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PROBABILISTIC LOAD MODEL DEVELOPMENT AND VALIDATION FOR COMPOSITE LOAD SPECTRA FOR SELECT SPACE PROPULSION ENGINES

R. Kurth
Battelle Memorial Institute
Columbus, Ohio

and

J.F. Newell
Rocketdyne Division, Rockwell International
Canoga Park, California

A major task of the program to develop an expert system to predict the loads on selected components of a generic space propulsion engine is the design, development, and application of a probabilistic loads model. This model is being developed in order to account for the random nature of the loads and assess the variable load ranges' effect on the engine performance.

There are several requirements of the probabilistic load model which restrict the use of some probabilistic methodologies. First, the methodology must be capable of addressing four different shapes for the sample paths in the stochastic processes describing the loads: nominal, random, spike (rare event), and periodic. This implies that the model must be capable of approximating a variety of different forms for the load processes, some, or all, of which may be non-stationary. Second, the model must be applicable to generic engines operating under a wide variety of possible mission history profiles, typified by the demanded power levels. This requirement implies that the model must be capable of dealing with both random variables, as well as stochastic processes, that may not be describable by standard distributional forms, for example bimodal behavior or discrete (on-off) processes. Also, there are sixty to seventy individual loads and/or engine parameters that can affect the composite load calculations (although, usually only ten to thirty of these are important for a single, specific composite load calculation), and, therefore, the methodology must be as efficient as possible without incurring a substantial loss of accuracy. Finally, the methodology is required to provide varying levels of accuracy, the level to be user specified.

A probabilistic model capable of addressing each of these topics has been developed. The model is based primarily on simulation methods, but also has a Gaussian algebra method (if all variables are near normal), a fast probability integrator routine (for the calculation of low probability events), and a separate, stand alone program for performing barrier crossing calculations. Each of these probabilistic methods has been verified with theoretical calculations using assumed distributional forms. The results of the these verification studies are discussed in the full presentation.

The governing philosophy for the probabilistic methodology is that each process can be described by a probability density function. To implement this philosophy for stochastic processes, approximate methods for modeling the mission history profile are needed during portions of the mission. Independent (controller), individual loads and engine parameters are treated as random variables whose distributional form and parameters are determined by the controller demanded power level (thrust). The dependent, individual loads and composite loads are then modeled by assuming a quasi-steady state system. This implies that during the power up and down, and throttle up and down phases of a mission the time step size be sufficiently small to warrant a steady state approximation, <u>from the probabilistic point of view.</u> That is, the physics may not be in a quasi-steady state, but it can be assumed that the loads of interest are stationary during this time. Between time steps the non-stationary loads are adjusted according to the data base information, or user supplied input. An example of the coupling of quasi-steady state and steady state phases will be discussed.

For transient events, such as engine start and cut-off, the changes in the magnitude of the loads is both large (relatively) and of short duration (one to four seconds). For these events the load profile is not assumed to be quasi-steady in order to keep the time step size relatively large and reduce the computational time. Instead, the fluctuations about the nominal response are ignored and the random nature of the transient is contained in the variable amplitude and time of occurrence. The load is modeled as a piecewise linear response over the duration of the transient. For example, in a two-stage engine, the temperature in the fuel pump is expected to have two or three spike values before settling down to a relatively steady rate of increase to the full power operation temperature level. The occurrence, or non-occurrence, of the third peak is handled statistically as a random variable, as well as the amplitude of the peak and the time at which the peak amplitude occurs. Examples of the transient model, and its coupling to other mission phase types is provided.

Because the probabilistic model is treating the problem in the time domain, special attention must be paid to periodic, or sinusoidal, loads. Since their magnitudes are usually more sensitive to frequency than they are to any time dependency (other than the time dependency of the frequencies), they are treated separately in the probabilistic model.

At this time most of the available data for the model validation has been obtained from the space shuttle main engine program. The data which has been examined thus far appears to agree, within statistically accuracy, with the model predictions obtained from the validation studies. Further testing with other engine data is planned to demonstrate the generic capability of the model. An example of a validation analysis is provided.

