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Composite Load Spectra For Select Space Propulsion Structural Components*

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The objective of the Composite Load Spectra (CLS) project is to build a knowledge-based system to synthesize probabilistic loads for selected space propulsion engine components. The knowledge-based system has a load expert system module and a load calculation module. The load expert system provides load information and the load calculation module generates the probabilistic load distributions.

The engine loads can be divided into four broad classes: the engine independent loads, the engine system dependent load, the component local independent loads and the component loads. The engine independent loads include engine operating conditions and the engine hardware parameters. The engine operating conditions are the O/F mixture ratio, and the engine fuel and oxidizer inlet conditions etc. The engine hardware parameters are for example the HPFTP pump efficiency, the HPOTP turbine efficiency, etc. The engine system dependent loads are the operating conditions of the engine subsystems such as the HPFTP turbine inlet and discharge pressures. The component loads including the local independent loads are loads internal to the engine subsystems. The component loads are evaluated with a multi-level engine model implemented on CLS. The multi-level engine model includes an engine probabilistic influence model and many component load models. The engine subsystem dependent loads are evaluated by the probabilistic influence model and they are in turn fed into the component load models to generate the component loads. Figures 1 and 2 illustrate the loads and the engine models.

The engine probabilistic influence model calculates the engine system dependent load variations from a set of engine influence coefficients as shown in Figure 3. The influence coefficients are dependent of the engine commanded power level. These influence coefficients were derived from the engine flight and test data. The engine model implemented on CLS has 64 independent loads and 99 system dependent loads. The load mean values, coefficient of variations and the influence coeficients are stored in the CLS knowledge base. They can be retrieved by the load expert system when needed. There are many component load models as listed in Figure 4, each of which is for a certain component load. For example, the pressure scaling model is for evaluation the component static pressure for the turbine blade, the transfer duct and other components. The probabilistic thermal load model is for evaluating the temperatures of the components. In many cases, each component has its own geometry model and related parameters. They are stored in a database format in the CLS knowledge base.

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The four engine components selected for implementation are the turbine blade, the transfer ducts, the LOX posts and the HPOTP discharge duct. The loads for these components important to the probabilistic structural analyses and reliability calculations are listed in Figure 5.

The load calculation module provides three probabilistic methods for generating probabilistic loads. They are the Gaussian moment method, the RASCAL (Random Sampling Condensation Algorithm) method and the Monte Carlo Method. The Gaussian moment method assumes all input loads are normally distributed. The dependent loads are evaluated analytically. The RASCAL is a discrete probability distribution method. It reduces computational time by restricting the sample space as it combines loads. The Monte Carlo method is a standard version of the Monte Carlo sampling method. The probabilistic models implemented on CLS are shown in Figure 6. They include models for calculating the steady state load and the transient state loads. At present, the steady state and the quasi-steady state models are available for duty cycle mission calculations. The other probabilistic models are available for stand alone calculations. Figure 7 shows a comparison of the results of the Gaussian method and the RASCAL method with the HPFTP discharge pressure data at 100% power level. The calculations match reasonably well with the data. Figures 8 and 9 show the confident interval calculations for the HPFTP turbine torque using RASCAL method with various bin numbers and different sampling options. The confident intervals compare well with the Monte Carlo method. Notice that the bin numbers used in RASCAL are much smaller than the Monte Carlo sample size.

The Composite Load Spectra knowledge-based system as delineated in Figures 10 and 11 are developed for load syntheses of selected space propulsion engine components. Its domain knowledge includes engine load information and probabilistic engine load models. The knowledge-based system has a built-in database system that can handle the database operations. It provides three basic probabilistic methods and numerous probability models for building models for component load calculations. The load expert system can retrieve the required load data and prepare input files for the load calculations. In an application study, presented separately in this conference, we have demonstrated that using the marginal distribution method the CLS can provide the composite load spectra to a structural analysis program for probabilistic analysis and thus eliminates the need of modeling the loads inside the structural analysis program.

