ADVANCED ENGINE HEALTH MANAGEMENT APPLICATIONS OF THE SSME REAL-TIME VIBRATION MONITORING SYSTEM

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Abstract

This paper describes the operational capabilities of the Real-Time Vibration Monitoring System (RTVMS) developed by the Marshall Space Flight Center (MSFC) for Space Shuttle Main Engine (SSME) high-speed turbomachinery vibration diagnostics and failure mitigation. RTVMS is now operational at the Stennis Space Center (SSC) during SSME static test firings to provide real-time vibration analysis and health monitoring capabilities during engine operation. The RTVMS produces real-time vibration spectral data from such critical SSME components as the high pressure turbomachinery. From this data, discrete spectral signatures, which are prime indicators of turbomachinery health, can be assessed at high speeds and utilized to mitigate potential catastrophic engine failures. The ability to monitor these potential failure indicators will allow the SSME Program to develop a digital engine health monitoring system based on vibration analysis and, for the first time in the history of the Space Shuttle flight program, activate a vibration flight redline for the engine high pressure turbomachinery.

Introduction

The Fluid Physics and Dynamics Group is part of the Space Transportation Directorate located at the NASA Marshall Space Flight Center (MSFC). One of the major roles of the Dynamics Group is to assess the SSME vibration data from static tests and Space Shuttle flights to determine the acceptability of the engine/engine components for flight. Primary interest is focused on the high pressure turbomachinery utilized on the SSME. Analysis of the vibration data from these turbopumps is critical due to the extreme rotordynamic conditions under which this hardware operates. The vibration data from these components yield critical rotordynamic spectral signatures that provide insight into the turbomachinery health. Parameters such as rotor mass balance, rubbing, cavitation, impeller blade wakes, bearing signatures (rolling element train, element spin, and race signatures) can be easily assessed for diagnostic purposes to determine component health.

MSFC has over 20 years of experience analyzing high frequency SSME vibration data and defining acceptability criteria for SSME flight hardware. Only recent technology advancements have allowed for the development of real-time processing systems capable of assessing vibration data at high speeds during SSME operation. MSFC began an effort in 1994 to develop a system based on parallel processing and incorporating MSFC analysis algorithms to monitor, in real-time, the health of the SSME high-speed turbomachinery. MSFC delivered and integrated the first RTVMS to SSC in October of 1996. Since this time, RTVMS has been an active, automated engine health monitoring and analysis system for the SSME static test fire program and has monitored engine turbomachinery for over 150 SSME test fires. MSFC also developed a sub-scale version of RTVMS that flew as part of the Human Exploration and Development of Space (HEDS) Technology Demonstration Flight 2 (TD-2) during STS-96 in May of 1999. This system demonstrated for the first time the ability to acquire vibration data from the SSME turbomachinery at high speeds and monitor discrete spectral signatures during flight operations.

Because of their experience with RTVMS, MSFC personnel will play critical roles in the development and implementation of the SSME Advanced Health Management System (AHMS). AHMS is a major Shuttle Flight Safety Upgrade program which incorporates, in the near-term, an SSME Controller modification that will utilize RTVMS technology to establish a turbomachinery vibration redline for flight. Furthermore, RTVMS will then be incorporated into the AHMS Health Management Computer (HMC), which is the main health system of the AHMS program. This paper provides an overview of RTVMS and its advanced engine health management applications for SSME.

