Probabilistic Fatigue: Computational Simulation

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ABSTRACT

Fatigue is a primary consideration in the design of aerospace structures for long term durability and reliability. There are several types of fatigue that must be considered in the design. These include low cycle, high cycle, combined for different cyclic loading conditions – for example, mechanical, thermal, erosion, etc.

The traditional approach to evaluate fatigue has been to conduct many tests in the various service-environment conditions that the component will be subjected to in a specific design. This approach is reasonable and robust for that specific design. However, it is time consuming, costly and needs to be repeated for designs in different operating conditions in general.

Recent research has demonstrated that fatigue of structural components/structures can be evaluated by computational simulation based on a novel paradigm. Main features in this novel paradigm are progressive telescoping scale mechanics, progressive scale substructuring and progressive structural fracture, encompassed with probabilistic simulation. These generic features of this approach are to probabilistically telescope scale local material point damage all the way up to the structural component and to probabilistically scale decompose structural loads and boundary conditions all the way down to material point. Additional features include a multi-factor interaction model that probabilistically describes material properties evolution, any changes due to various cyclic load and other mutually interacting effects. The objective of the proposed paper is to describe this novel paradigm of computational simulation and present typical fatigue results for structural components. Additionally, advantages, versatility and inclusiveness of computational simulation versus testing are discussed. Guidelines for complementing simulated results with strategic testing are outlined. Typical results are shown for computational simulation of fatigue in metallic composite structures to demonstrate the versatility of this novel paradigm in predicting a priori fatigue life.

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PROBABILISTIC FATIGUE: COMPUTATIONAL SIMULATION

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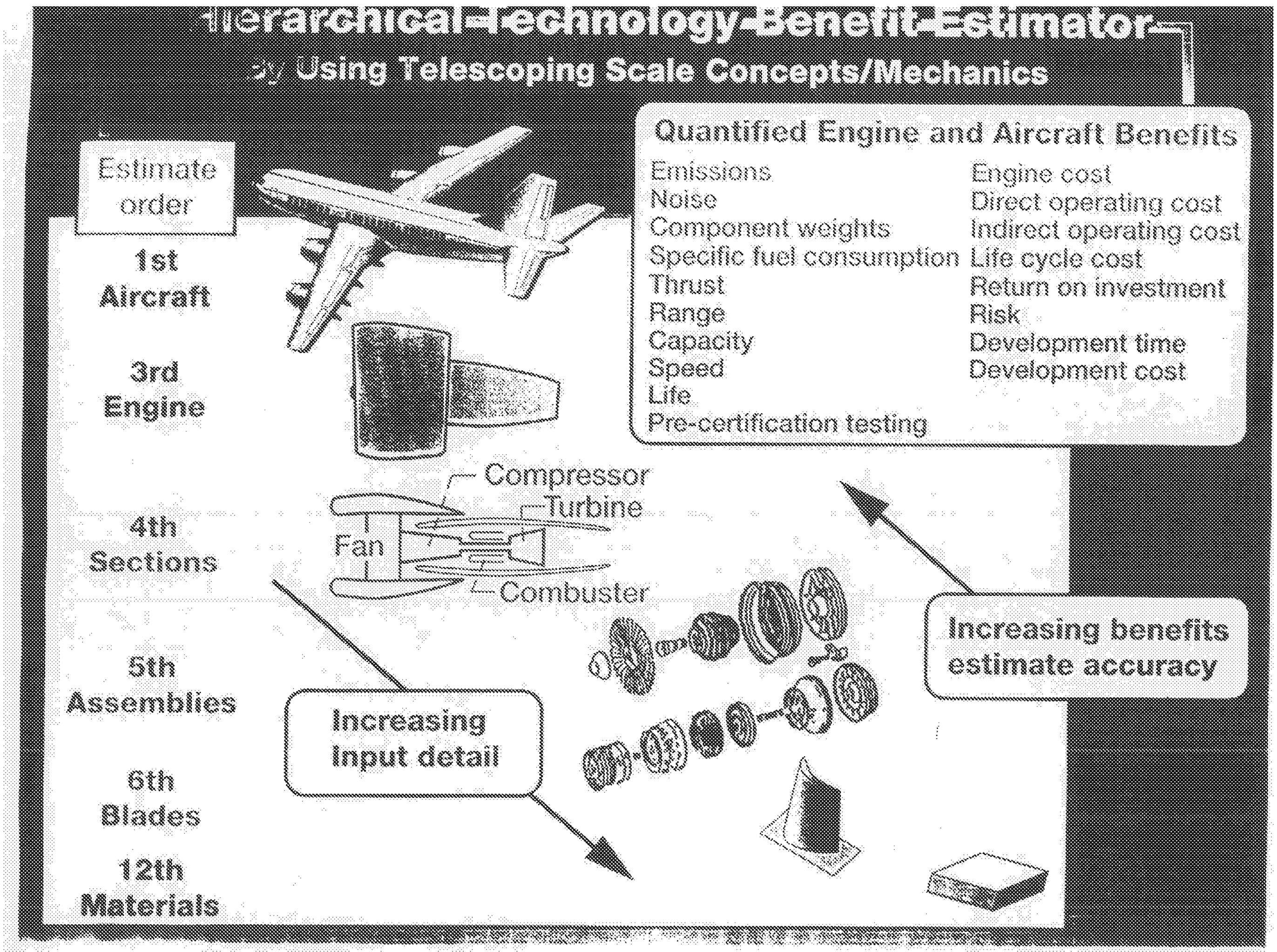
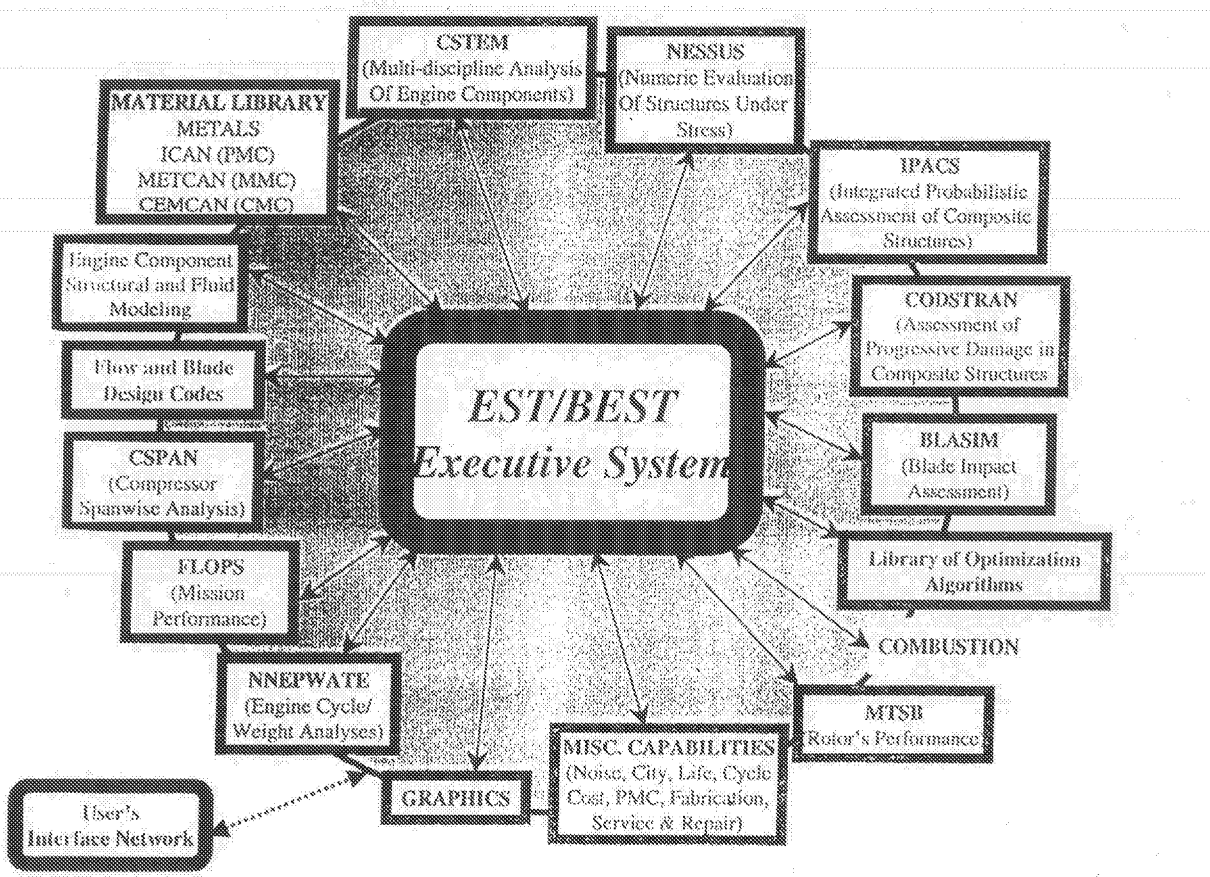
BACKGROUND:

