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EXAMINATION OF THE EFFECT OF PROPULSION SYSTEM PERFORMANCE VARIABLES ON THE LIFE PREDICTION FOR THE SSME LOX POST

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The objective of this task is to calculate damage evolution at the critical location of selected components of reusable space propulsion systems as a function of their operating environment(s) and to relate the evolution of damage at the critical locations to the performance variables of the propulsion system using advanced constitutive and damage models. The models so developed will be oriented toward use in an advanced diagnostic/prognostic health monitoring system for reusable propulsion systems. Further, the models developed must be amenable to a probabilistic interpretation in the future. The intent is to build on the state of the art of previous work in these fields whenever possible rather than to develop new models. The components to be modelled include, a Lox Post (injector element), a thrust chamber, and a turbine blade. The study conducted on the Lox Post is reported here.

The loads that contribute to the main injector lox post damage evolution are temperature, static and dynamic pressure loads, and vibration loads. The temperature load on the post is controlled by engine system variables such as preburner mixture ratio, hot gas temperature and flow rate, Lox temperature and flow rate, local hot gas and coolant film coefficients, and any other local geometric and material property parameters. The pressure loads are a function of fluid drag and turbulence and static pressure differential. In this particular application damage at a row 12 Lox post thread root location is computed and related to system variables. It is apparent that generation of a link between performance variables and damage will span several disciplines such as engine performance, fluid mechanics, heat-transfer, structural analysis, and material science.

In general, for any component only a subset of the system variables that influence damage are directly measured in an actual flight. Thus it becomes necessary to rely on a numerical engine model that will compute the system variables that influence damage directly from a set of measured more primitive(independent) and/or local system variables that control engine health, thrust and performance. The most frequently used form of the model is the influence coefficient model which derives its origin from the more computationally intensive engine balance model and test measurements. Typically, the influence coefficient model is generated such that it accurately portrays engine performance in the plus or minus 3 sigma range of engine

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performance. One such influence coefficient model is used as part of this task.

The development of the system variable to structural response link require a large number of one time heat transfer and structural analysis runs covering the entire start transient, steady state, and cut off transient. Several parametric heat transfer analyses were run to set up influence coefficient models for different regions of the Lox Post that help to quickly compute the entire temperature field in the Lox Post over the full duty cycle given the local system variables. Using heat transfer influence coefficient models several parametric nonlinear structural analyses over two duty cycles were run to establish the link between system variables to temperature,stress levels, strain levels and, multiaxial factors at the critical locations of the hysteresis loop. A very refined axisymmetric model was used for this purpose.
Since the temperature was low enough for this component, the standard rate independant plasticity model was considered adequate for this application.

The dynamic response due to random pressure and mechanical vibration was computed using a detailed beam finite element model. The pressure P.S.D.shape and power, correlation length and their relation to local mass flow rate and fluid density were obtained from fluid dynamics unit. These system variables are linked to other system variables through engine system models. The r.m.s.stresses due to mechanical vibration (harmonics and random) were obtained using a multibase excitation analysis. Thus the r.m.s. high frequency stress response due to dynamic excitation is linked to system variables.

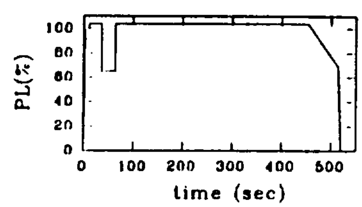
Thus at the end of above steps, the link between system variables to response variables that control damage evolution has been established. The damage computation module has been written with enough modularity to compute damage due to linear as well as nonlinear accumulation algorithms using the damage curve approach. Given the system variables, power level, and their duration the module computes the damage accumulated and if necessary computes the remaining flight life assuming that the last flight profile will be repeated in future flights. Several further options are available for the user to experiment with different stress amplitude distributions, order effect, hydrogen embrittlement and mutiaxiality factors, etc.