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SYSTEM CLASS OF LOADS

- STEADY STATE
  - DIRECT VARIABLES – THRUST, INLET CONDITIONS
  - RANDOM VARIABLES – HARDWARE, TEST VARIATIONS
- TRANSIENTS
  - START AND CUTOFF CONTROLLED
  - LOCAL EFFECTS

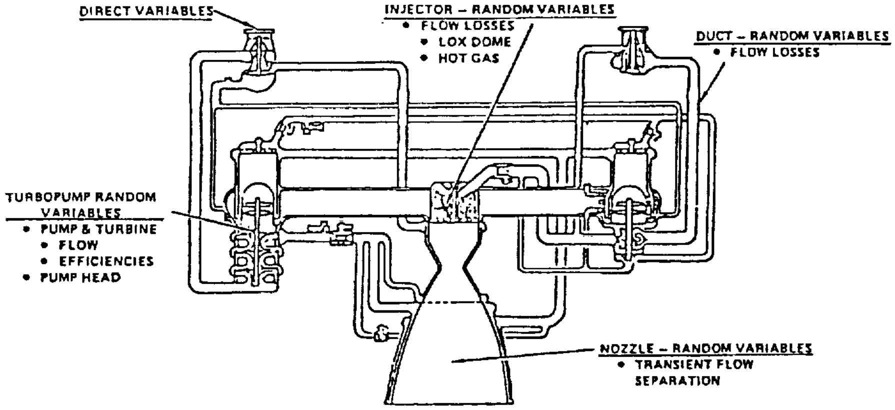


Figure 1 .

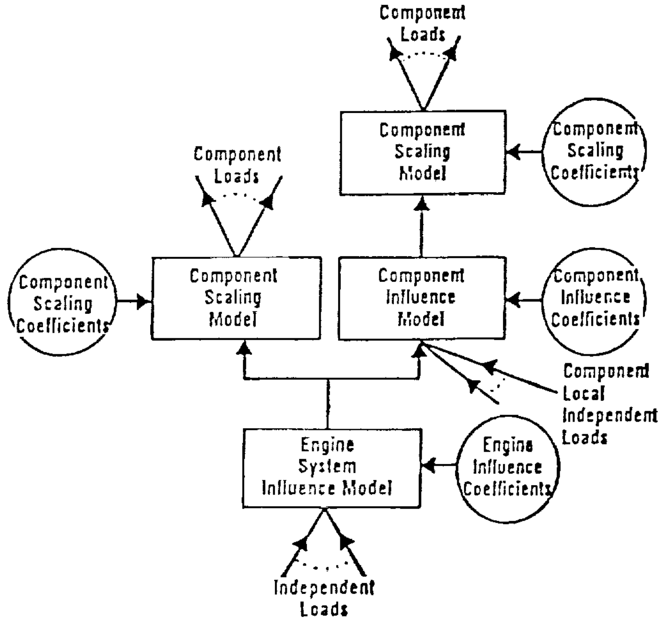


Figure 2.

COMPOSITE LOAD SPECTRA
MULTI-LEVEL ENGINE MODEL

- ENGINE SYSTEM MODEL
  - PROBABILISTIC INFLUENCE MODEL

$$\frac{\Delta Y_j}{Y_{jo}} = \sum_i (IC)_{ji} \frac{\Delta X_i}{X_{io}}$$

WHERE X_i's ARE ENGINE INDEPENDENT LOADS

e.g. ENGINE MIXTURE
FUEL AND OXIDIZER INLET PRESSURES AND INLET TEMPERATURES
HPFTP & HPOTP PUMP EFFICIENCIES
HPFTP & HPOTP TURBINE EFFICIENCIES, ETC.

Y_j's ARE ENGINE SYSTEM DEPENDENT LOADS
e.g. HPFTP TURBINE INLET PRESSURE AND DISCHARGE PRESSURE
HPOTP TURBINE TORQUE, ETC.

$(IC)_{ji}$ ARE THE INFLUENCE COEFFICIENTS
THEY ARE FUNCTIONS OF THE COMMANDED POWER LEVEL

- KNOWLEDGE BASE
  - ENGINE LOAD KNOWLEDGE - MEAN, CV, DISTRIBUTION TYPE
  - INFLUENCE MODEL - INFLUENCE COEFFICIENT SET, GAIN INFORMATION, DUTY-CYCLE DATA

Figure 3.

