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

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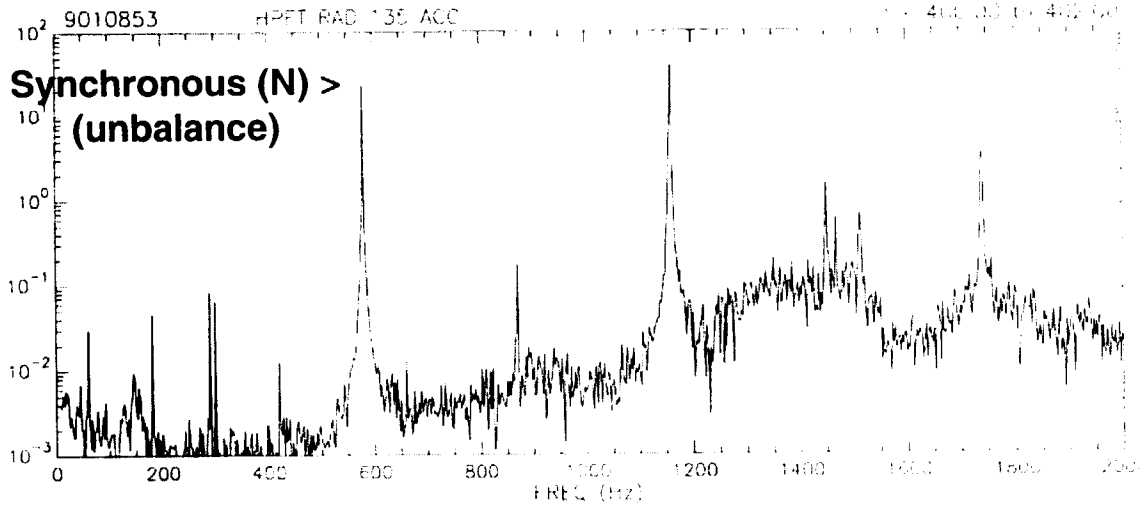
- **What is the Real-Time Vibration Monitoring System (RTVMS)?**
  - RTVMS is a 32-channel high speed vibration data acquisition and *processing system* developed at Marshall Space Flight Center (MSFC).
  - Delivers sample rates as high as 51,200 samples/second per channel.
  - Performs Fast Fourier 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 -

Hz	G SQ/Hz
1160.0	39.310
580.0	22.953
1740.0	3.374
1450.0	1.519
1512.5	0.718
1467.5	0.607
1350.0	0.199
1755.0	0.195
1415.0	0.188
1385.0	0.16[illegible]

NAVG = 5
BW = 2.50
COMP = [illegible]6.912



Hz	G SQ/Hz
1160.0	60.321
580.0	3.839
870.0	1.359
1737.5	1.150
290.0	0.805
1450.0	0.382
157.5	0.331
1175.0	0.263
1947.5	0.260
1350.0	0.260

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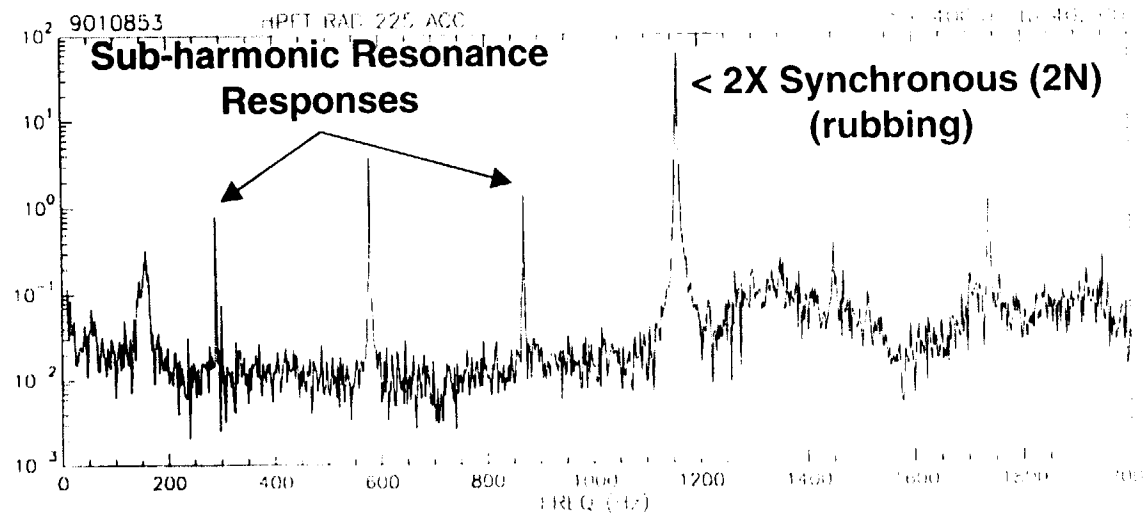