RTVMS Description and Theory of Operation

The vibration source data (accelerometers) from the SSME must be acquired at high sample rates in order to provide the best time and frequency resolutions in the frequency domain for performing enhanced engine health monitoring. Most historical catastrophic engine failures involving the engine turbomachinery occurred rapidly. Time resolution is critical. Furthermore, higher sample rates result in a much wider spectral band thus yielding more discrete signatures for assessment. After the high-speed acquisition task is performed, the data must be transferred rapidly to Digital Signal Processing (DSP) modules. The DSP modules take the digital data, perform a Fast Fourier Transform (FFT) to produce frequency spectral data, and summarily run the pertinent health algorithms on-board the DSP chips. The complexity of the DSP operations is dependent on the health algorithms being utilized (generally, the type and number of spectral analysis operations being performed), the number of channels being assessed, the digital acquisition rates and the FFT operational block size. The DSPs can act independently if the processing load is light or may be utilized as multiple parallel processors (MPP) if the processing tasks are heavy. The use of MPP operations allows a system to utilize multiple DSP's, which communicate through the DSP communication ports, and act in parallel to perform immense processing tasks without any additional and harmful processing latency. The system is a real-time distributed processing system that performs Multiple Instructions on Multiple Data (MIMD). It uses a static scheduled kernel and is able to process synched operations due to consistent block rates.

The RTVMS utilizes 14 TIC40 DSP modules mounted on quad boards and 32 16-Bit Sigma-Delta A/D converters mounted on octal boards to acquire and process 32 channels of SSME vibration data. The DSPs and A/Ds are housed in a VME chassis and communicate to two Personal Computers, used for control/display and data storage, via DSP communication ports at speeds up to 20 Mbytes per second. The system is capable of sampling data up to 51,200 samples per second and has a data throughput for storage of up to 7 Mbytes per second.

For the RTVMS application at SSC, the SSME accelerometer data is acquired at a rate of 20,480 samples per second and an FFT is performed on every 50 milliseconds of data (1024 samples), which provides a frequency resolution of 20 Hz. The system uses 12 of its DSPs to process accelerometer data for the monitoring of three turbomachinery vibration redlines at high speeds and can automatically terminate an engine test in as little as 100 milliseconds. Two of the redlines are setup for monitoring the High Pressure Fuel Turbopump (HPFTP) and one is for the High Pressure Oxidizer Turbopump (HPOTP).

RTVMS has the capability to monitor up to 10 separate vibration redlines. The current redlines are based on the analysis of the most singularly important discrete vibration signature to be examined from the turbomachinery accelerometer data. This signature, known as synchronous, is a response generated by the rotation of the shaft in the engine high pressure turbomachinery and can be located in the vibration spectra at pump speed. The overall magnitude of the vibration from the synchronous response, as well as its frequency trends, is the primary indicator of the turbomachinery rotordynamic health.

To locate the synchronous frequency for the HPFTP, the system utilizes a speed probe input that provides four pulses per shaft revolution and uses search algorithms to locate the fundamental frequency of the speed probe input and subsequently the fundamental frequency of the shaft speed from the accelerometer data. Since a speed probe does not exist for the HPOTP, the system uses search algorithms to locate harmonics of synchronous in the accelerometer data that are produced by blade wakes from the HPOTP pump impeller.

Although the system at SSC is configured primarily to monitor synchronous and its harmonics, RTVMS employs all of the basic analysis algorithms and some of the advanced algorithms developed at MSFC and can be used to look for other discrete signatures that may be an indication of turbomachinery degradation. The system has the capability of providing 4 separate windows of plots and each window can contain up to 25 plots. Figure 1 on the following page shows an example of the real-time display output from SSC SSME static test 902-770 for the HPFTP vibration redline monitor. Going from top to bottom and left to right, the first 7 plots in the figure are the synchronous amplitude trackings from pump end accelerometers located on the HPFTP. The last two plots are amplitude trackings of 2 times (2x) synchronous (1st harmonic which can be an indicator of rubbing in the HPFTP) from turbine end accelerometers. The data provided in this figure indicate that this test exhibited nominal synchronous and 2x synchronous vibration levels.