- Fatigue is a primary consideration in the design of aerospace structures for long-term durability and reliability.
- There are several types of fatigue that must be considered in the design, such as: low cycle, high cycle, combined for different cyclic loading conditions – for example, mechanical, thermal, erosion, etc.
- The traditional approach to evaluate fatigue has been to conduct many tests in the various service-environment conditions that the component will be subjected to in a specific design.
- This approach is reasonable and robust for that specific design.
- However, it is time consuming, costly and needs to be repeated for designs in different operating conditions in general.



…ierarchical Technology Benefit Estimator
…y Using Telescoping Scale Concepts/Mechanics
Quantified Engine and Aircraft Benefits
Emissions
Noise
Component weights
Specific fuel consumption
Thrust
Range
Capacity
Speed
Life
Pre-certification testing
Engine cost
Direct operating cost
Indirect operating cost
Life cycle cost
Return on investment
Risk
Development time
Development cost
Estimate order
1st Aircraft
3rd Engine
4th Sections
5th Assemblies
6th Blades
12th Materials
Compressor
Turbine
Fan
Combuster
Increasing input detail
Increasing benefits estimate accuracy

EST/BEST ENGINE STRUCTURES TECHNOLOGY BENEFIT ESTIMATOR



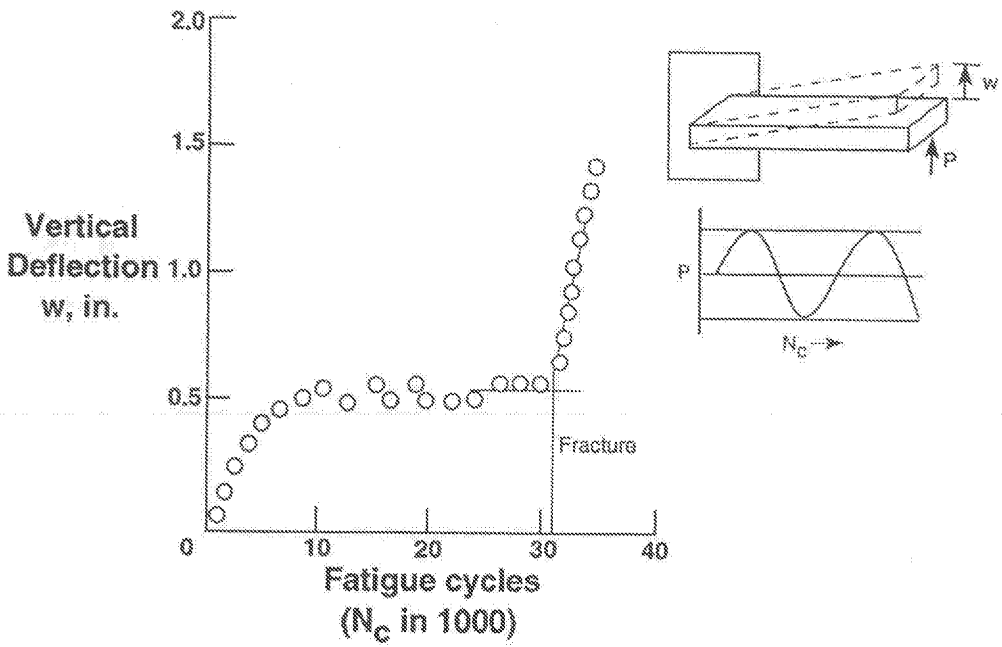
NEED:

- There is a continuing need to develop a method to reduce cost in long-life fatigue evaluations.
- Recent research has demonstrated that fatigue of structural components/ structures can be evaluated by computational simulation based on a novel paradigm.