Future efforts involve the examination of system variables on life prediction of Main Combustion Chamber Liner and Turbine Blades. The main combustion chamber liner effort involves the implementation of thermal rachetting and crack growth prediction models and turbine blade effort involves implementation of life prediction methodologies for anisotropic superalloys.

LIFE PREDICTION TASK OBJECTIVES

- DEVELOP LINK FROM PERFORMANCE VARIABLES TO DAMAGE
- USE ADVANCED CONSTITUTIVE AND DAMAGE MODELS
- MODELS USED MUST BE AMENABLE FOR EXTENSION TO PROBABILISTIC DOMAIN
- DEMONSTRATE METHODOLOGY FOR LOX POST, MAIN COMBUSTION CHAMBER LINER, TURBINE BLADE

LIFE PREDICTION LINK TO HEALTH MONITORING SYSTEMS

FLIGHT OR TEST DATA	• 
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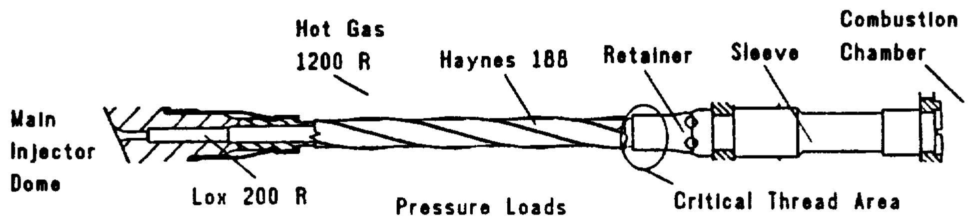
NUMERICAL ENGINE MODEL	• APPROXIMATION MODEL DERIVED FROM FULL FLEDGED ENGINE BALANCE MODEL
↓	
RESPONSE HISTORY COMPUTATION MODEL AT CRITICAL LOCATIONS	• APPROXIMATION MODEL DERIVED FROM FULL FLEDGED FINITE ELEMENT AND ADVANCED CONSTITUTIVE MODELS
↓	
DAMAGE CALCULATION MODEL	• DAMAGE CALCULATION USING ADVANCED MODELS

LOADS ON MAIN INJECTOR ELEMENT
ROW 12



- DOMINANT LOADS
  - TEMPERATURE DIFFERENTIAL
  - FLUID LOADS (DRAG AND DYNAMIC PRESSURE FLUCTUATION)
- LESS DOMINANT LOADS
  - MECHANICAL VIBRATION
- CRITICAL AREA LOOKED AT IS THE THREAD LOCATION

