Advanced Engine Health Management
Applications of the SSME Real-Time Vibration Monitoring System

AIAA 2000-3622
36th AIAA/ASME/SAE/ASEE Joint Propulsion Conference
July 19, 2000

Tony R. Fiorucci
NASA Marshall Space Flight Center
• What is the Real-Time Vibration Monitoring System (RTVMS)?

  - RTVMS is a 32-channel high speed vibration data acquisition and processing system developed at Marshall Space Flight Center (MSFC).

  - Delivers sample rates as high as 51,200 samples/second per channel.

  - Performs Fast Fourier Transform (FFT) processing via on-board digital signal processing (DSP) chips in a real-time format.
• Why is RTVMS important?

  – *Real-time* FFT processing yields *real-time* vibration spectral data.

• Advanced engine health assessment is achieved by utilizing the vibration spectra to provide:
  
  – accurate sensor validation
  – enhanced engine vibration redlines

• Discrete spectral signatures (such as synchronous) that are indicators of imminent failure can be assessed and utilized to mitigate catastrophic engine failures - a first in rocket engine health assessment.

  – High sample rates provide for enhanced time and frequency resolution over a broader frequency spectra.
- Vibration spectral signatures utilized by the RTVMS -

**Synchronous (N) >**
(unbalance)

**Sub-harmonic Resonance Responses**

< 2X Synchronous (2N)
(rubbing)
RTVMS spectra yields both frequency and amplitude trends.

**RTVMS Data Surrounding 130 Second Event during test 901-853**
- Time 128-140 seconds -
Pump-End Power Spectral Density Showing Subsynchronous

Pump-End Synchronous Vibration Levels

HPFTP/AT Unit 6–4 Incident

First Stage Turbine Blade Array
• Operational History - Ground Testing

- RTVMS has been deployed at the Stennis Space Center since October 1996

- RTVMS has actively monitored over 150 SSME static hot-fires.

- The system monitors 3 separate engine vibration redlines
  • 2 high pressure fuel turbopump (HPFTP) vibration redlines
  • 1 high-pressure oxygen turbopump (HPOTP) vibration redline.

- The RTVMS installed at SSC provides:
  • data acquisition at 20,480 samples/second for 32 channels
  • real-time vibration redline amplitude trackings and power spectral densities (PSD's)
  • automatic engine test termination in 100 milliseconds (50 millisecond resolution)
RTVMS Real-Time Tracking Display
SSME Test 902-770

Marshall Space Flight Center

---

HPFPRAD 129 SYNC

---

HPFPRAD 125 SYNC

---

FASCOHPPRAD 231 SYNC

---

HPFPRAD 141 SYNC

---

FASCOHPPRAD 225 SYNC

---

HPFPRAD 225 SYNC

---

FASCOHPPRAD 219 SYNC

---

HPFPRAD 225 SYNC
Operational History - Flight

- A sub-scale version of RTVMS flew aboard STS-96 as part of the HTD-2 flight experiment.

- During the flight, the RTVMS module:
  
  - acquired data from 8 vibration measurements (one flight engine) at 10,240 samples/second
  - processed the digital data real-time
  - actively located and monitored the synchronous vibration responses for the HPOTP and HPFTP for flight duration
  - provided real-time discrete frequency and amplitude trackings of both high pressure turbopumps

- The RTVMS flight experiment proved the concept of high-speed vibration data acquisition and real-time processing in a flight environment.
HTD-2 SSME RTVMS

- Components
  - (1) Ruggedized high-speed data acquisition (A/D) board
  - (1) Ruggedized digital signal processing (DSP) board
  - MSFC turbopump signature tracking algorithm
  - (8) Existing SSME vibration measurements consisting of:
    - (3 ea) High-Pressure Fuel Turbopump (HPFTP) and High-Pressure Oxidizer Turbopump (HPOTP) accelerometers
    - (1 ea) Gimbal Bearing and Oxidizer Preburner (OPB) accelerometers

- Technology
  - Engine vibration health monitoring

- Benefit
  - Mitigation of engine catastrophic failures
  - Real-time high-speed digital acquisition and processing
  - Reduced post-flight processing

- Range
  - 266 G peak-to-peak

- Data Availability
  - T-10 seconds to MECO + 15 seconds
HTD-2 SSME RTVMS Results

• Successful acquisition of accelerometer data at 10,240 samples/second per channel
  – Data was written to on-board flash storage.