OBJECTIVE:

- Describe the novel paradigm and present structural component results that illustrate versatility, inclusiveness and that - <u>YES IT CAN BE DONE</u>!

Progressive Fracture Under Cyclic Load
(Experimental data: Mandel, et al)



APPROACH:

MAIN FEATURES IN THIS NEW PARADIGM ARE:

- Progressive Structural Fracture
- MFIM for Material Behavior
- Telescopic Scale Mechanics

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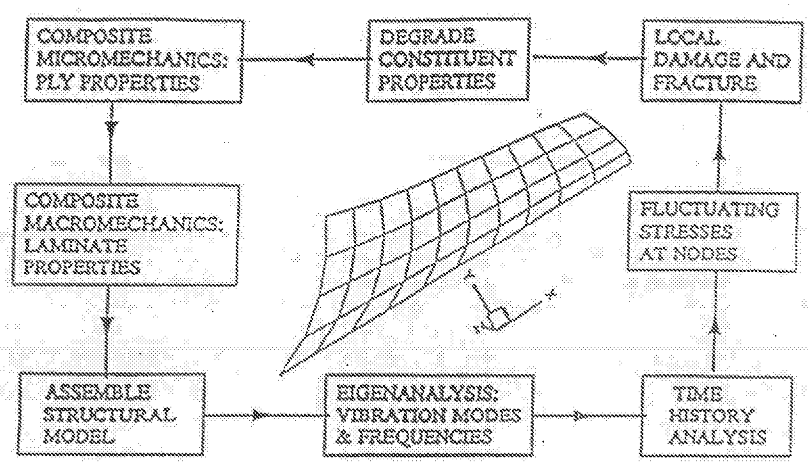
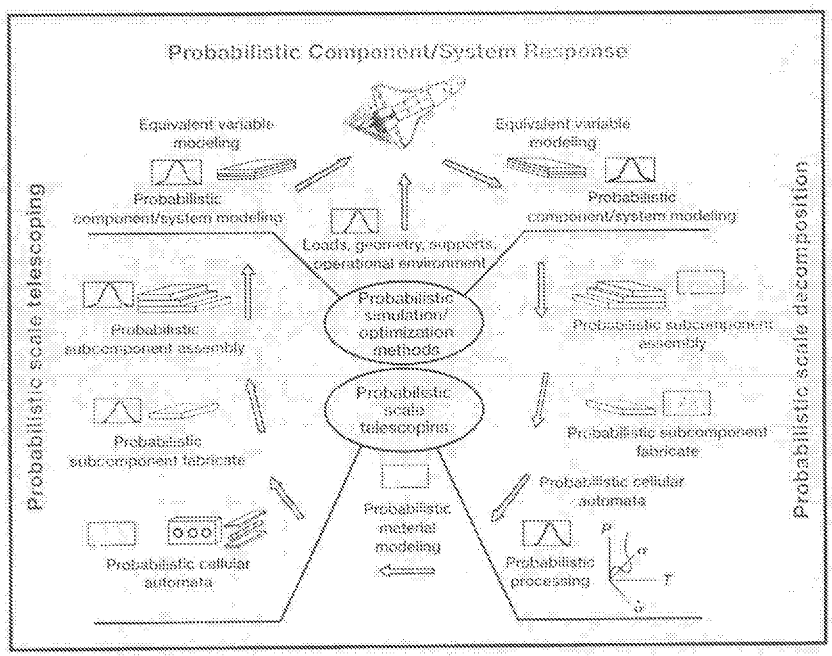
COMPUTATIONAL SIMULATION CYCLE



Non-Deterministic/Non-Traditional (ND/NT) Methods for Design to Cost in the Presence of Uncertainties

(Simulation Iterative Cycle)



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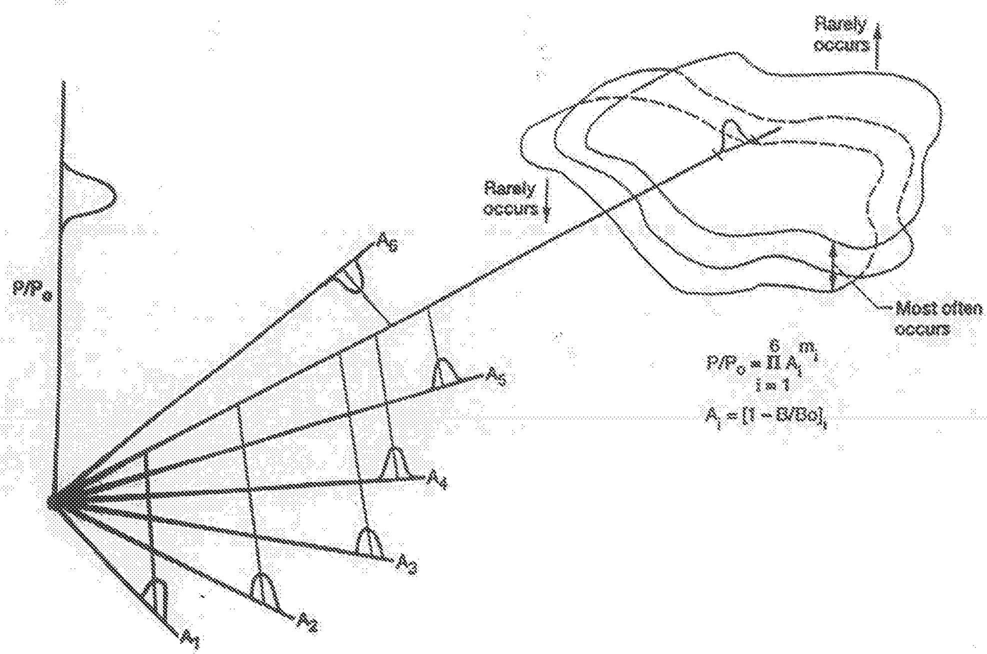
TYPICAL RESULTS:

