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EVALUATION OF SSME TEST DATA REDUCTION METHODS

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INTRODUCTION

Accurate prediction of hardware and flow characteristics within the Space Shuttle Main Engine (SSME) during transient and main-stage operation requires a significant integration of ground test data, flight experience, and computational models. The process of integrating SSME test measurements with physical model predictions is commonly referred to as data reduction. Uncertainties within both test measurements and simplified models of the SSME flow environment compound the data integration problem.

SSME performance models require specification of a number of hardware characteristics including turbomachinery maps and other hardware specific parameters. These characteristics are required in order to obtain formal closure of the engine mathematical model. They contain the accumulated historical data base of SSME performance. Each hardware parameter has an uncertainty consistent with the data base dispersion upon which its value is estimated.

Complete specification of SSME performance requires the identification of thermodynamic properties and flow rates throughout the engine system, as well as specification of various hardware characteristics such as valve positions, torques, and speeds. These performance characteristics are obtained by solution of a set of nonlinear relations incorporating the physical requirements of subsystem mass and energy conservation as well as semi-empirical relations for duct/valve pressure losses, turbomachinery performance, and a variety of other hardware specific operating properties. Mathematically the performance prediction problem can be expressed as

$$F(P;H) = 0$$

where

F - the set of nonlinear physical relations governing SSME performance
P - the set of solution variables including thermo-fluid properties, etc.
H - the set of assumed constant hardware characteristics based on past test experience.

Individual engine tests provide indications of specific physical characteristics in set **P**. If these characteristics are fixed at test values, a like number of hardware characteristics must be allowed to vary in order to satisfy the set of governing equations. The revised data reduction problem can be expressed as

$$F(Po, Ho \; ; \; P^*, H^*) = 0$$

where

Po - the remaining set of physical property variables (**P-P***)
Ho - the new set of variable hardware characteristics
P* - the set of physical conditions fixed by specific test data
H* - the remaining set of fixed hardware characteristics (**H-Ho**).

The data reduction process is depicted conceptually in Figure 1. Abscissa values represent hardware characteristics and ordinate values represent physical characteristics. The line **F = 0** represents combinations of physical and hardware characteristics providing exact solutions to the physical relations. The point **(H,P)** represents an initial solution prior to new test data input. The point **(H*,P*)** represents the data reduction solution after incorporation of new test data. Since exact solutions to nonlinear system equations are rare, neither point is on the exact solution curve, however, both must lie within a tolerance limit for convergence.

Uncertainty bands associated with hardware characteristics (**UH**), physical properties (**UP**), and model balance relations (**UF**) are also shown in Figure 1. **UH** represents uncertainty in the experience base which is associated with the fixed hardware characteristics **H**. **UP** represents uncertainty in the physical test measurements and **UF** represents balance point uncertainty due to model simplification of physical relations.

DATA REDUCTION STRATEGIES

The first objective of this effort was to establish an acceptability criterion for data reduction solutions. Any solution that falls within the uncertainty band intersection depicted in Figure 2 is acceptable. More "exact" reduction techniques which attempt to enforce balance within tight tolerance limits are severely limited by normal dispersions in reduction test data. These dispersions can prevent tight tolerance solution or enforce unrealistic physical balances in an attempt to match data exactly at measurement points.

Within large system projects, the traditional data reduction approach is heuristic. In an effort to match test results precisely, physical relations are relaxed in a simplistic manner. This can lead to questionable results which enforce agreement with the hardware experience base but sacrifice physical consistency [1]. Typical results of a heuristic data reduction techniques are presented in Figure 3. In extreme cases, the desire to match new test data can provide solutions outside the experience base as depicted in Figure 4. Predictions from heuristic reduction strategies often fall outside the common acceptable region described in Figures 2-4. These are at best difficult to defend and at worst provide erroneous predictions costly both in time and resources.

An ongoing effort to improve data reduction capability is currently being supported by NASA/MSFC/EP14. A new approach termed the reconciliation strategy [2] was developed to improve data reduction capability within the existing SSME performance model. The reconciliation method is based on a systematic optimization strategy that incorporates test information, the historical data base, and balance relation uncertainties within a computational procedure that returns the best possible estimate of engine performance characteristics. The reconciliation method requires a physically consistent model of system operation in order to achieve high quality data integration. In another ongoing effort to improve performance prediction capability, NASA supported development of the ROCket Engine Transient Simulation or ROCETS [3] system. ROCETS is a well documented and structured platform for modeling liquid rocket propulsion systems. It provides a modular high level programming capability for constructing physically consistent engine performance simulations. The ROCETS platform does not, however, explicitly incorporate a data reduction strategy.