AN APPROXIMATE ENGINE PERFORMANCE MODEL
INFLUENCE COEFFICIENT MODEL

- EXTRACTED FROM NONLINEAR BALANCE MODEL
- POLYNOMIAL REGRESSION FIT
- STRONGLY CORRELATED WITH POWER LEVEL

INFLUENCE COEFFICIENT → $IC_{ij}(PL) = C_0 + C_1PL + C_2PL^2 + C_3PL^3$

DEPENDENT VARIABLE MEAN VALUE → $y_i(PL) = a_0 + a_1PL + a_2PL^2 + a_3PL^3$

- MAGNITUDE EVALUATION OF DEPENDENT VARIABLES

$$\frac{\Delta y_i}{y_i} = \sum_j IC_{ij}\frac{\Delta x_j}{x_j}$$

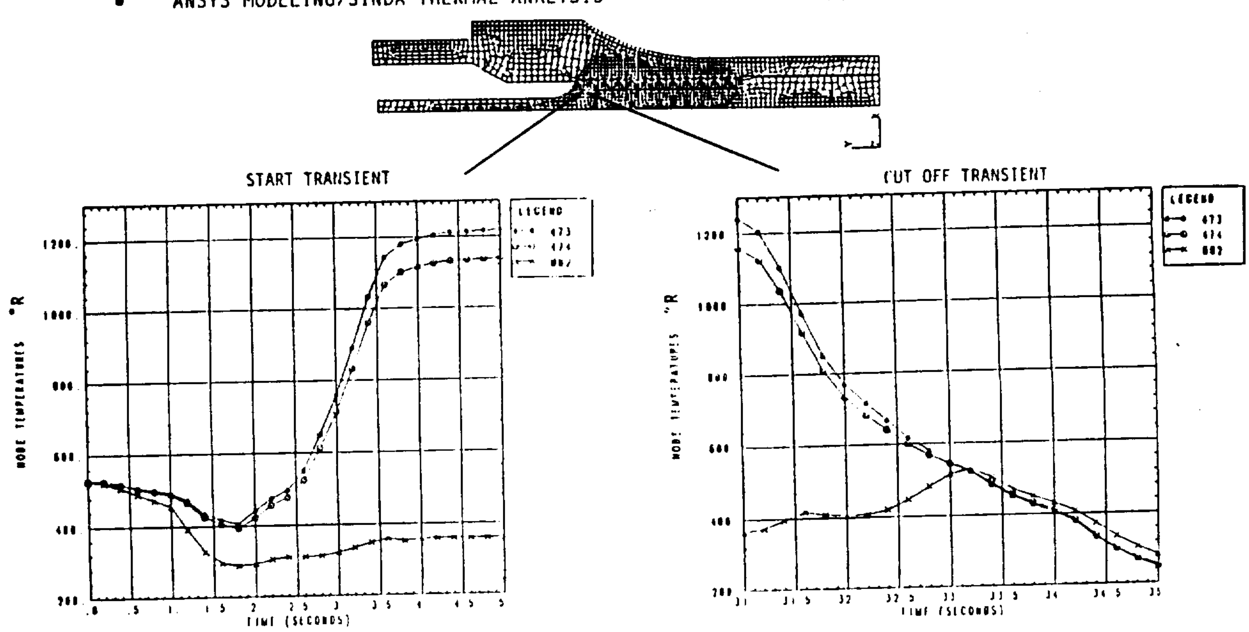
AN EXAMPLE OF INDEPENDENT AND DEPENDENT VARIABLE SET

	INDEPENDENT VALUES	
1.	FACILITY MIXTURE RATIO	6.0260
2.	FUEL INL TOTAL PR (PSIA)	30.0000
3.	OXID INL TOTAL PR (PSIA)	100.0000
4.	FUEL INL TEMP (DEG R)	37.0000
5.	OXID INL TEMP (DEG R)	164.0000
6.	HPFTP TURB NOZZ AREA	10.8000
7.	HPOTP TURB EFF MULT	1.0310
8.	HPOTP TURB NOZZ AREA	2.8960
9.	THRUST CHAMB C* MULT	1.0053
10.	HPFTP TURB EFF MULT	.9240
11.	POWER LEVEL	1.0400
12.	ETC. ...	

	DEPENDENT VALUES	
1.	HPOTP SPEED (RPM)	28335.8600
2.	HPFTP SPEED (RPM)	35660.2700
3.	HPOTP PUMP DIS PR (PSIA)	4321.3460
4.	HPFTP PUMP DIS PR (PSIA)	6521.7120
5.	OPB CHAMBER PR (PSIA)	5308.2630
6.	FPB CHAMBER PR (PSIA)	5213.4570
7.	ENGINE OXID FLOWRATE	930.5878
8.	ENGINE FUEL FLOWRATE	154.2625
9.	ENGINE THRUST	490784.4000
10.	OXID PRESSURANT F/R	1.6580
11.	FUEL PRESSURANT F/R	.7280
12.	OPOV POSITION	.6706
13.	FPOV POSITION	.8001
14.	MCC INJECTOR END PR	3126.2170
15.	HPOP INLET PR (PSIA)	386.2080
16.	HPFP INLET PR (PSIA)	206.8424
17.	PBP DISCH PR (PSIA)	7389.5130
18.	HPOP INLET TEMP	169.7184
19.	HPOP DISCH TEMP	192.0415
20.	HPFP DISCH TEMP	98.1692
21.	PBP DISCH TEMP	205.3588
22.	HPFP INLET TEMP	42.3058
23.	LPOTP SPEED	5166.0650
24.	LPFTP SPEED	15130.7500
25.	HPOT DISCH TEMP A	1285.8410
26.	HPOT DISCH TEMP B	1285.8410
27.	HPFT DISCH TEMP A	1735.9330
28.	ETC. ...	

