Technique	Apply a univariate failure prediction algorithm using a signal processing technique to rocket engine test firing data to provide an early failure indication. The predictive maintenance technique involves tracking the variations in the average signal power over time.

ROCKET ENGINE FAILURE PREDICTION USING AN AVERAGE SIGNAL POWER TECHNIQUE

Use performance prediction algorithms during rocket engine tests for identification of incipient failures

Benefits	This technique will therefore reduce unnecessary failures attributed to the traditionally used redline-based system. The average signal power algorithm can be used with engine test firing data to provide significantly earlier failure indication times than the present method of using redline limits. Limit monitoring techniques are not capable of detecting certain modes of failures with sufficient warning to avoid major hardware and facility damage.
Key Words	Rocket Engines, Failure Detection, Detectability
Application Experience	Space Transportation System (STS)
Technical Rationale	Detection of anomalous behavior is critical during the operation of the Space Shuttle Main Engine (SSME). Increasing the detectability of failures during the steady-state operation of the SSME will minimize the likelihood of costly engine damage and maintenance. The average power signal algorithm is superior to the time series algorithm because more parameters contribute to the first simultaneous failure indication times. This increases the agreement between several parameters, thus increasing the likelihood that an engine anomaly has occurred. This method also reduces the number of false failure indications that can prematurely shut down the engine during testing or operation.
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Rocket Engine Failure Detection Using An Average Signal Power Technique
Technique AT-5

For discrete random processes, probabilistic functions are used to describe the behavior of the rocket engine system. The Power Spectral Density (PSD) is computed to describe how the variation of the random process is distributed with frequency. For stationary signals, the PSD is bandlimited to ±1/(2T), where T is the sampling interval in seconds.

Average Signal Power Calculations
The PSD is defined as the discrete-time Fourier transform of an autocorrelation function. (The derivation of the autocorrelation function is shown in Reference 1.) When the autocorrelation function is evaluated at zero lag, then an expression for the average signal power (ASP) of a random stationary process results:

$$ASP = r_{xx}[0] = \int_{-\frac{1}{2T}}^{+\frac{1}{2T}} P_{xx}(f)df \qquad (1)$$

where:

$P_{xx}(f)$ = discrete-time Fourier Transform
$r_{xx}[0]$ = inverse discrete-time Fourier transform

The average signal power for several SSME parameters is determined by calculating the autocorrelation at zero lag for the parameters provided in Table 1. The assumption is made that the signal is stationary over the computation interval. The average signal power calculations are performed over 2-second, 50-percent overlapping window for nominal test firings at both 104- and a 109-percent-rated power levels. A smaller time increment must be used to improve the failure detection capability of the algorithm.

Table 1: Signal Threshold and Safety Factor for SSME's

Parameter	*Average Power*	
	Threshold	*Safety Factor*
Mixture Ratio	0.00112	1.5
MCC Coolant Discharge	200	1.5
MCC Hot Gas Injector Pressure	125	1.5
LPOP Shaft Speed	1598	2.5
LPFP Discharge Pressure	2509	1.5
HPFP Discharge Pressure	436	1.5
Fuel Preburner Chamber Pressure	232	1.5
PBP Discharge Pressure	911	1.5
HPOP Discharge Pressure	268	1.5
PBP Discharge Temperature	0.04	3.0
MCC Pressure	47	1.5
HPFP Inlet Pressure	4	1.5
HPOP Inlet Pressure	6	1.5
HPFT Discharge Temperature A	32	2.0
HPFT Discharge Temperature B	38	2.5
HPOT Discharge Temperature A	154	3.5
HPOT Discharge Temperature B	104	3.5
HPFP Shaft Speed	550000	3.5

The average plus three standard deviations of the average signal power are computed for all the nominal firings at both engine power levels. These values are combined to calculate the thresholds (see Reference 1).

A safety factor ranging from 1.5 to 3.5 is needed to ensure no false failure indications are computed for the nominal firings. The range of safety factors reflected signal behavior variations that occurred over seven nominal A2 firings. When used in the failure detection mode, failure of the average signal power of a parameter to fall outside its threshold results in a failure indication. Also shown in Table 1 are the thresholds calculated from the SSME nominal test firings based on the average signal power algorithm along with the associated safety factors.

Algorithm Implementation

A system identification and signal processing software package on a RISC workstation provides the average signal power algorithm. Command and Data Simulator (CADS) data from a predetermined number of SSME test firings are used to establish the failure indication thresholds.

Several system conditions must be considered to ensure that the algorithm does not erroneously indicate an engine fault. These conditions include sensor failure, propellant tank venting and pressurization, and propellant transfer. Sensor failure detection techniques must be exercised before, or concurrently, with safety monitoring algorithms in order to eliminate the possibility of a sensor failure being interpreted as an engine problem. Typically, all parameters exhibiting sensor problems are removed prior to the application of the algorithm.

Failure indication thresholds are established by applying the average signal power algorithm to a set number of nominal tests. For the SSME four anomalous firings and one nominal firing were tested using the thresholds shown in Table 1. An example of the application of the average signal power algorithm to a SSME anomalous test firing is shown in Figures 1 and 2.

Figure 1 illustrates the interval over which the average signal power was computed for a single parameter, HPFP discharge pressure and one test firing.

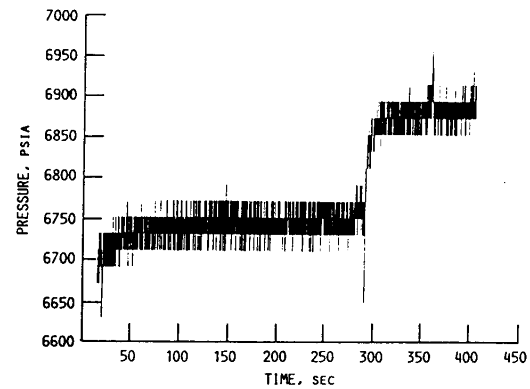

Figure 1: Application of the Average Signal Power Algorithm to the HPFP Discharge Pressure

Figure 2 displays the resulting average signal power, as a function of time. As shown, the threshold for the average signal power algorithm has been exceeded.

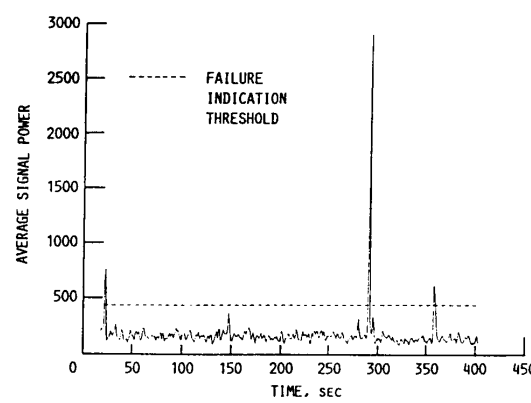

Figure 2: Average Signal Power for that Interval with the Failure Indication Threshold

Nomenclature:

HPFP	high pressure fuel pump
HPFT	high pressure fuel turbine
HPFTP	high pressure fuel turbopump
HPOP	high pressure oxidizer pump
HPOT	high pressure oxidizer turbine
LPFP	low pressure fuel pump
MCC	main combustion chamber
PID	parameter identification
SSME	space shuttle main engine

Reference

Meyer, C.M., Zakrajsek, J.F., *Rocket Engine Failure Detection Using System Identification Techniques*, AIAA Paper 90-1993, July 1990.