- MFIM – Behavior Illustration
- Blade Thermomechanical Fatigue – GRC Simulation
- Two-Stage Rotor Fatigue – GRC Simulation
- Tank Fatigue – SWRI Simulation
- Large Shell Fatigue – GRC Simulation

MULTI-FACTO-INTERACTION MODEL WITH SUBSTRUCTURING



Time dependent Multi-Factor Interaction Equation (MFIE):

$$\frac{P}{P_o} = \left(\frac{T_{gw}-T}{T_{gw}-T_o}\right)^m \left(1-\frac{\sigma}{S_f}\right)^n \left(1-\frac{\sigma t}{S_f t_f}\right)^q \left(1-\frac{\sigma_M N_M}{S_f N_{fM}}\right)^r \left(1-\frac{\sigma_T N_T}{S_f N_{fT}}\right)^u$$

where:

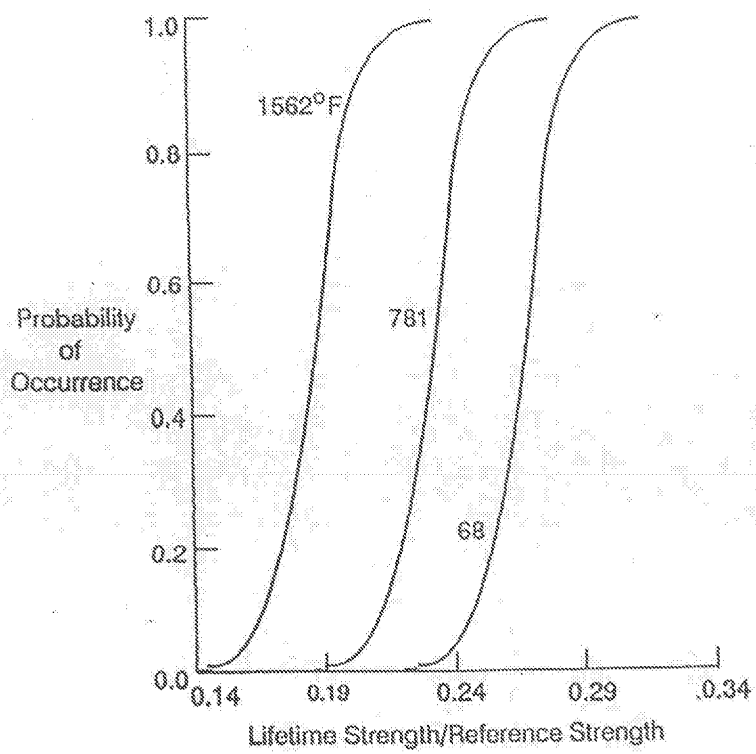
P - Property
T - temperature
S - strength
σ - stress
N - number of cycles
t - time

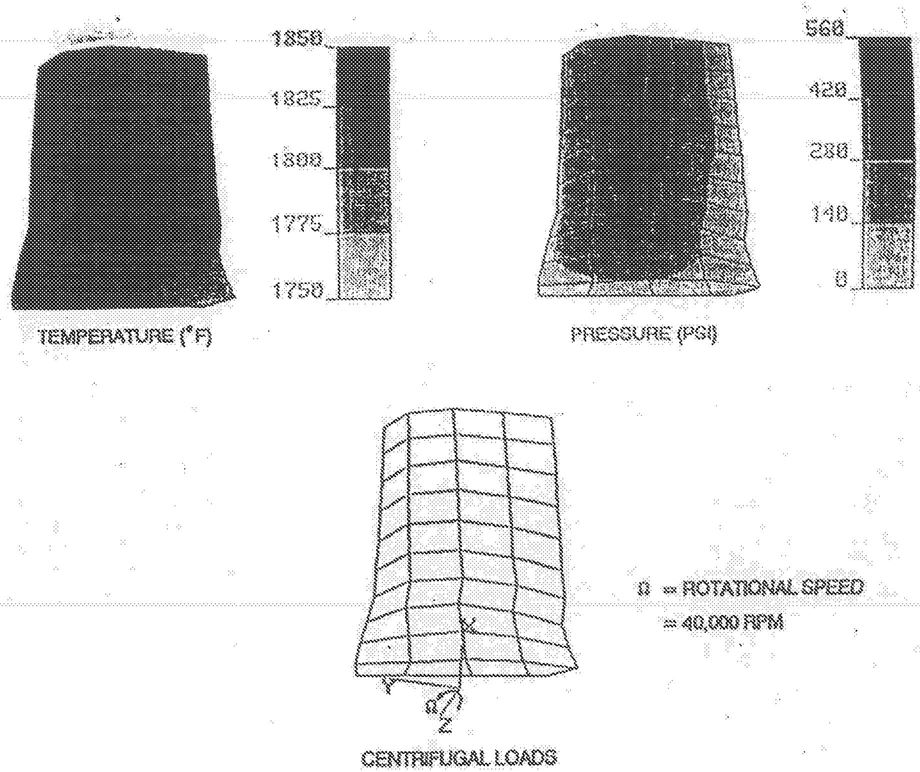
subscripts:

gw - wet glass temperature
o - reference condition
f - final condition
M - mechanical load
T - thermal cyclic load.

superscripts: m, n, q r and u are exponents for the material that describe the behavior path from the reference to the final values

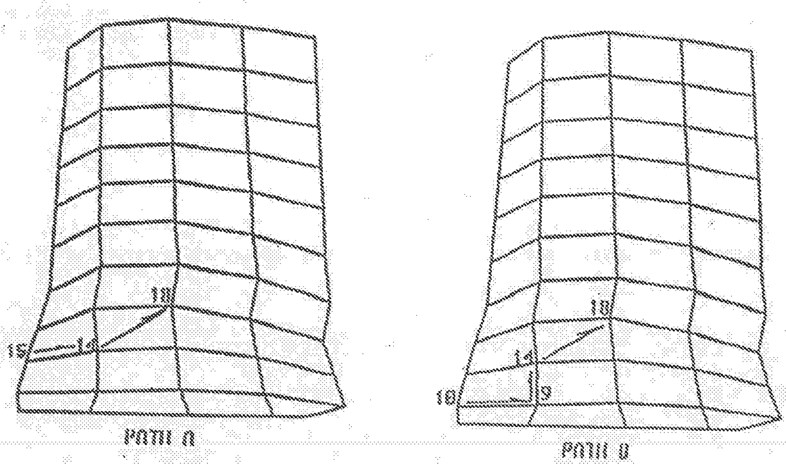
PMBM-SIMULATED LIFETIME STRENGTH FOR A NICKEL-BASED SUPERALLOY SUBJECTED TO 3162 STRESS CYCLES AND 100 HOURS OF CREEP