• All digitally acquired data was accurately processed, real-time, by the DSP board.
  – Produced real-time frequency spectra.
  – Discrete frequency responses were available for in-flight monitoring and analysis.

• The MSFC algorithm examined the frequency spectra real-time during engine operation for the synchronous frequency response.
  – Synchronous is the primary indicator of SSME turbopump rotordynamic health.
  – The algorithm accurately located synchronous for both high-pressure pumps.
  – Synchronous was monitored real-time throughout engine operation.
  – All synchronous frequency and amplitude tracking results were written to on-board flash storage.
RTVMS HPOTP Power Spectral Densities
STS-96 SSME Position 3

**Note: The synchronous response is labeled as “1N”.

---

Marshall Space Flight Center

12
HTD-2 RTVMS HPOTP Tracking Results
STS-96 SSME Position 3

RTVMS HPOTP Synchronous (Speed) Frequency Tracking

RTVMS HPOTP Synchronous Amplitude Trackings

- PBP RAD 40
- PBP RAD 151
- PBP RAD 130
HTD-2 RTVMS HPFTP Tracking Results
STS-96 SSME Position 3

**Note: The synchronous response is labeled as “1N”**.
HTD-2 RTVMS HPFTP Tracking Results
STS-96 SSME Position 3

RTVMS HPFTP Synchronous (Speed) Frequency Tracking

RTVMS HPFTP Synchronous Amplitude Trackings
• RTVMS and the Advanced Health Management System (AHMS)

  – RTVMS is the basis for the SSME AHMS Shuttle Safety Upgrade Program

• AHMS Phase I is a modified SSME Controller which will incorporate the RTVMS synchronous vibration redline methodology.

• AHMS Phase II is the Health Management Computer (HMC) which will incorporate the full RTVMS analysis package module.

  – MSFC/TD63 has also developed sensor validation software which will reside on RTVMS on AHMS Phase I and II
AHMS RTVMS Synchronous Redline Logic Example

- Example is from test 901-853 which was a turbine failure of HPFTP/AT 8306

- Synchronous frequency amplitude levels violate threshold limit indicating possible hardware failure

- Sensor validation logic reviews factors and determines sensors are valid

- RTVMS synchronous logic issues signal for engine shutdown
HMC RTVMS Advanced Analysis Methodology

- The six turbopump accelerometers that will be processed and analyzed real-time contain numerous spectral responses pertinent to pump health

- Analysis of the frequency spectra can be performed out to 10,000 Hz

- Current analysis plans for the HMC RTVMS include:
  
  - tracking and redline monitoring of synchronous vibration response (N)
    - primary indicator of pump health (mass unbalance indicator)
  
  - tracking and analysis of synchronous harmonics
    - 2N and 3N (primary indicators of internal rotor rubbing)
    - 4N/8N (HPOTP) and 6N (HPFTP) (blade wake responses from pump impellers)
  
- detection of sub-harmonic resonance (forced vibration response such as bearing deadband interaction) and limit-cycle whirl (rotor instability) responses
• HMC RTVMS Advanced Analysis Methodology

  - Future analysis upgrades will include:

  • determination and tracking of bearing related frequencies (Cage, Ball Spin, Inner Race and Outer Race) to determine the health of the bearings

  • cavitation detection and active signature phase correlation algorithms

  • nonlinear algorithms to distinguish differences between rotating and non-rotating related turbopump phenomena

  • active unknown anomaly identification and monitoring
• Conclusions

- RTVMS delivers the capability to detect and mitigate potential catastrophic SSME turbomachinery failures through real-time extraction of discrete vibration frequency components.

- The AHMS HMC with the RTVMS, Linear Engine Model (LEM), and Optical Plume Anomaly Detector (OPAD) subsystems provides an advanced, reliable health management capability for the SSME.