RTVMS TRACKINGS

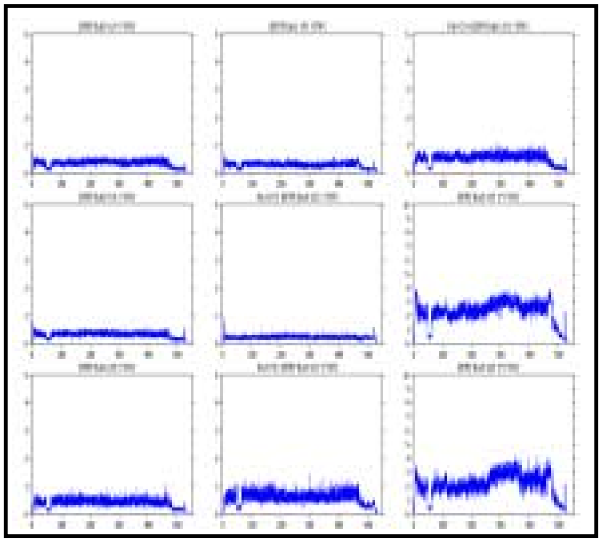

Figure 1. RTVMS HPFTP Real-Time Synchronous Amplitude Tracking Results from SSME Test 902-770

Operational History

Historical databases provide the information necessary to determine nominal and off-nominal operating conditions for the SSME turbomachinery. The RTVMS was needed and developed to protect the SSME against potential catastrophic failures by not allowing the turbomachinery to operate outside of a safe vibration condition. SSME static test 901-853 involved a failure which was caused by degradation of the HPFTP. Figure 2 is a Power Spectral Density (PSD) plot from a pump end accelerometer taken during a time after the initial failure point had occurred.

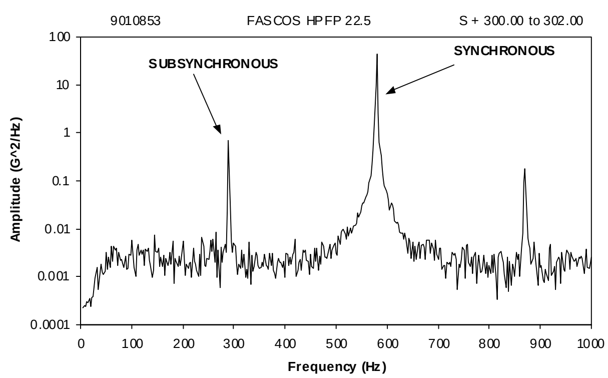

Figure 2. PSD from SSME Static Test 901-853

The plot indicates the synchronous response is very prominent in the vibration spectra. A sub-synchronous response (known as a sub-harmonic resonance) is also present and is also indicative of the impending failure. Figure 3 is the synchronous amplitude tracking from the same accelerometer in Figure 2.

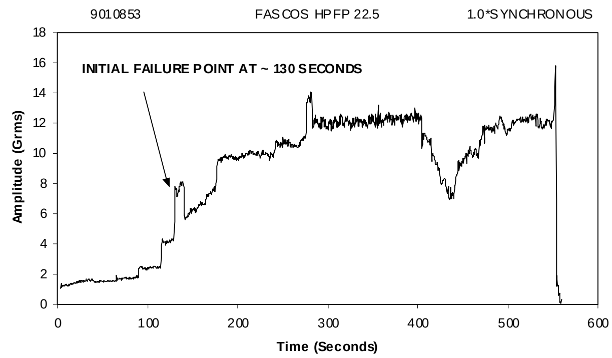

Figure 3. Synchronous Amplitude Tracking from SSME Static Test 901-853

At approximately 130 seconds into the test, the synchronous amplitude exceeded the nominal level. This is the first indication during the test of degradation of the high pressure fuel turbopump and indeed indicated a major loss of rotordynamic balance (brought on, in this case, by the loss of turbine blade and blade seal material). The high pressure turbopump failure experienced during this test prompted the immediate implementation of RTVMS at SSC as an active SSME vibration health monitoring system. Since the deployment of RTVMS in 1996, the system has been an active vibration monitor for the SSME high pressure turbomachinery for over 150 engine static tests without any RTVMS system failures.