THERMAL MECHANICAL LOADS ON SSME BLADE

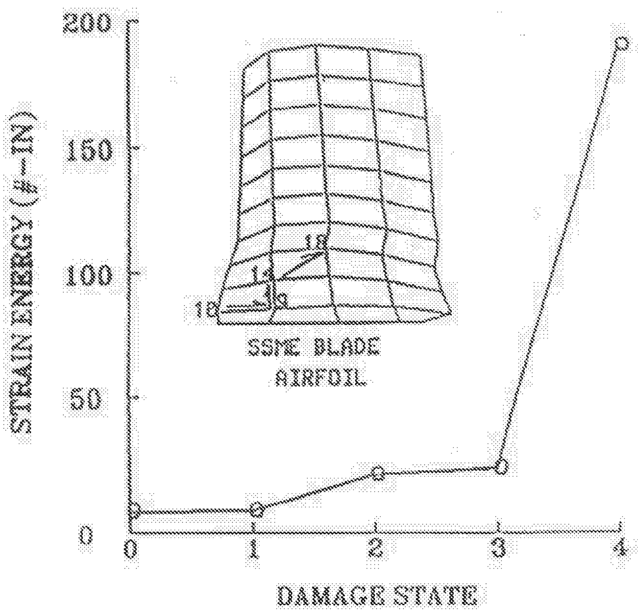
PROBABILITY OF COMPONENT DAMAGE PROPAGATION PATH
CAUSED BY 100,000 FATIGUE CYCLES