COMPOSITE LOAD SPECTRA
MULTI-LEVEL ENGINE MODEL

- COMPONENT LOAD MODELS
  - COMPONENT STATIC PRESSURE SCALING MODEL
  - TURBINE BLADE DYNAMIC PRESSURE LOAD MODEL
  - TRANSFER DUCT FLUCTUATION PRESSURE MODEL
  - PROBABILISTIC THERMAL LOAD MODEL
- KNOWLEDGE BASE
  - COMPONENT LOAD MODELS
    - DEPENDENCY ON ENGINE LOADS
    - LOAD PARAMETER DATABASE
    - INFLUENCE AND SCALING COEFFICIENTS
  - COMPONENT GEOMETRY DATABASE

Figure 4.

SUMMARY MATRIX OF INDIVIDUAL LOADS

VS COMPONENTS

INDIVIDUAL LOAD	TURBINE LOAD	TRANSFER DUCT	LOX POST	HPOTPOD FORMAT	LOAD FORM/ TEST DATA FORMAT
• STATIC PRESSURE	X	X	X	X	DUTY CYCLE
• DYNAMIC PRESSURE					
• CHUGGING (TRANSIENT)	-	X	-	-	AMS, STATOS
• TURBULENCE					
• SINUSOIDAL (REPEATED PULSE)	X				AMS, PSD, STATOS
• RANDOM	-	X	X	X	AMS, PSDS
• CENTRIFUGAL	X	-	-	-	DUTY CYCLE
• TEMPERATURE	X	X	X	X	DUTY CYCLE
• STRUCTURAL VIBRATION					
• TRANSIENT	-	X	X	X	AMS, STATOS
• STEADY STATE	-	X	X	X	AMS, PSD, STATOS

Figure 5.

COMPOSITE LOAD SPECTRA
ANLOAD = THE LOAD CALCULATION MODULE

- PROBABILISTIC METHODS
    - GAUSSIAN MOMENT METHOD
    - RASCAL (A VARIANCE OF DPD METHOD)
    - MONTE CARLO
- PROBABILISTIC MODEL
    - STEADY STATE
    - TRANSIENT STATE
        - QUASI-STEADY STATE
        - POISSON ARRIVAL
    - RARE EVENT
    - PERIODIC MODEL AND PSD

Figure 6.

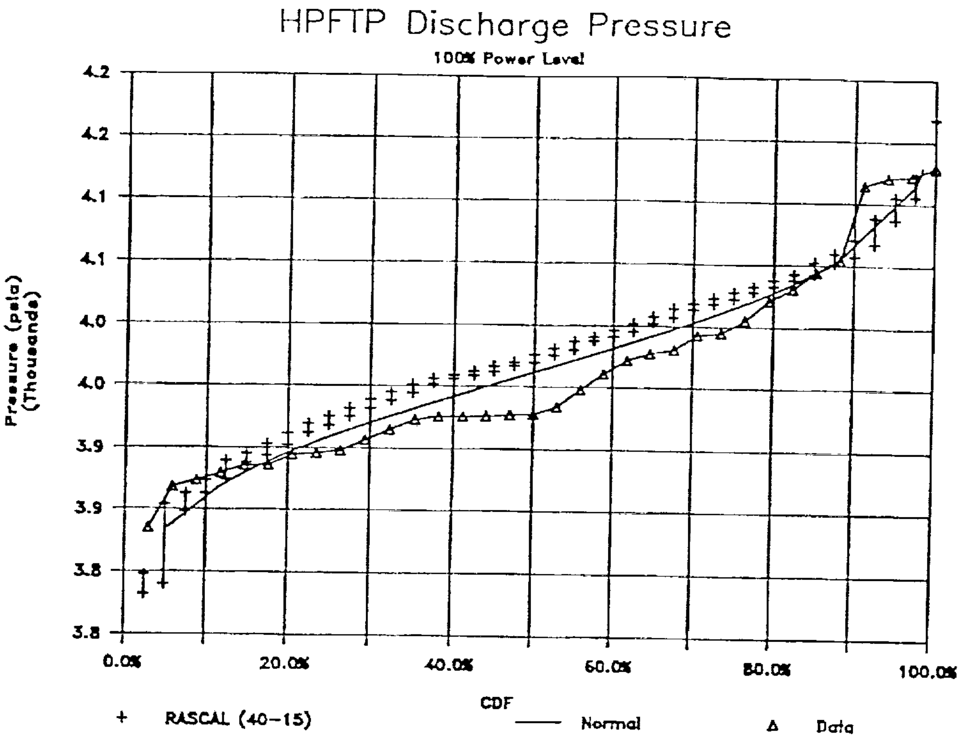


Figure 7.

