strain gage records were monitored and statistically compiled into range/mean tables according to mission classification, mission segment, wing angle and flap position. The cruise data was further defined by altitude range. The list of strain gage data segments with significant quantities of data is shown in TABLE 8. Stress spectra at the strain gage locations were recompiled from the L/ESS

Data ID	Description	Wing angle	Flap	Altitude	Weight
1	Post Take Off Climb	< 22.5	Extend		
2	Climb	< 22.5	Extend		
3		< 22.5	Up		
4		22.5 - 30			
5		> 60			
6	Cruise	< 22.5	Extend	< 15000	
7		< 22.5	Extend	> 15000	
8		< 22.5	Up	< 15000	
9		< 22.5		> 15000	
10		22.5 - 30		< 15000	
11		22.5 - 30		> 15000	
12		50 - 60			
13		> 60		< 15000	
14		> 60		> 15000	
15	Refuel	22.5 - 30			
16	Descent	< 22.5	Extend		
17		< 22.5	Up		
18		22.5 - 30			
19		> 60			
20	Pre TF Descent	22.5 - 30			
21		> 60			< 315
22					> 315
23	Post TF Climb	22.5 - 30			< 310
24					> 310
25		> 60			< 310
26					> 310
27	Low Alt (TFR off)	> 60			< 310
28					> 310
29	Terr. Foll - Hard Ride				< 310
30					< 310
31	Terr. Foll -Med Ride				
32	Terr. Foll - Soft Ride				< 310
33					> 310
34	Airwork	22.5 - 30			
35		> 60			
36	Go Around	> 22.5	Extend		
37		> 22.5	Clean		
38	Pre-land	> 22.5	Extend		
39		> 22.5	Clean		
40	Ground				

TABLE 8 - Strain Gage Records (Typical)