The success of RTVMS led MSFC to develop a sub-scale version of the system that flew as part of the HTD-2 mission during STS-96 in May of 1999. The flight system was developed to demonstrate the ability to digitally acquire SSME accelerometer data at high speeds, process the data real-time, examine the resultant frequency spectra data, and track the pertinent frequency response (synchronous) amplitudes real-time in a flight environment. The HTD-2 version of RTVMS acquired vibration data from the SSME located in orbiter position 3. This data set consisted of 8 accelerometers, 6 of which were located on the two high-pressure turbopumps. The data was acquired at a sample rate of 10,240 samples/second and was processed on a quad- DSP board with an FFT block size of 4096 points. These acquisition and processing parameters insured direct comparison to standard post-flight analyses results. Once the data was processed, the MSFC/RTVMS synchronous frequency tracking algorithm was employed, real-time, to delineate and track the respective turbopump synchronous frequency and its amplitude. Figures 4 through 7 are results of the amplitude trackings that were processed real-time during mission ascent and stored on board the orbiter.

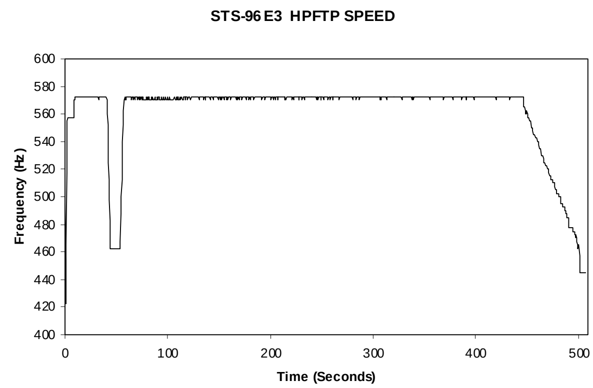

Figure 4. HPFTP Synchronous Frequency Tracking from STS-96 Main Engine 3

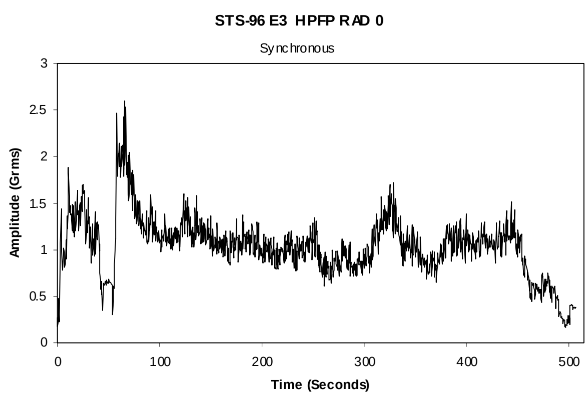

Figure 5. HPFTP Synchronous Amplitude Tracking from STS-96 Main Engine 3

Figure 4 shows the tracking of the synchronous frequency of the HPFTP with Figure 5 exhibiting the corresponding amplitude tracking of the synchronous frequency for one of the HPFTP accelerometers. Figure 6 shows the tracking of the synchronous frequency of the HPOTP with Figure 7 exhibiting the corresponding amplitude tracking of the synchronous frequency for one of the HPOTP accelerometers. The results from the flight RTVMS compared exceptionally well with results from the standard post-flight data analysis.