THERMAL TRANSIENT ANALYSIS USING A REFINED THERMAL MODEL

- ANSYS MODELING/SINDA THERMAL ANALYSIS
- FOUR DISTINCT ZONES



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AN APPROXIMATE THERMAL ANALYZER MODEL
QUICK COMPUTATIONS ON TEMPERATURE FIELD

- INDEPENDENT VARIABLES
  - HOT GAS TEMPERATURE AND FLOW RATE
  - LOX TEMPERATURE AND FLOW RATE
  - LOX PRESSURE
  - HOT GAS AND LOX h FACTOR
  - HAYNES 188 K FACTOR
- INFLUENCE COEFFICIENT MODEL
- COEFFICIENTS OBTAINED FROM LARGE NUMBER OF PARAMETRIC RUNS

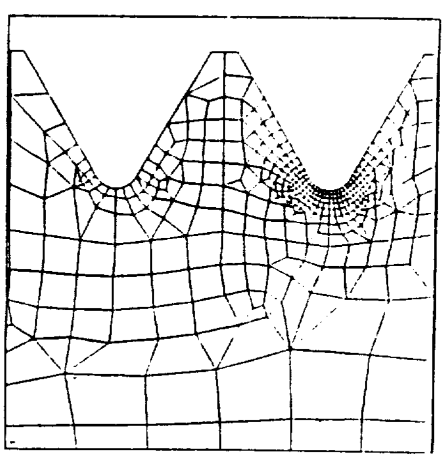
$$\frac{Max.Twg - Ref.Max.Twg}{Ref.Max.Twg} = k_1\left[\frac{V - Ref.V}{Ref.V}\right] + k_2\left[\frac{V - Ref.V}{Ref.V}\right]^2$$

$$\frac{Min.Twg - Ref.Min.Twg}{Ref.Min.Twg} = k_1\left[\frac{V - Ref.V}{Ref.V}\right] + k_2\left[\frac{V - Ref.V}{Ref.V}\right]^2$$

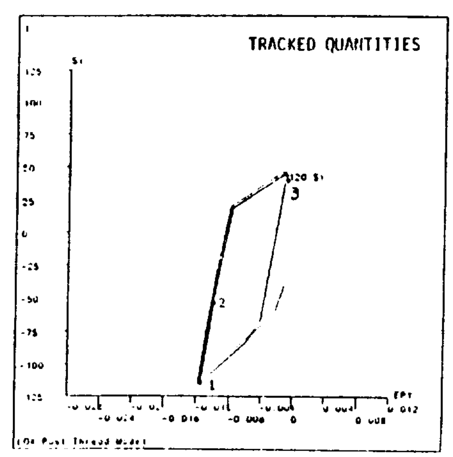
- DIFFERENT INFLUENCE COEFFICIENTS FOR FOUR ZONES

STATIC NONLINEAR ANALYSIS FOR TWO DUTY CYCLES USING A REFINED MODEL

- ANSYS COMPUTER CODE USED
- SEVERAL PARAMETRIC ANALYSES CORRESPONDING TO PERTURBATIONS OF SYSTEM VARIABLES
- TWO DUTY CYCLE TEMPERATURE CYCLING