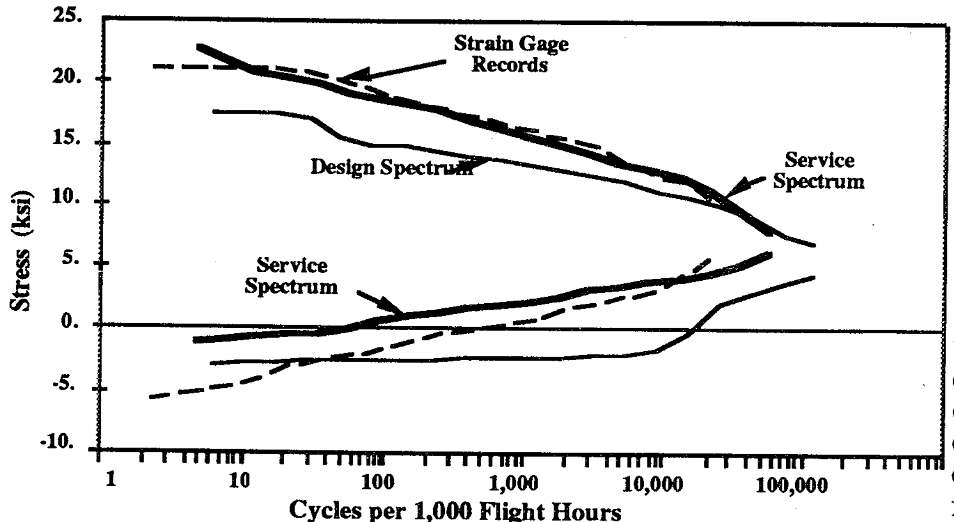

FIGURE 6 - Stress Spectra Comparison at Wing Strain Gage Location

database using the mission mix of TABLE 6. The spectra generated from strain gages were created in a similar manner to the load factor spectra but using the strain gage range/mean tables. The resulting spectra, representing 100 flights, are the stress spectra at each strain gage location. In order to provide a statistical representation of the 100 flight spectrum that could define the spectrum severity, an exceedance curve was generated for each strain gage location. Similar exceedance curves were generated from the analytic spectrum using the methods described previously to obtain the spectrum at the strain gage locations. This task was completed for all the structural locations for which the strain gage records were available but only those pertaining to the wing and fuselage will be presented and discussed here. The compiled exceedance data are shown in FIGURES 6 and 7 for the wing and fuselage strain gage locations respectively. The curve defined as the "Service Spectrum" is based on the service recorded load factors and flight profiles and the analytically generated NASTRAN internal loads at the location of the strain gage. The curve defined as the "Strain Gage Records" was compiled from the L/ESS strain gage data while that defined as the "Design spectrum" was derived analytically from the original B-1B design criteria of expected usage and loads.

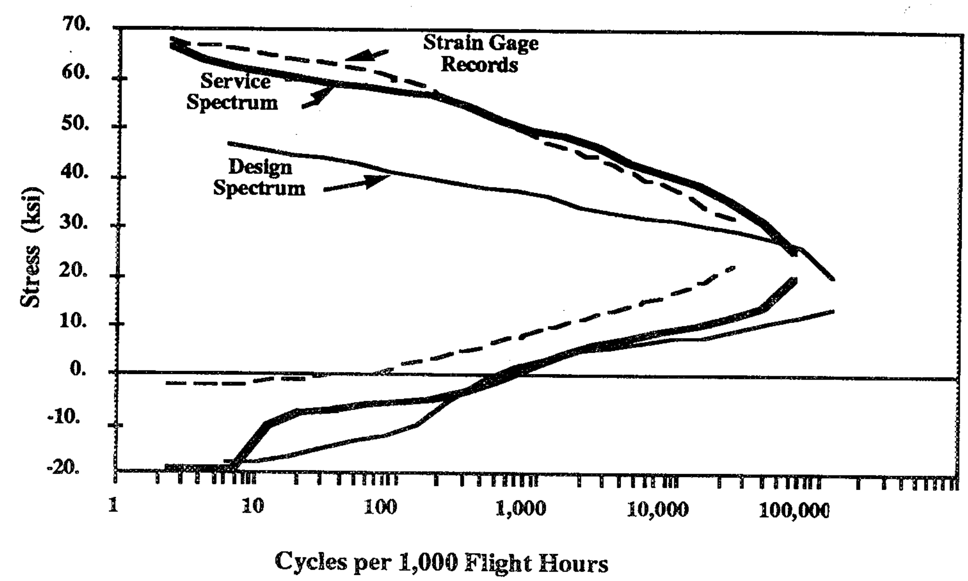

FIGURE 7 - Stress Spectra Comparison at Fuselage Strain Gage Location

The study showed good correlation between the load factor/analysis spectrum and the strain gage records for both wing and fuselage, providing confidence that the spectrum derived from the L/ESS load factors and profiles gives a good representation of the service structural environment throughout the wing and fuselage. The difference between the service exceedance curves and the design spectrum curves indicates a more severe usage experienced in service than was predicted by the design criteria.

TAILORING A SPECTRUM GENERATION PROCEDURE

Creation of an accurate fatigue spectrum requires that it include all operational and environmental events that cause significant changes in load. Spectra are therefore unique not only for aircraft types and models but also for various components within a structure. While many aspects of spectrum generation are common, a completely generic spectrum generation program is probably impractical. The spectrum generation procedure described in this paper was tailored to the product using extensive engineering knowledge of diverse subjects such as operational requirements, aerodynamics, performance, flight controls, aircraft response to the gust environment, external and internal loads, stress analysis and fatigue and fracture mechanics. One area of tailoring is the selection of recorded parameters where consideration must be given to the type of aircraft operations, aircraft design and performance, special aircraft geometry such as variable sweep wings and to the impact of flight control systems. Another area is in the setting up of the L/ESS database where the possible degrees of freedom of all recorded parameters leads to an unacceptably large database with many empty cells. The database for the B-1B, for example, has a much higher resolution for terrain following segments as a consequence of the high load cycle activity than it does for high altitude cruise. The final area specially written for the B-1B was the spectrum generation routines which selected range mean data and internal loads conditions from the available databases.