PROBABILITY OF
PATH A OCCURS
= 0.00001

PROBABILITY OF
PATH B OCCURS
= 0.0002

STRAIN ENERGY INCREASES AS THE DAMAGE PROGRESSES



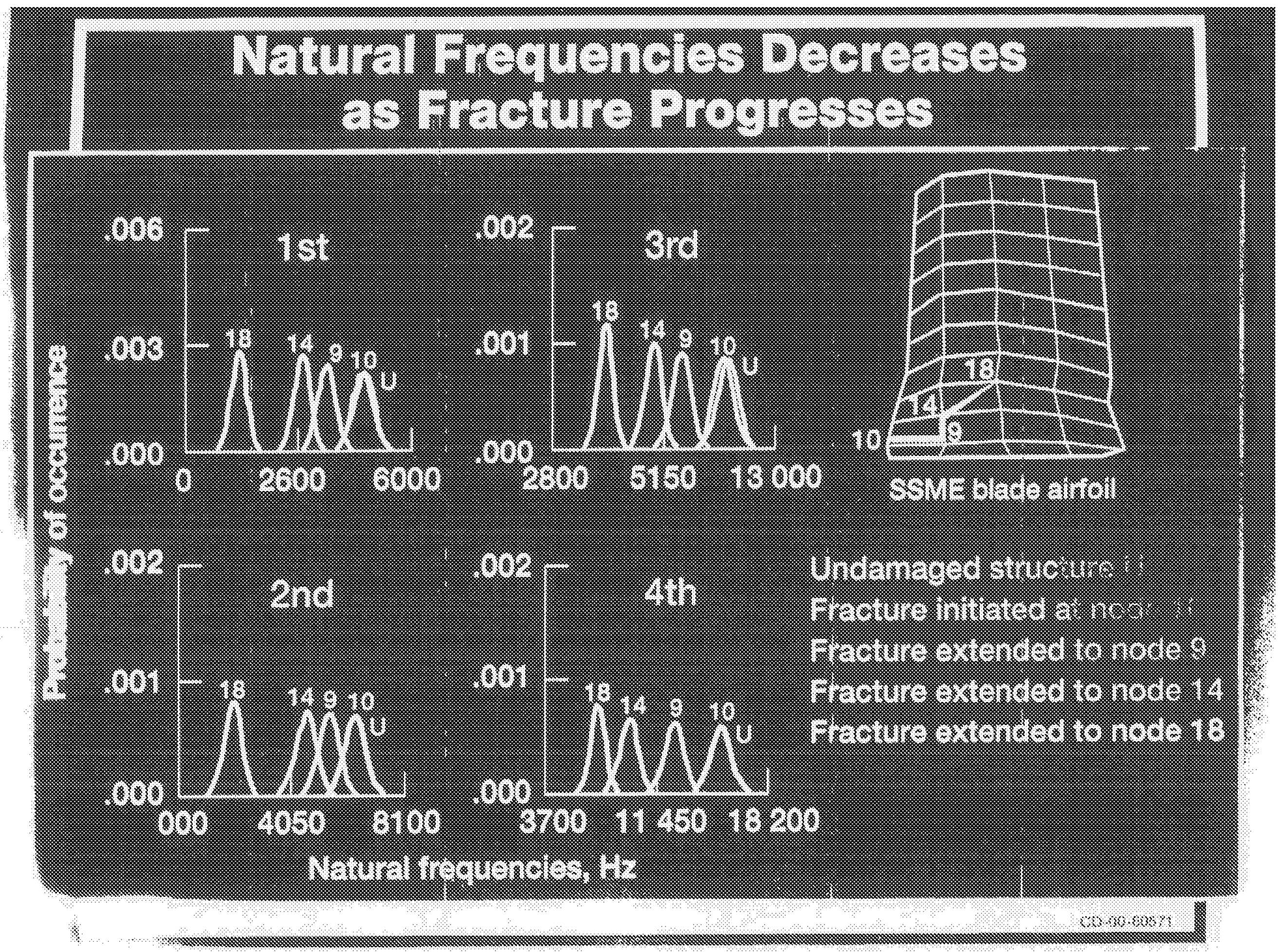
STATE 0
UNDAMAGED STRUCTURE

STATE 1
DAMAGE INITIATED AT NODE 10

STATE 2
DAMAGE EXTENDED TO NODE 9

STATE 3
DAMAGE EXTENDED TO NODE 14

STATE 4
DAMAGE EXTENDED TO NODE 18


Natural Frequencies Decreases as Fracture Progresses
Probability of occurrence
1st
2nd
3rd
4th
.006
.003
.000
.002
.001
18
14
9
10
U
0
2600
6000
000
4050
8100
2800
5150
13 000
3700
11 450
18 200
Natural frequencies, Hz
SSME blade airfoil
Undamaged structure
Fracture initiated at node
Fracture extended to node 9
Fracture extended to node 14
Fracture extended to node 18
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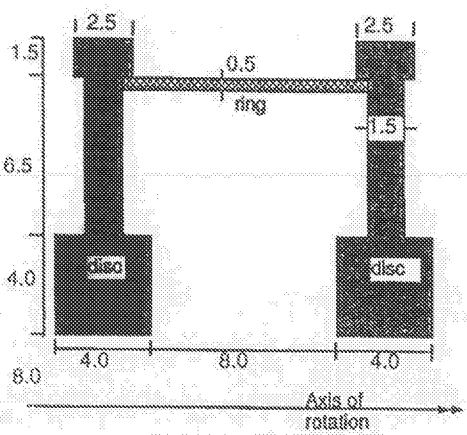
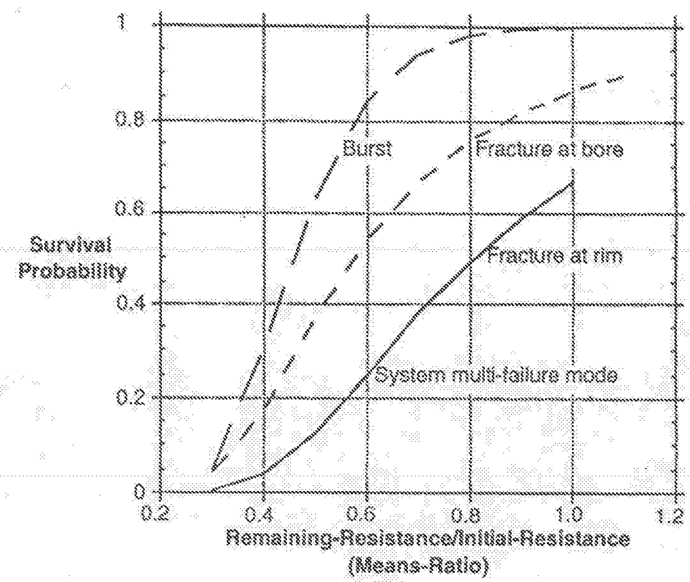
Rotor System Survival Probability Under Multiple Failure Modes



(Dimensions in inches)



Failure Mode	S	R
1. Disc burst	Average stress	Burst strength
2. Fracture at bore	Fracture life	10,000 cycles
3. Fracture at rim	Fracture life	10,000 cycles
4. Progressive damage	Yielding of the ring	Yield strength

Note: Yielding of ring affects all other modes through mutual interaction.

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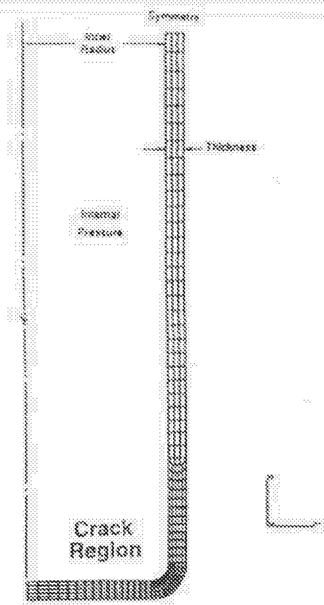
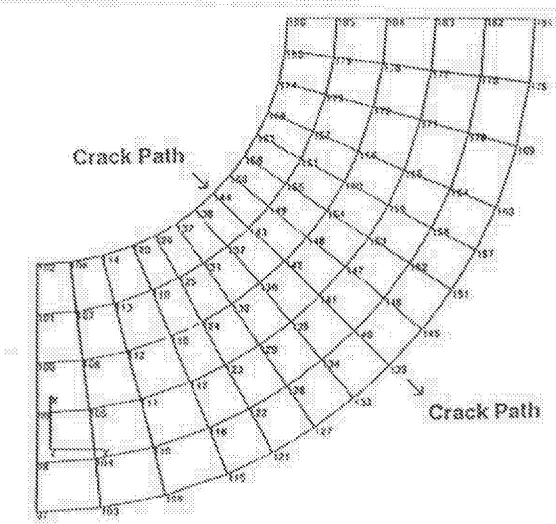
Sensitivity Factors of Rotor System Failure Probability

Name	In u(i) Space
E_ROT	0.016011
E_RIN	-0.002698
ROTOR DENS	0.438499
RING DENS	-0.000386
SPEED	0.850827
TEMPE	0.170793
BURST	-0.011983
RINGY	0.073086
RK1C	-0.061872
AO	0.057976
C	0.133702
NI	-0.000008
Kt	0.060917
A_LCF	-0.005132
TOLER	0.0