INTRODUCTION

Probabilistic Load Analysis

- The primary goal is the development of a probabilistic methodology that is capable of handling any generic space propulsion engine

- Requires that any anticipated distribution of engine load or parameters must be addressable by the model

- Must be able to analyze, in a manner consistent with the stochastic process being modeled, either linear or non-linear ombinations of the inputs which may be non_stationary

Probabilistic Load Model

The above points have led to the development of a model based on the following points:

- Tabulation of means, variances, and distribution types for
- Scaling laws, or expert opinion, for modifications of data base for engines currently not included
- A probabilistic model that provides varying levels of sophistication for calculating the stochastic load processes
- Capability to analyze nominal, random, or periodic loads

PROBABILISTIC LOAD MODEL

Stochastic Processes

- The stochastic load processes are modeled using PDF's to describe the individual load variables and engine parameters

- There are four primary shapes that are modeled:
  (a) Nominal
  (b) Random
  (c) Spike
  (d) Peridoic

- Because the load is a stochastic process there are three different methods for displaying the results:
  (a) Nominal plot
  (b) Sample function plot
  (c) Probability tables of exceeding specified load levels

PROBABILISTIC LOAD MODEL
(continued)

Individual loads

- Probability density functions
- Data analysis, or calculated using engine influence coefficient

Composite loads

- User supplied:
  - Mission history profile
  - Accuracy required
  - Output desired
- Composite load is calculated from the probabilistic method selected from the input accuracy needed and the desired output

Non-stationary processes

- Computer program decides if the individual loads are non-stationary (This option can be suppressed). If they are not stationary, then new distribution parameters are calculated based on the current power level
- Relatively small time step is used to approximate a stationary process over the time increment

Probabilistic Methodology

- Methodology based primarily on simulation methods
- Gaussian algebra, fast probability integrator (Wirsching and Wu), and barrier crossing methods are also available for specialized calculations
- Distribution fitting subroutine is included in the model to provide summary statistics on the stochastic processes or random variables

Displayed Output

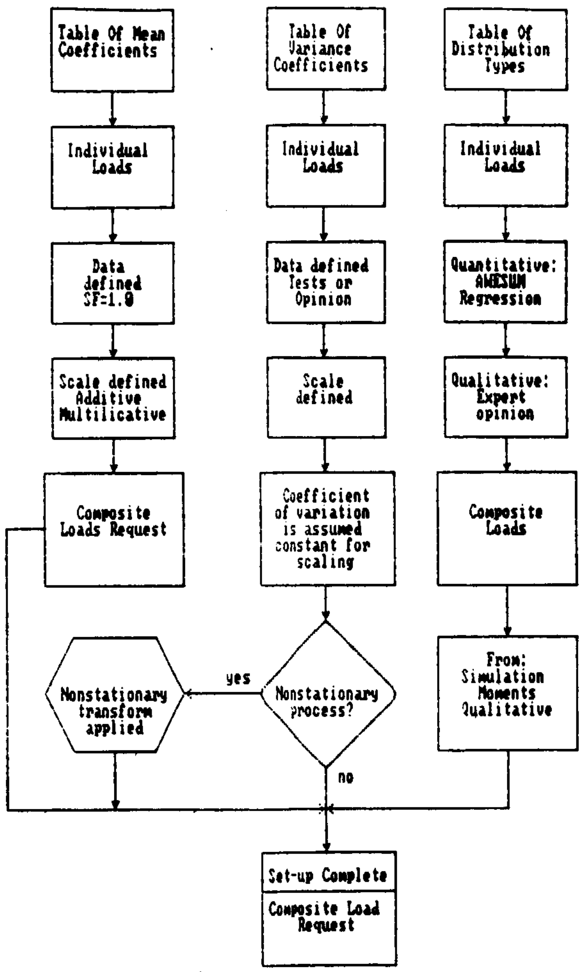
- Discrete load level, with its associated probability
- Updated distributions for the individual load (where warranted) and composite loads at specified times
- Interface with printer plot or LOTUS plotting packages
- All output is stored on a file called DPD.OUT

Data Base Update

- If data analysis for individual load has been performed, it is inserted in the data base (not currently automated)
- The output for the composite load will be cataloged so that future users may simply refer to this analysis without having to re-do the entire calculation