SSME ROCETS MODEL DATA REDUCTION PROCEDURE

The second objective of this effort was to investigate the data reduction potential of the ROCETS simulation platform. A simplified ROCETS model of the SSME was obtained from the MSFC Performance Analysis Branch (EP14). This model was examined and tested for physical consistency. Two modules were constructed and added to the ROCETS library to independently check the mass and energy balances of selected engine subsystems including the low pressure fuel turbopump (LPFTP), the high pressure fuel turbopump (HPFTP), the low pressure oxidizer turbopump (LPOTP), the high pressure oxidizer turbopump and preburner pump (HPOTP+PBP), the fuel preburner (FPB), the oxidizer preburner (OPB), the main combustion chamber coolant circuit (MCC clnt), and the nozzle coolant circuit (NOZ clnt).

A sensitivity study was then conducted to determine the individual influences of forty-two hardware characteristics on fourteen high pressure region prediction variables as returned by the SSME ROCETS model. The object of this study was to determine appropriate hardware characteristics to vary in order to match ROCETS predictions with performance variable test data. Table 1 includes a partial listing of normalized sensitivities, defined as the percent change in physical characteristic (left column) divided by the percent change in hardware characteristic (top rows).

A reduction procedure was implemented within the SSME ROCETS model by adding balances that would enforce agreement with specific test measurements. SSME data was obtained from a recent TTB test (TTB-50). Results of the sensitivity study were used to help construct a series of reduction analyses with increasing numbers of measurement anchor points.

SSME ROCETS MODEL DATA REDUCTION RESULTS

The independent balance calculations verified that the SSME ROCETS model obtained mass flow balance in all devices. Energy flows were balanced in all pure component flow systems. However, energy imbalance predictions were relatively large in devices with hot gas flows. Although energy related computations were physically consistent, hot gas enthalpy calculations were performed using a crude ideal gas model. Standard state indexing for combustion calculations was similarly crude. The independent balance module was unable to verify accurate energy calculations in the hot gas region due to the lack of water property data.

Table 2 presents results from the ROCETS SSME data reduction model. Column one contains test data for various SSME internal parameters obtained at 100% rated power level during TTB-50. Column two contains theoretical predictions derived at the corresponding SSME inlet conditions. The next four columns represent adjustments to the theoretical predictions based on matching specific SSME measurements to specific engine hardware characteristics. Of the seventeen parameters evaluated, seven were anchored to test data. The final data reduction results showed that of the ten parameters that were allowed to vary, three moved towards measured test data. These three parameters were characterized within the adjusted engine hardware characteristics. Solutions for the other seven parameters diverged from measured test data. This may be the result of incomplete modeling of the SSME hardware, as well as inherent weakness in the "exact" data reduction strategy. This observation supports the need for a reconciliation strategy which recognizes uncertainty limitations within the physics, test data, and hardware characteristics. Information needed to establish an accurate and fundamentally sound approach to test data reduction has been developed during this effort..

RECOMMENDATIONS

Based on a study of data reduction procedures and experience with the SSME ROCETS model as a data reduction tool, the following recommendations are made:

1. The SSME ROCETS model should be developed as a production level performance prediction platform. Improvement of hot gas property computations is needed to provide confidence in energy computations. SSME system detail should be added to the existing model including POGO flow refinement, repressurization systems, MCC and Nozzle leakage, and pump cavitation computations.

2. A robust reconciliation strategy for system level data reduction should be implemented as an option within the SSME ROCETS model. The reconciliation strategy should be phased in as a replacement for existing heuristic reduction methods.

3. Uncertainty estimates associated with SSME test measurements, hardware characteristics, and model balance relations should be established to provide a logical basis for data reduction.

4. A procedure for systematic updating of SSME hardware performance characteristics within the SSME ROCETS model should be implemented. A method for maintaining model integrity needs to be established.

REFERENCES

1. Santi, L. M., "Validation of the Space Shuttle Main Engine Steady State Performance Model," NASA contract report NGT-01-002-099, 1990.
2. Santi, L. M., "Integrated Model Development for Liquid Fueled Rocket Propulsion Systems," UAH subcontract associated with NASA contract NAG8-212, Task No. 6, June, 1993.
3. "ROCETS System Design Specification," Pratt & Whitney FR-20284, May, 1990.