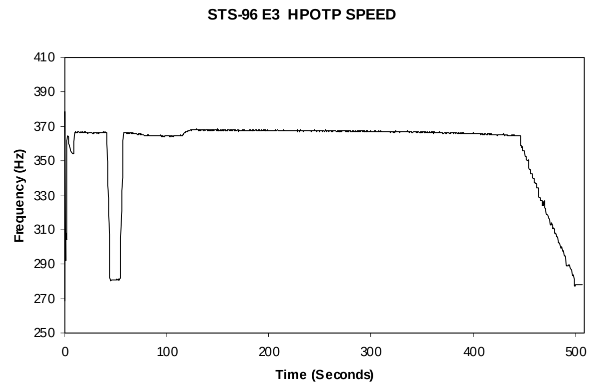

Figure 6. HPOTP Synchronous Frequency Tracking from STS-96 Main Engine 3

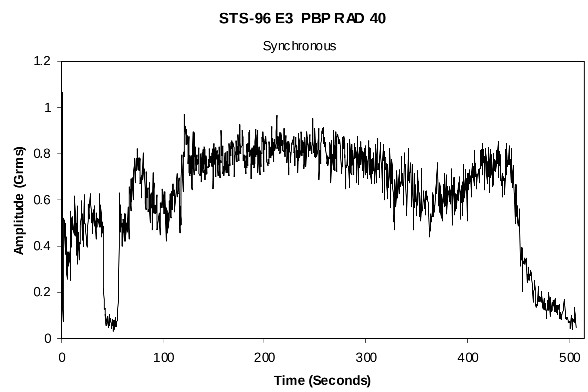

Figure 7. HPOTP Synchronous Amplitude Tracking from STS-96 Main Engine 3

RTVMS Applications for Flight

The HTD-2 flight demonstration coupled with the continued success of the ground-based RTVMS at SSC led the SSME Project Office to pursue implementation of RTVMS technology for all Space Shuttle flights. In 1999 MSFC became the lead for the development and implementation of the SSME Advanced Health Management System (AHMS), a Shuttle Safety Upgrades Project that will initially modify the SSME Controller to include RTVMS synchronous tracking technology and also develop a Health Management Computer (HMC) aimed at improving the safety and reliability of the Space Shuttle system. The HMC will consist of three distinct health monitoring systems:

- Advanced Real Time Vibration Monitoring (RTVMS) System
- Optical Plume Anomaly Detection (OPAD) System

– Linear Engine Model (LEM) System

The SSME Controller upgrade will retrofit 20 flight controllers to provide vibration redline capability and add a High Speed Serial Interface to communicate with the HMC. The controller modification will incorporate the RTVMS synchronous tracking and sensor validation algorithms. The sensor validation algorithm was developed by MSFC and uses comparisons between the synchronous frequency amplitude and background noise levels combined with cross-channel comparisons and signal-to-noise ratio checks to determine if the data sensors are supplying reliable data. The first flight of the upgraded controller is scheduled for the year 2003 with the last upgraded controller scheduled for delivery in the year 2008.

The development of the Health Management Computer (HMC) is one critical element of the AHMS project. Figure 8 on the following page depicts a block diagram of the HMC including the interface to the modified Space Shuttle Main Engine Controller, other external interfaces and the individual internal modules which implement the HMC. The HMC uses the open architecture Versa Module Eurocard (VME) bus as the system backplane. This widely used bus standard facilitates the use of Commercial-Off-The–Shelf (COTS) Circuit Card Assemblies (CCAs) and eases the design of custom in-house CCAs. The decision to use the VMEbus was made after an extensive trade study comparing other available bus standards. Criteria for the trade study included the availability of rugged COTS CCAs, the data transfer rate supported and the maturity and resistance to obsolescence. Each of the three subsystems making up the HMC will have the ability to become the VMEbus owner thereby improving overall data transfer efficiency. The HMC chassis will be designed to provide expansion capability for a second redundant channel and for additional health management features if and when they prove viable.

The System/LEM controller will reside in slot #1 of the VMEbus and as such will contain the VMEbus arbitration logic. This function will be implemented using a COTS PowerPC single board computer (SBC). The COTS PowerPC SBC consists of processor memory, flash memory for nonvolatile storage, an Ethernet interface, a high speed serial interface and a Peripheral Component Interconnect (PCI) Mezzanine Card (PMC) slot for possible expansion. The LEM monitors the Engine Inlet Parameters to determine overall engine health. It is planned that the LEM will mature into a system capable of monitoring the engine inlet parameters along with output from both the RTVMS and real-time OPAD modules to make a better determination of overall SSME health. The System/LEM controller provides another critical function by implementing the RS-485 High Speed Serial Interface to the Space Shuttle Main Engine Controller. This interface will currently be used by the HMC to send status information to the SSMEC for possible download to the ground to monitor HMC performance during flight. This interface is also used by the HMC to receive Vehicle Data Table (VDT) information from the SSMEC. Future flight qualified versions of the HMC could use this interface to "command" the SSMEC to take some required action, such as throttling back the engine or shutting down an engine, to avoid a catastrophic event. The System/LEM controller using the onboard Ethernet interface also provides a ground support equipment (GSE) port. This port will be used for monitoring and commanding the HMC, downloading code to HMC subsystems and for downloading Mass Memory data post flight.