Probabilistic Model Flowchart

Model Input and Set-up



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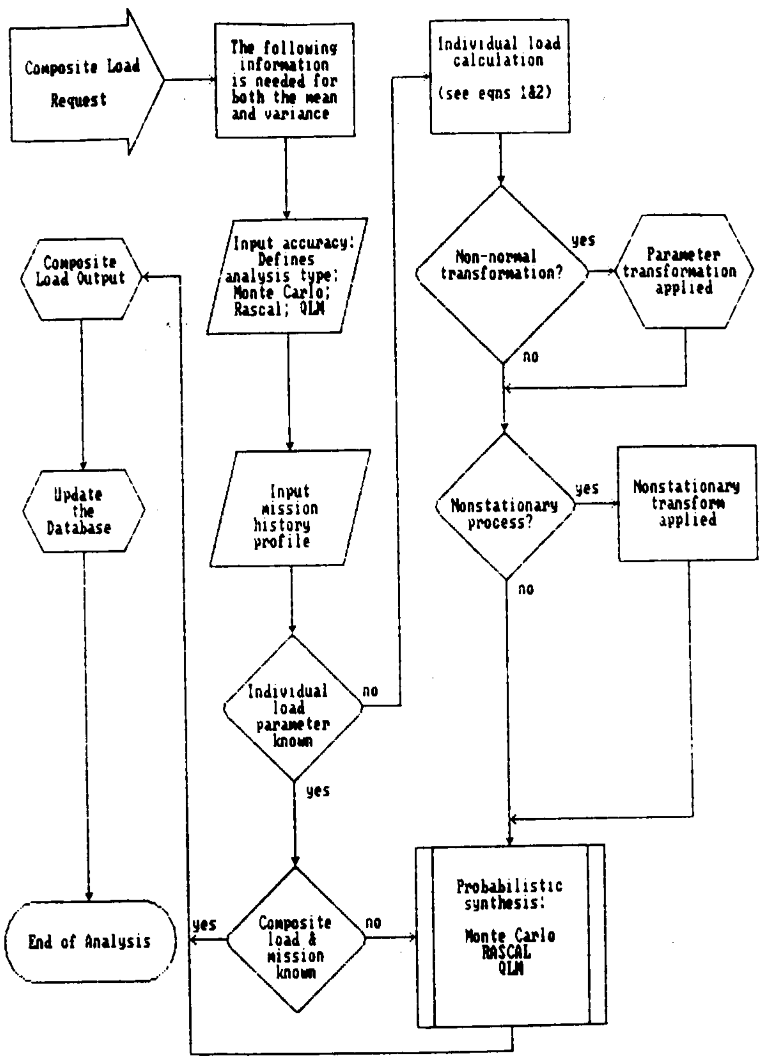
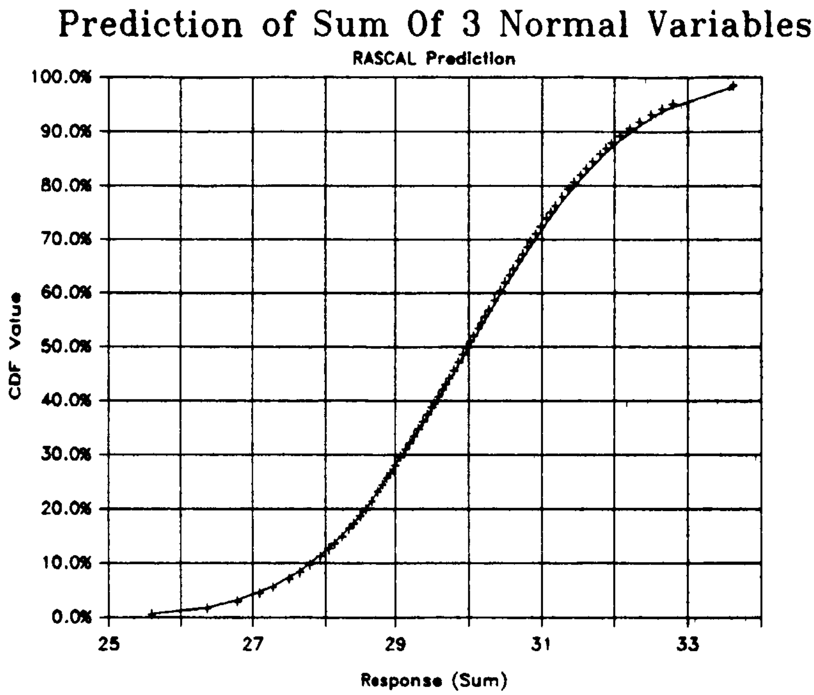
Probabilistic Model Flowchart