Figure 1. Data Reduction Process

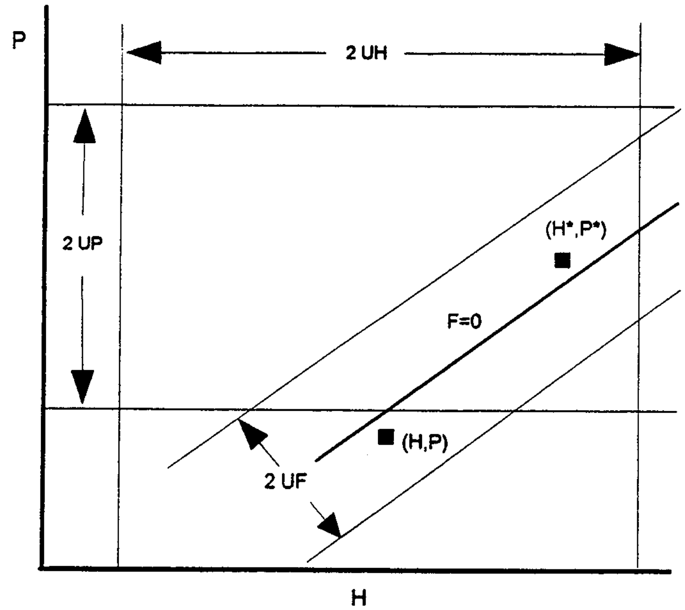

Figure 2. Acceptable Point Region

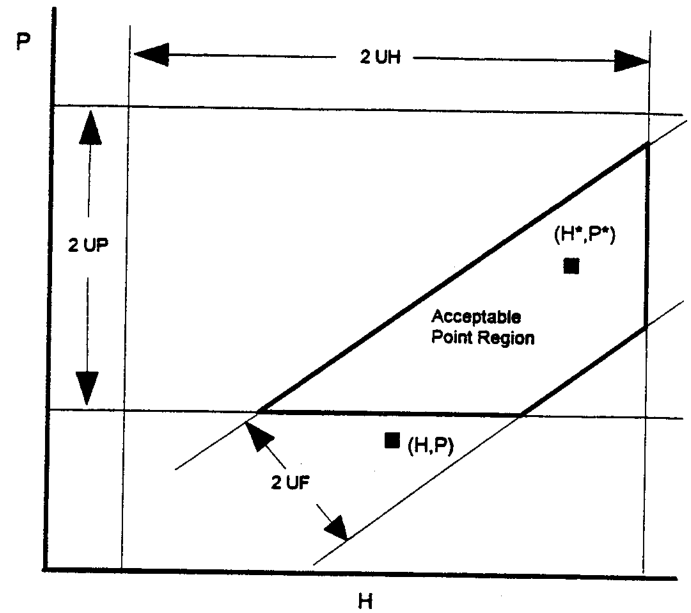

Figure 3. Typical Heuristic Solution

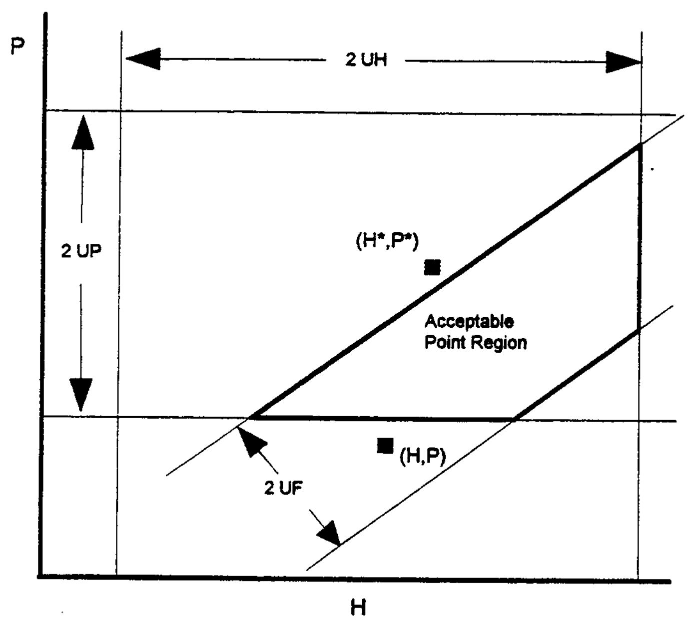

Figure 4. Unacceptable Solution

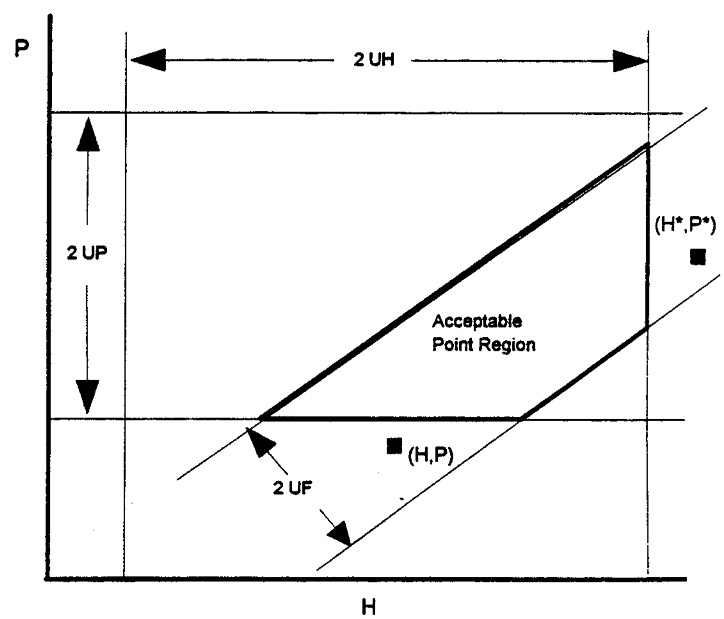

Table 1. Normalized Sensitivities from SSME ROCETS model

HARDWARE	ETA M HPOT	ETA M HPFT	TORQ M HPOP	TORQ M HPFP	TORQ M PBP	RES M MFV	AREA M LPFT
PHYSICAL							
HPOT DS T	-1.827	1.094	1.910	-1.629	0.103	0.412	0.102
HPFT DS T	0.390	-1.339	-0.419	1.869	-0.023	-0.096	0.090
OPB Pc	-0.259	-0.055	0.279	0.080	0.015	0.063	-0.003
FPB Pc	-0.040	-0.299	0.043	0.453	0.002	0.009	-0.003
PBP DS PR	0.104	0.248	-0.079	-0.352	-0.044	0.232	-0.015
HPOP DS PR	0.016	0.045	0.010	-0.063	-0.001	0.246	-0.003
HPFP DS PR	-0.079	-0.144	0.085	0.285	0.004	0.019	-0.022
MCC CLNT DS PR	-0.052	-0.100	0.057	0.161	0.003	0.013	-0.222
OPB FUEL FLOW	0.836	-0.810	-0.909	1.266	-0.049	-0.206	-0.074
OPB OXID FLOW	-1.500	0.651	1.672	-1.045	0.088	0.355	0.051
FPB OXID FLOW	0.150	-1.130	-0.163	1.650	-0.011	-0.038	0.035

Table 2. TTB Data Reduction Results

(Power level = 100% RPL, MCC Pc = 2746 PSIA, M/R = 6.090)
(LPOP in Pr = 137.6 psia, LPOP in Tmp = 167.3 ^{o}R, LPOP in W = 901.0 lb/sec)