At this time the RTVMS component of the HMC provides the most critical, real-time indication of engine health. To ensure the highest reliability, an MSFC custom built digital signal processing (DSP) CCA will be designed to implement the RTVMS Subsystem. One DSP CCA will be used to monitor the health of the High Pressure Fuel Turbopump (HPFTP) while a second will be used to monitor the High Pressure Oxygen Turbopump (HPOTP). The DSP CCA will consist of 4 Texas Instrument TMS320C40 DSPs, associated data and program memory, a Master/Slave interface to the VMEbus and the control logic required to collect and buffer turbopump accelerometer data from the Analog to Digital Converters (ADCs). Full multiple parallel processing (MPP) will be made possible by connecting all 4 DSP to one another using the DSP communication ports. This will allow for each DSP to act independently when the processing load is light thereby achieving a good level of redundancy for fault tolerance. If, on the other hand, the processing demands are high the processors can act together in a MPP arrangement thereby ensuring the minimal processing latency. This DSP arrangement allows for growth of the RTVMS algorithm as required without incurring considerable processing delays.

The advanced RTVMS module on board the HMC will not only encompass the analysis attributes of the current ground-based system but will also incorporate advanced, evolutionary algorithms that examine the vibration data in the phase domain as well as time and frequency. Examination of the vibration frequency spectra for unknown anomalies relies, in part, on