Model Calculations



Sample Calculation I
RASCAL Verification



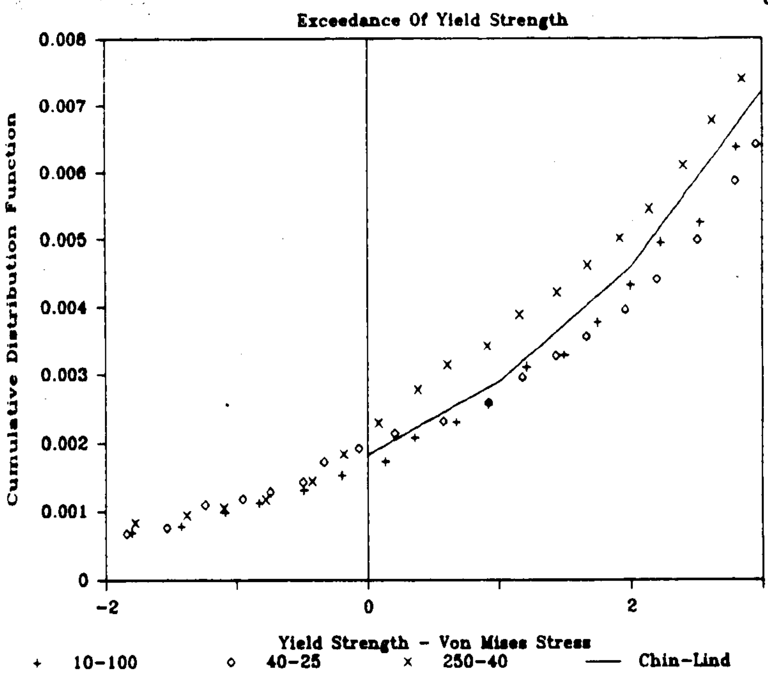
- Sum of three normal variables N(10, 1)

- Known mean of 30 and variance of 3

- Prediction obtained from the 1% to 99% values of the CDF is within 0.02% relative error of the theoretical distribution

Sample Calculation II
Low Probability Calculations

RASCAL Prediction: Failure Probability



- Pressure vessel failure probability model used because previous analysis is available for comparison
- Fast probability integerator (Wirsching and Wu)
- RASCAL and FPI predictions closely agree

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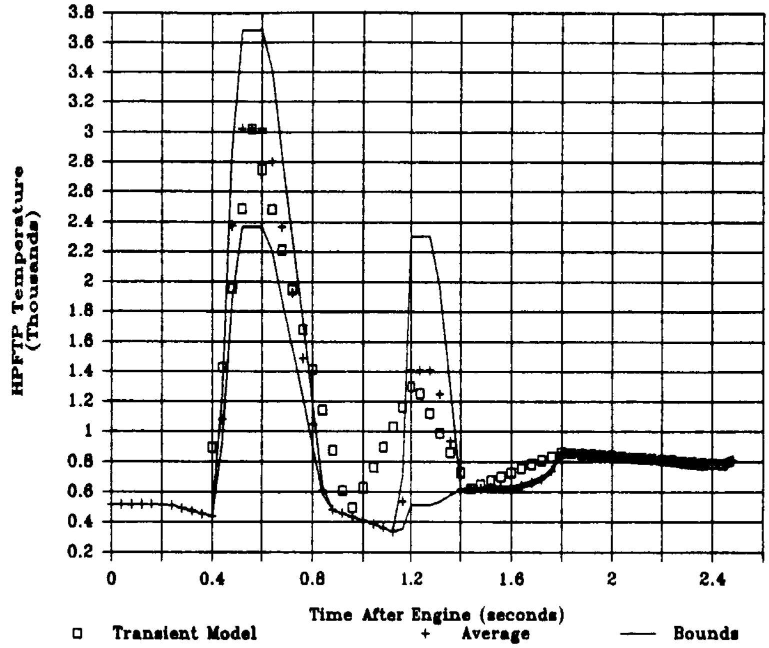
Sample Calculation III
Transient Load Model