A REFINED MODEL



A TYPICAL AXIAL σ - ϵ RESPONSE

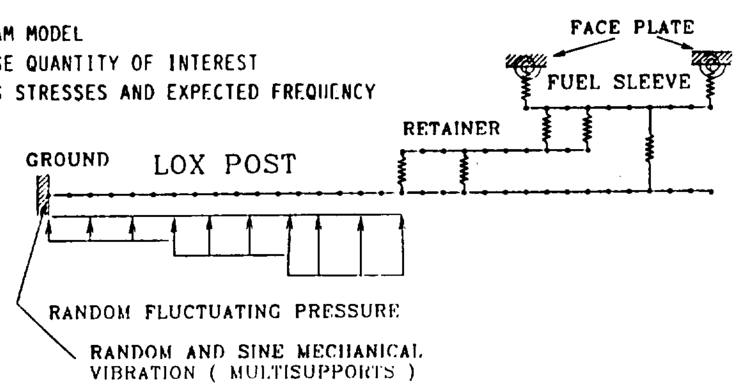
APPROXIMATE STATIC ANALYSIS MODEL LINKING RESPONSE TO SYSTEM VARIABLES
LCF DAMAGE DRIVERS

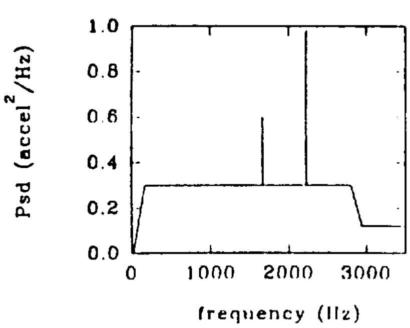
- RESPONSE VARIABLES
  - EFFECTIVE STRESS
  - TOTAL EFFECTIVE STRAIN
  - PLASTIC STRAIN
  - TEMPERATURE
  - MULTIAXIALITY FACTOR
- TRACKED AT THREE POINTS OF HYSTERESIS LOOP TO CALCULATE LCF DAMAGE
- A TYPICAL INFLUENCE MODEL

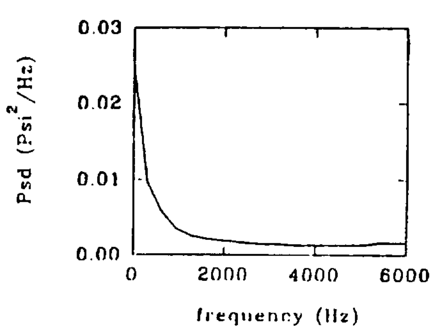
$$\epsilon_j^{tot} = b_0 + \sum_{i=1,9} b_i var_i^{indep} \qquad \text{at the } j^{th} \text{ point of the loop}$$

DYNAMIC ANALYSIS OF LOX POST
HCF DAMAGE DRIVERS

- FEM BEAM MODEL
- RESPONSE QUANTITY OF INTEREST
  - RMS STRESSES AND EXPECTED FREQUENCY







LINKING RMS RESPONSE TO SYSTEM VARIABLES

- SCALING RELATION

$$\sigma^{p}_{RMS}(\dot{m},\rho) = \sigma_{RMS,Ref}\sqrt{\frac{\rho_{Ref}}{\rho}\left(\frac{\dot{m}}{\dot{m}_{Ref}}\right)^{3}}$$

- TOTAL

$$\sigma_{RMS} = \sqrt{(\sigma^{p}_{RMS})^{2} + (\sigma^{Mech}_{RMS})^{2}}$$

- SINCE DYNAMIC RESPONSE IS DOMINATED BY FIRST BENDING MODE OF THE POST (1800HZ), EXPECTED FREQUENCY HAS NO SENSITIVITY TO SYSTEM VARIABLES

DAMAGE ACCUMULATION

- LOW AND HIGH CYCLE DAMAGE ACCUMULATION: LINEAR OR NONLINEAR (DAMAGE CURVE)
- LCF STRESS-STRAIN STATE DEPENDENT ON SPECIFIC MISSION INPUTS
- HCF DYNAMIC STRESS DEPENDENT ON TIME AT DIFFERENT POWER LEVELS DURING MISSION
- TEMPERATURE DEPENDENT FATIGUE CURVE
- ADJUSTMENT OPTIONS TO INCREASE LCF STRAIN RANGE DUE TO HCF "MAX" AMPLITUDE
- ADJUSTMENTS TO FATIGUE CURVE FOR MULTIAXIALITY AND HYDROGEN EFFECTS