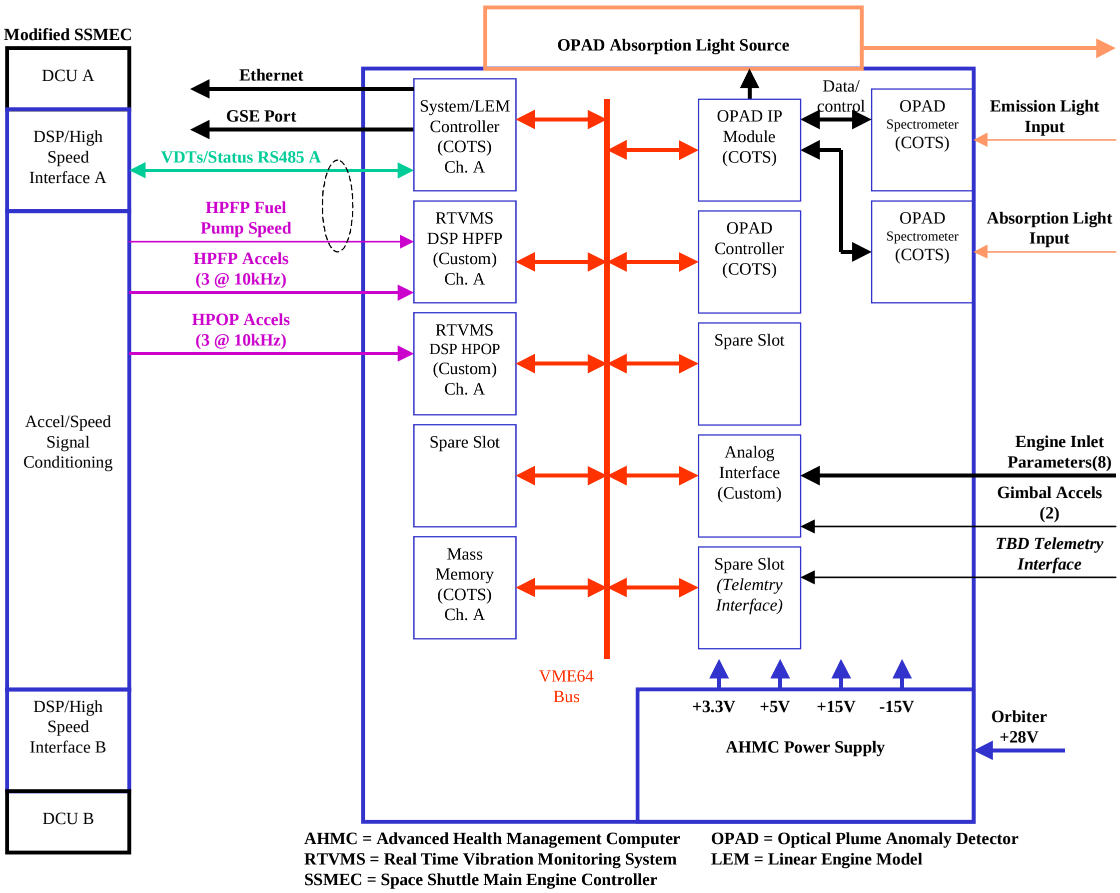

Figure 8. Health Management Computer Block Diagram

advanced algorithms which will both detect these signatures and compare them (in the phase domain) to other known signatures to assign attributes that better define the anomaly source. In the case of the high pressure turbomachinery, these algorithms can aid in defining the source of anomalous signatures as either static or rotating component-related. Intra-spectra signature phase comparisons as well as cross-channel signature phase comparisons provide much greater insight into the source of anomalies to determine whether these signatures are benign or are a true indicator of an imminent problem. As a result, these advanced algorithms will provide greater reliability and robustness to the RTVMS logic and ensure an informed health management system decision.

The other HMC module, known as the Optical Plume Anomaly Detector (OPAD), consists of the most individual subassemblies and is the most complicated HMC subsystem. As seen in the figure, the OPAD subsystem is made up of an OPAD controller, an OPAD industry pack (IP) carrier module, two spectrometers and a lamp source and power supply. What is not seen in the figure is the required fiber optic cables and SSME nozzle mounted optical heads. The OPAD controller is implemented with a PowerPC SBC, and is in fact a second copy of the System/LEM controller PowerPC SBC. Providing the interface to the spectrometers is an IP carrier CCA that allows the use of up to 4 IP modules. The IP modules that plug into the IP carrier are available COTS in many input/output (I/O) varieties. The OPAD subsystem requires a 16 channel discrete IO IP module, two analog input IP modules and a timer/discrete I/O IP module. Two separate optical systems make up the OPAD subsystem: an absorption system and an emission system. These are both used to observe the SSME exhaust plume for metal constituents which would indicate engine wear and in severe cases engine component failure. At the present time, the OPAD subsystem works only in a data-collecting mode for post flight analysis.

Serving all three HMC subsystems is a COTS Mass Memory CCA. This CCA uses flash memory to provide on a single baseboard up to 512MegaBytes of non-volatile storage. By using daughterboards attached to the baseboard it is possible to configure the CCA to accommodate up to 4 GigaBytes of non-volatile storage. As data is collected by each of the three HMC subsystems it will be written to this Mass Memory CCA. During post flight operations this memory can be dumped to GSE via the System/LEM controller for thorough post flight data analysis.

There will be three HMC's for each of the four orbiters and an undefined number built for ground test operations and logistical support. The first flight of a protoflight HMC unit for Space Shuttle flight testing is scheduled for late year 2003 with the first flight of the actual flight system scheduled for late 2005.

Conclusions

The RTVMS is a powerful, multi-benefit engine vibration monitoring system that has proven its reliability in SSME ground test operation and has proven its ability to operate exceptionally in the flight environment. The RTVMS is an extremely flexible, fully functional system that incorporates sound logic with modern digital technology for SSME health monitoring. The implementation of RTVMS into the SSME Controller and HMC in the AHMS for Shuttle flight operations will provide obvious benefits derived from the system's ability to mitigate potential engine catastrophic failures and enhance Shuttle safety and reliability. Combined with the LEM and OPAD subsystems resident in the HMC, enhanced and reliable health management for the SSME in the flight environment is now a reality.

Acknowledgments

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