(LPFP in Pr = 40.4 psia, LPFP in Tmp = 36.6 ^{o}R, LPFP in W = 149.0 lb/sec)

	PARAMETERS	TTB-50 TEST DATA	ROCETS PREDICTION	P(1)-HPOT EFF P(2)-HPFT EFF	P(1)-HPOT EFF P(2)-HPFT EFF P(3)-HPOP TRQ P(4)-HPFP TRQ	P(1)-HPOT EFF P(2)-HPFT EFF P(3)-HPOP TRQ P(4)-HPFP TRQ P(5)-PBP TRQ	P(1)-HPOT EFF P(2)-HPFT EFF P(3)-HPOP TRQ P(4)-HPFP TRQ P(5)-PBP TRQ P(6)-MFV RES P(7)-LPFT AREA
P(1)	HPOT Td (AVG)	**1269**	1336	**1269**	**1269**	**1269**	**1269**
P(2)	HPFT Td (AVG)	**1492**	1502	**1492**	**1492**	**1492**	**1492**
	LPFTP SPEED	**15460**	14353	14289	15285	15281	15636
	HPFTP SPEED	**33360**	31855	31810	41535	41502	40705
	OPOV POSITION	**64.3**	60.1	58.8	58.4	57.4	57.8
	FPOV POSITION	**74.2**	71.3	70.8	73.4	71.9	72.7
P(3)	OPB Pc	**4536**	4489	4444	**4536**	**4536**	**4536**
P(4)	FPB Pc	**4555**	4401	4375	**4555**	**4555**	**4555**
P(5)	PBP DS PR	**6688**	6598	6619	6540	**6688**	**6688**
P(6)	HPOP DS PR	**3907**	3718	3723	3696	3698	**3907**
	HPFP DS PR	**5507**	5451	5424	5869	5868	5858
P(7)	MCC CLNT DS PR	**4236**	4005	3992	4093	4093	**4236**
	LPFT INL FLOW	**26.50**	25.28	25.10	24.63	24.64	23.69
	OPB FUEL FLOW	**33.16**	32.10	32.68	35.16	35.16	35.46
	OPB OXID FLOW	**24.20**	20.74	19.81	18.74	18.75	18.65
	FPB FUEL FLOW	**76.63**	71.60	71.24	69.72	69.72	70.31
	FPB OXID FLOW	**57.54**	55.45	54.77	57.65	57.72	57.65