HCF ACCUMULATION

- DYNAMIC STRESS AMPLITUDE DISTRIBUTION COULD BE RAYLEIGH OR USER DEFINED
- RANDOMIZED AMPLITUDE SELECTION OR BIN INTEGRATION METHOD FOR CALCULATING DAMAGE
- SHAKE DOWN OF MEAN DUE TO PEAK STRESS EXCEEDING YIELD
- NONLINEAR MEAN STRESS CORRECTION FOR POSITIVE MEAN STRESS

ADDITIONAL ELEMENTS OF THE DAMAGE MODEL

- DETERMINATION OF CONSISTENT CONSTITUTIVE AND FATIGUE CURVE
  ASSUMPTIONS: RAMBERG-OSGOOD FORM OF CYCLIC STRESS-STRAIN CURVE, MANSON-COFFIN TYPE OF FATIGUE CURVE

$$\sum_{LCF}\left[\Delta\epsilon_i - \left(BN_i^b + CN_i^c\right)\right]^2 + \sum_{HCF}\left[\frac{2}{E}\frac{\Delta\sigma_j}{2} + C\left(\frac{2}{BE}\right)^{c/b}\left(\frac{\Delta\sigma_j}{2}\right)^{c/b} - \left(BN_j^b + CN_j^c\right)\right]^2 \to \min$$

- EFFECT OF MAXIMUM RANDOM HCF LOAD ON LCF STRAIN RANGE THROUGH NOTCH PLASTICITY
  ASSUMPTIONS: NEUBER'S RULE APPLIES AT POINT 2 OF THE HYSTERESIS LOOP

$$\sigma^{adj}(\epsilon^{adj} - \epsilon_2^{plast}) = \frac{(\sigma_2 + 3\sigma^{random})^2}{E}$$

- EFFECT OF THE MULTIAXIALITY FACTOR (MF) ON LIFE
  MODIFIED FATIGUE CURVE CONSTANTS:

$$C' = \frac{C}{MF} \qquad B' = \left(\frac{B}{MF}\right)^{b/c}$$

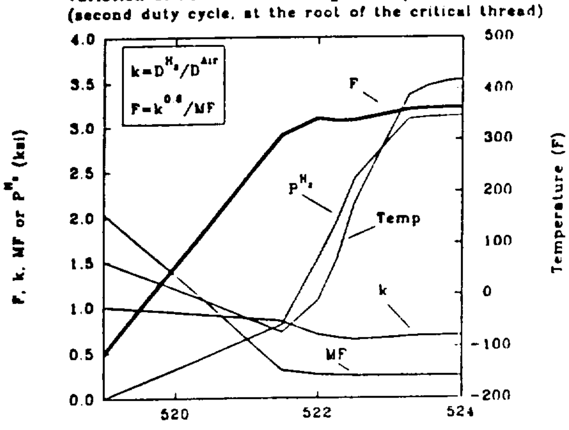
- EFFECT OF H_2 ENVIRONMENT THROUGH DUCTILITY LOSS
  MODIFIED FATIGUE CURVE CONSTANT ACCORDING TO UNIVERSAL SLOPES EQUATION:

$$C' = \left(\frac{D^H}{D^{air}}\right)^{0.6} C$$

ADDITIONAL ELEMENTS OF THE DAMAGE MODEL (CONTINUED)

- CUMULATIVE MULTIAXIAL AND H_2 EFFECT IS DOMINATED BY MULTIAXIALITY NEAR THE END OF THE DUTY CYCLE

Variation of Parameters during Startup Transient (second duty cycle, at the root of the critical thread)



Variation of Parameters during Shutdown Transient (second duty cycle, at the root of the critical thread)