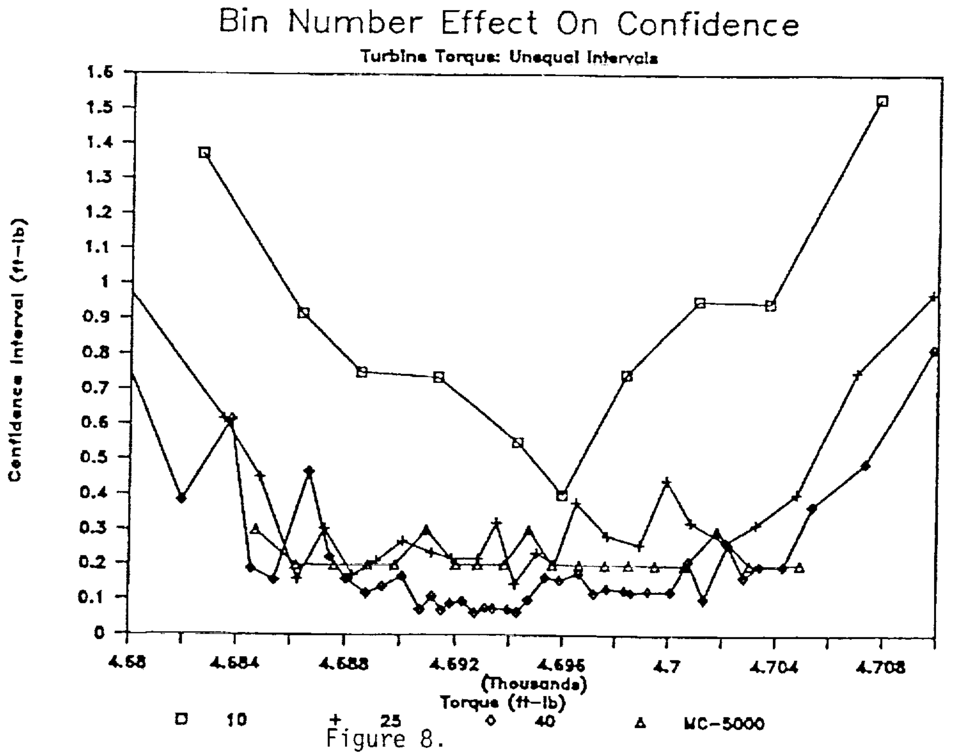
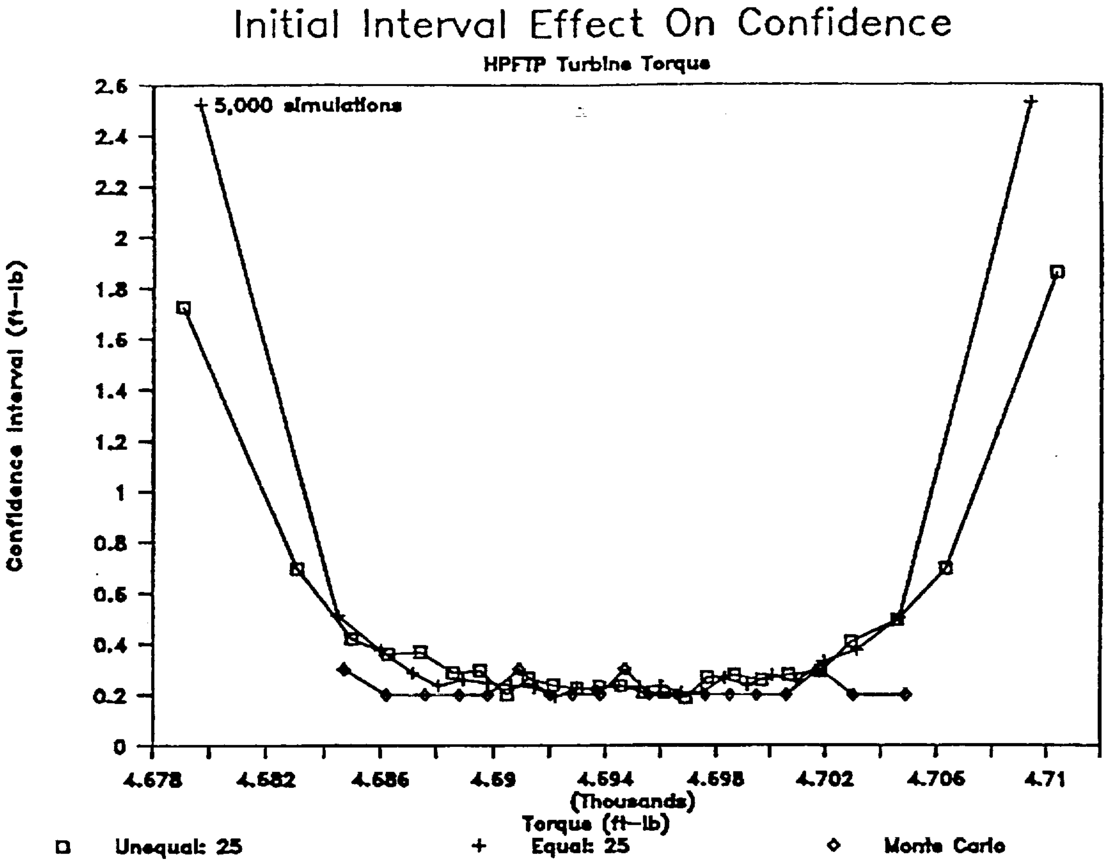