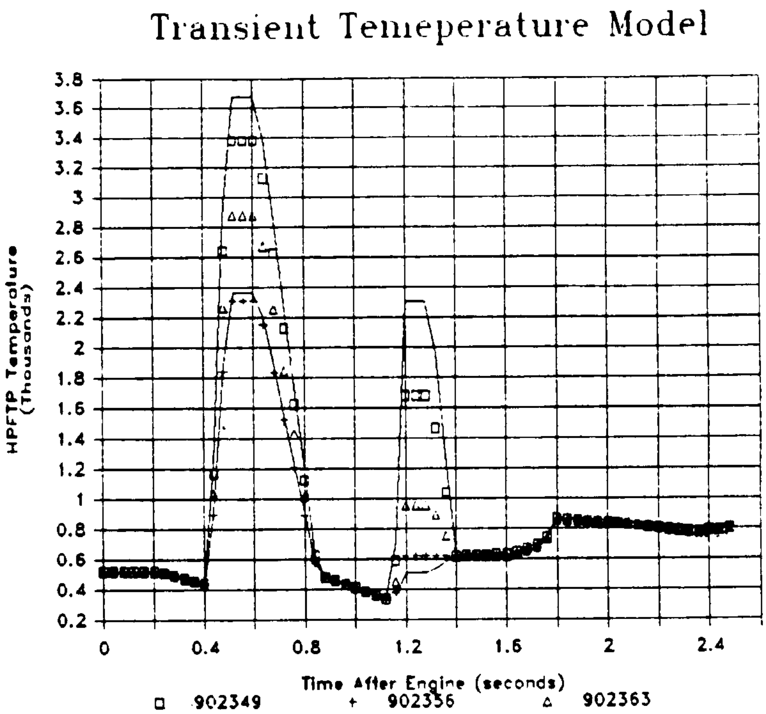
Transient Temeperature Model



- Frequency of:
  - Number of peak amplitudes
  - Magnitude of peak amplitudes
  - Timing of peak amplitudes
- Piecewise linear model is used
- Plot compares model to ensemble average for the verification.

Sample Calculation IV

Transient Model Validation

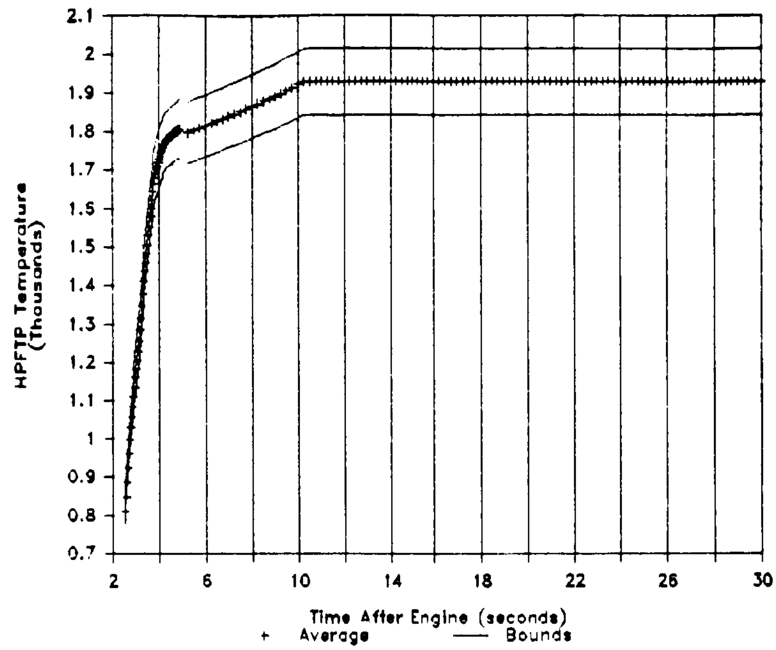


- SSME HPFTP data was examined for data sets that spanned the the possible range of sample paths
- Plot compares transient model and three selected test sets
- Comparison appears very good

Sample Calculation V

Mission Phase Linking

Transient Temeperature Model



- Transient spike values not shown
- Influence function only valid above 65% rated power level
- Extrapolation used to move from the end of the tranmsient data set to the beginning of the quasi-steady phase
- Agreement between the point reached from extrapolation and the 65% level for temperature is very good

SUMMARY

- A probabilistic load model has been developed that is capable of addressing all portions of the mission profile
- The model can address constant, random, spike, and periodic load forms
- Comparisons to date have shown the model to work well in comparison to available data