STRUCTURAL SYSTEM RELIABILITY CONSIDERING PROGRESSIVE FRACTURE EXAMPLE



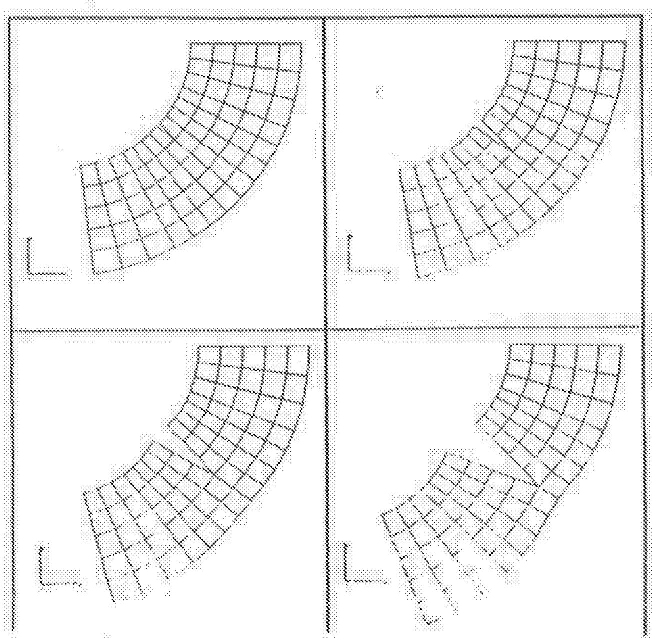
Finite Element Model of Axisymmetric Structure Under Internal Pressure



Crack Path Region

STRUCTURAL SYSTEM RELIABILITY CONSIDERING PROGRESSIVE FRACTURE EXAMPLE

Crack Growth: Bottom Events Modeled through Node Unzipping. Each Bottom Event Corresponds to Crack Initiation or a Crack Growth Increment



STRUCTURAL SYSTEM RELIABILITY CONSIDERING PROGRESSIVE FRACTURE EXAMPLE

Fatigue Calculations

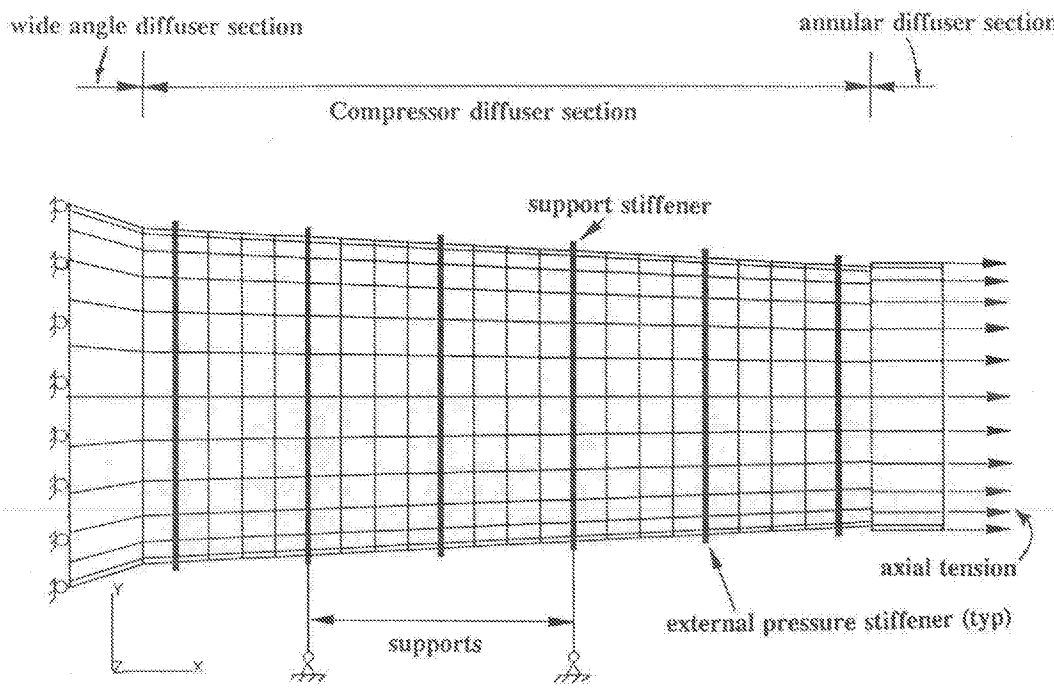
Number of Cycles to Grow Crack Computed Using Crack Growth Law Given Crack Increment

Cycles to Failure Results	
Event	# Cycles
Crack Initiation at node 144	$1.00 * 10^{+4}$
Fracture, N 144 → N 143	$1.80 * 10^{+4}$
Fracture, N 143 → N 142	$5.99 * 10^{+3}$
Fracture, N 142 → N 141	$2.99 * 10^{+3}$
Total	$3.70 * 10^{+4}$