Figure 8.



CONFIDENCE BAND CALCULATIONS

- MONTE CARLO BANDS ARE CALCULATED USING CLASSICAL STATISTICAL RESULTS
- MONTE CARLO CONFIDENCE BAND INTERVALS BECOME SMALLER (I.E. ACCURACY INCREASES) WITH INCREASING NUMBER OF SIMULATIONS
- RASCAL CALCULATIONS INCLUDE THE CONTINUOUS PORTION OF THE PROBABILITY SPACE IN THE CONFIDENCE BAND CALCULATIONS
- THE CONTINUOUS PROBABILITY SPACE THAT IS NOT REPRESENTED IN THE INDIVIDUAL DISCRETE DISTRIBUTIONS CAUSES A DECREASE IN THE POINT ACCURACY BY RASCAL
- THEREFORE, THE CONFIDENCE BAND INTERVALS BECOME SMALLER WITH AN INCREASING NUMBER OF INITIAL DISCRETE INTERVALS

Figure 9.

LDEXPT LOAD EXPERT SYSTEM

- **EXPERT SYSTEM DRIVER**
  - DECISION TREE INFERENCE
  - QUERY ON THE DATABASE KEY VARIABLES
- **LOAD DATABASE SYSTEM**
  - STAND-ALONE DATABASE SYSTEM
  - EXPERT SYSTEM INTERFACE
    - KEY VARIABLES ARE ATTRIBUTES OF THE EXPERT SYSTEM
    - USER/EXPERT SYSTEM SELECT OPTIONS ON KEY VALUES
- **SIMPLE WORKING MEMORY MODEL**
  - PASSING INFORMATION BETWEEN RULE MODULES
- **LDEXPT RULE MODULES**
  - IMPLEMENTING PROCESS AND CONTROL KNOWLEDGE
    - e.g., RETRIEVING LOAD INFORMATION
  - IMPLEMENTING PROBLEM-SOLVING KNOWLEDGE
    - e.g., SELECTING INDEPENDENT LOADS BASED ON GAINS
- **PROBABILISTIC LOAD MODULE – ANLOAD (BATTELLE)**

Figure 10.

LDEXPT: LOAD EXPERT SYSTEM

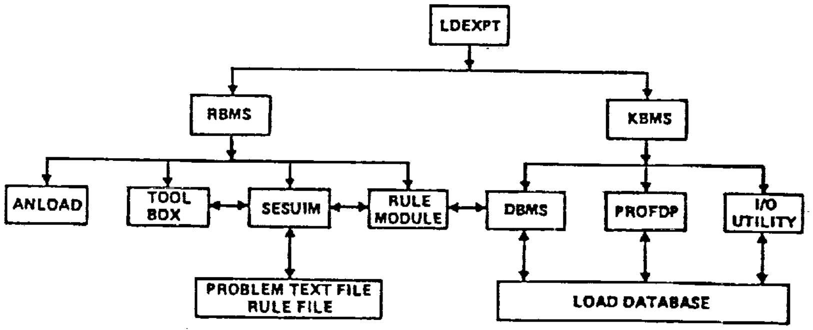


Figure 11.