SUCCESS FACTORS

The success of the project, as measured by the comparison of the analytically derived spectrum with the strain gage records and by its ability to support structural life assessment analyses, was due to the following:

1) Developing a system that could be operated in a production mode with minimal user input while at the same time be adaptable in providing spectra for the evolving mission scenarios required by the USAF. The changing role of the B-1B within the USAF has resulted in the need to develop load spectra, in support of structural assessment, for a variety of missions. The L/ESS database and the spectrum generation programs have provided rapid response capability.
2) The L/ESS software that could efficiently handle enormous quantities of data, approximately 40,000 pieces of data per flight, and output a succinct graphical summary of each mission for timely engineering evaluation. The summaries provide weight, Mach Number, altitude and wing sweep plots as well as load factor and strain gage plots.
3) The many hundreds of hours spent reviewing the recorded data in order to understand the operational mission details and their relationship to the structural loads on the various structural components. This allowed the mission profiles to be accurately described and the programs refined as new types of missions were undertaken by the USAF.
4) The use of range/mean tables to statistically describe the random cyclic data. Unlike the normally used exceedance curves, which maintain only the overall frequency of peaks and valleys, range/mean tables keep the frequency of cycles completely defined by the load range and the mean load. The reconstitution of a load trace from a range/mean table more closely matches the original load trace than does one rebuilt from exceedance data due to the inclusion of cycles with small ranges of load about high and low mean load levels.
5) External and internal loads were generated for ninety two (92) conditions. These conditions covered the various flight segments and associated parameters, the aircraft geometry and types of loading encountered within the flight profiles.
6) An automated spectrum generation program linking the mission profiles, recorded load factor data and the internal structural loads from the NASTRAN finite element models. The automated program allows generation of stress spectra at any location within the structure with minimal user input.
7) Clipping the infrequent high loads to the level that occurred once in 100 flights. This ensured the inclusion of all load levels that may be statistically expected at least 20 times in a lifetime while eliminating the very infrequent high loads that may cause excessive crack growth retardation and an optimistic life assessment.

SUMMARY

As discussed in the introduction, the spectrum is an extremely important ingredient to the structural life assessment. The procedures defined in this paper provided a spectrum for the B-1B life assessment that closely matched the service experience. The benefit of a spectrum devised in this manner is a significantly improved estimate of the structural life over that computed from the design criteria usage. In addition this spectrum together with the large L/ESS database provides a reliable platform from which various mission scenarios can be assessed as to their impact on the airframe. The structural life computations based on these spectra provided an assessment of the economic life of the structure and the inspection requirements necessary to ensure safety.

The methodology was validated at six (6) discrete structural locations by comparing the results with strain gage records compiled from service records. This gave a high degree of confidence that the procedure was acceptable throughout the structure.

While most of the ideas discussed in the paper can be translated directly to other projects there are, as shown in the body of the paper, a number of aspects of the task of extracting load spectra from recorded flight data that must be tailored to the aircraft under consideration.

The primary lesson learned was that detailed engineering knowledge covering many disciplines in the fields of aerodynamics and structures was invaluable in establishing the validation criteria for recorded data and recognizing causes of significant load cycles. This knowledge was used to define those situations where more extensive analysis and review of service records were necessary in the interest of accuracy while spending less time on less important events. Another important lesson was that spectra generated by programs such as this are complex and long. The 100 flight spectrum for the B-1B wing for example contains 54000 cycles defined by 21000 peak/valley load steps. While efficient crack growth and fatigue programs operating on modern main frame and work station computers can handle spectra of this length it is the necessary to prioritize the mission events and the loading parameters to prevent unacceptably long spectra.