Paris Crack Growth Law

$$\frac{da}{dn} = C\,(\Delta k)^m$$

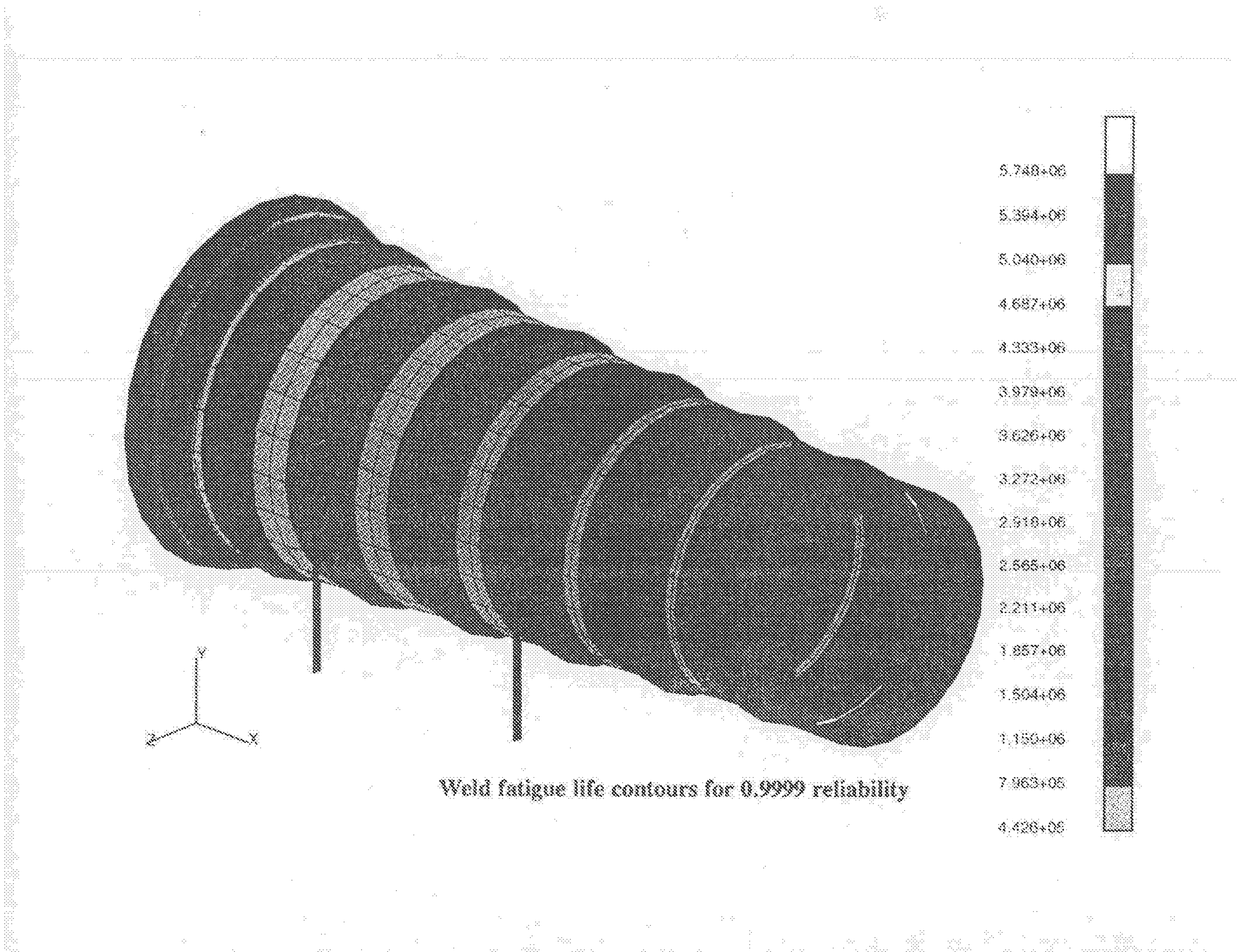
$$N_f = \frac{2[a_f^{(1-n/2)} - a_i^{(1-n/2)}]}{C\,(2-n)\,(Y\,\sigma_{max}\sqrt{\pi})^n} \qquad n \neq 2$$



National Wind Tunnel - structure and components

National Wind Tunnel Details:

- Dimensions:
  - Length = 133 ft.
  - Diameter at wide angle diffuser end = 51.67 ft
  - Diameter at annular diffuser end = 41.25 ft
- Material A516 Grade 70 steel
- Load: Internal pressure = 5 atm (73.0 psi)



Weld fatigue life contours for 0.9999 reliability

SUMMARY:

- Probabilistic fatigue by computational simulation is doable and can be adapted throughout the design practice.
- One way to enhance its implementation is to identify appropriate staff and task them to do it.
- The method constitutes a "virtual" statistical desk-top laboratory applicable at all stages of the design, development and service life cycle.
- Probabilistic fatigue evaluations rely on computational simulation results while statistic methods rely on experimental data.

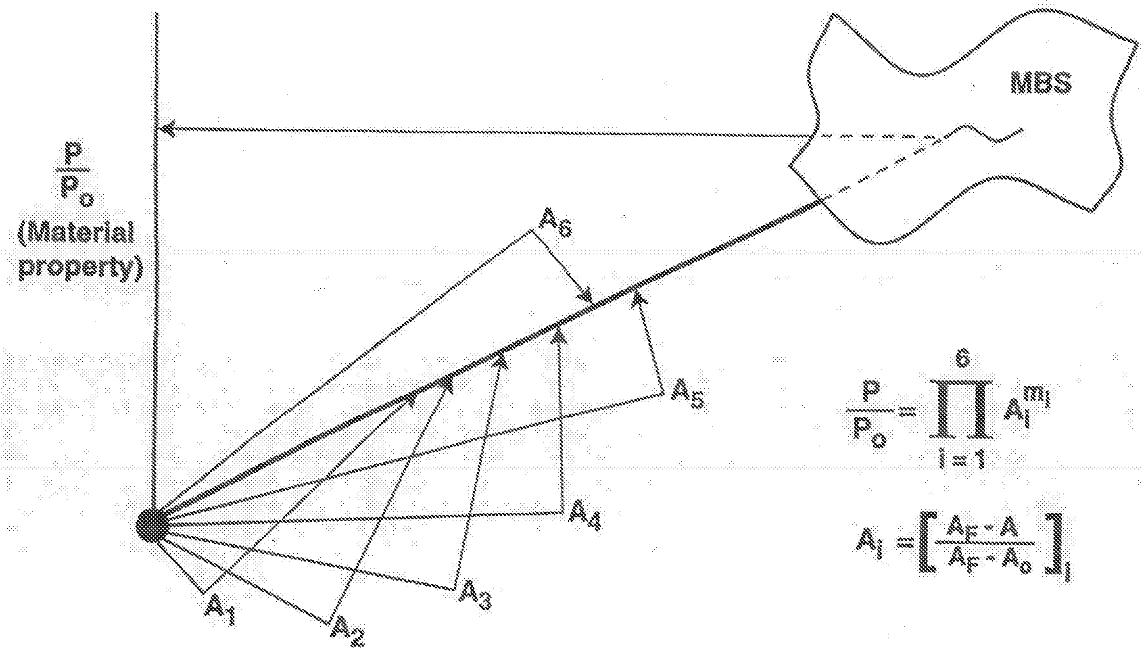
WHAT IS THE FUTURE OF PROBABILISTIC FATIGUE METHODS?

- The future is an exponential use of Probabilistic Fatigue Methods because the drive for Better-Cheaper-Faster engines necessitates quantification of risk for the utilization of unproven:

  -- Design Concepts
  -- Material
  -- Processes
  -- Etc.

- Probabilistic Fatigue Simulation is the most effective formal method to quantify risk and justify commitment of required resources.

Multi-Factor Interaction Model for Material Behavior Space (MBS)



$$\frac{P}{P_o} = \prod_{i=1}^{6} A_i^{m_i}$$

$$A_i = \left[\frac{A_F - A}{A_F - A_o}\right]_i$$

Factors influencing material behavior

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