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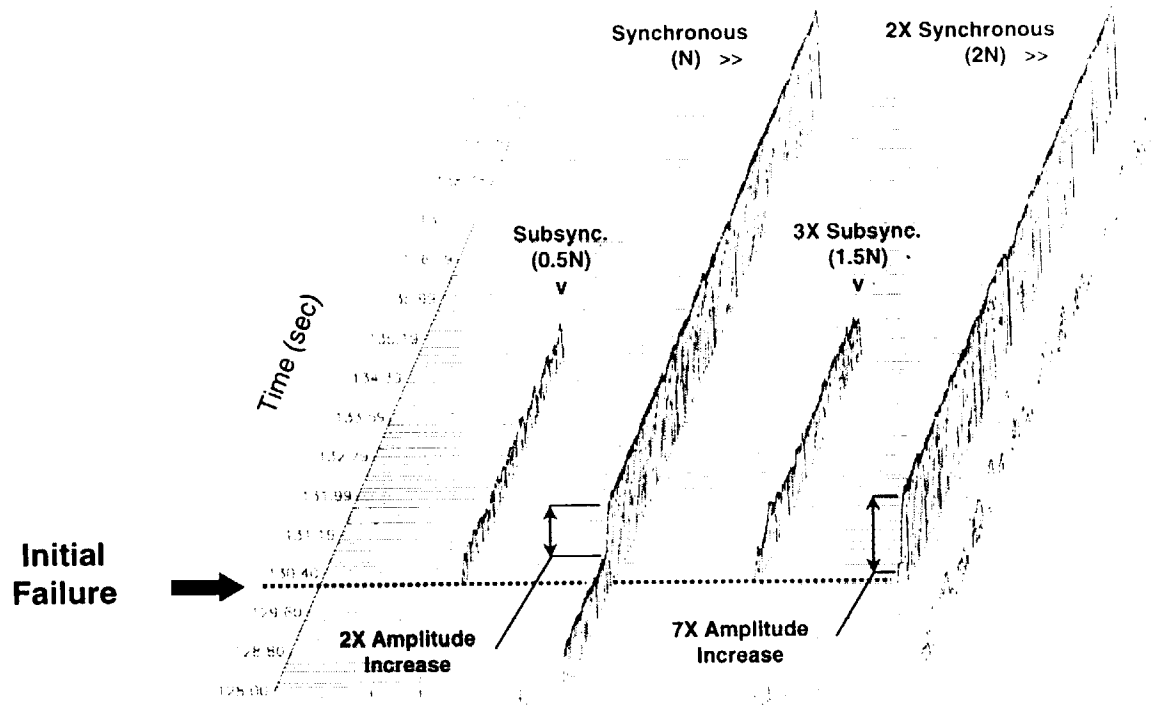
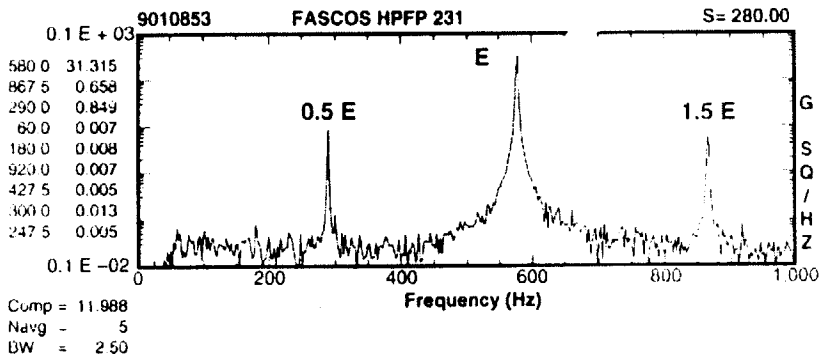
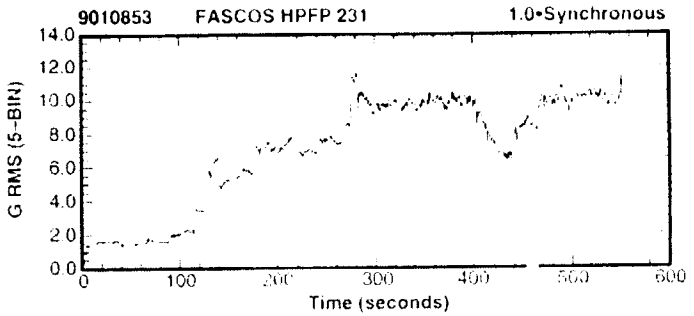
- RTVMS spectra yields both frequency and amplitude trends -



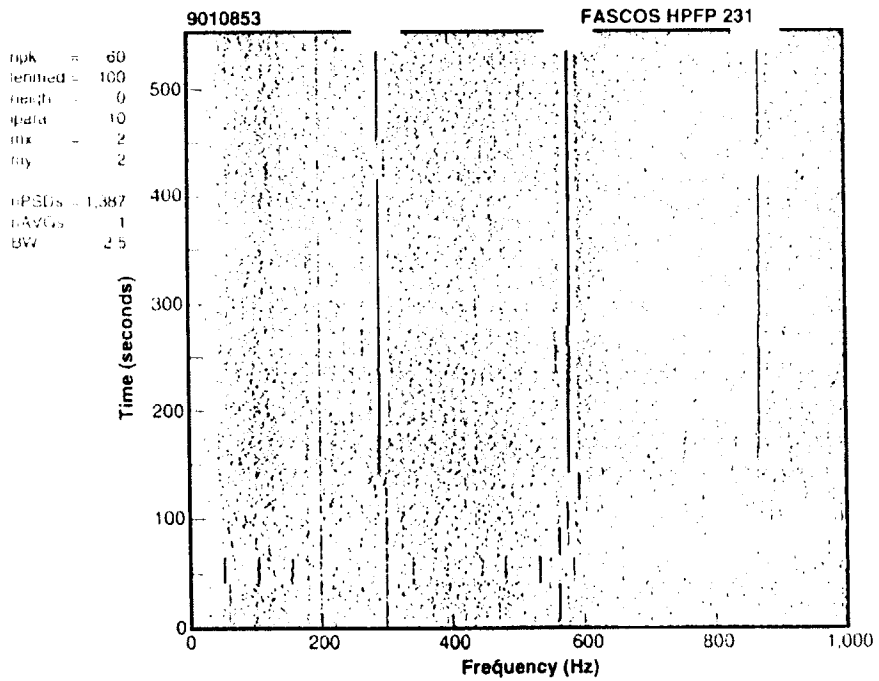
RTVMS Data Surrounding 130 Second Event during test 901-853
- Time 128-140 seconds -

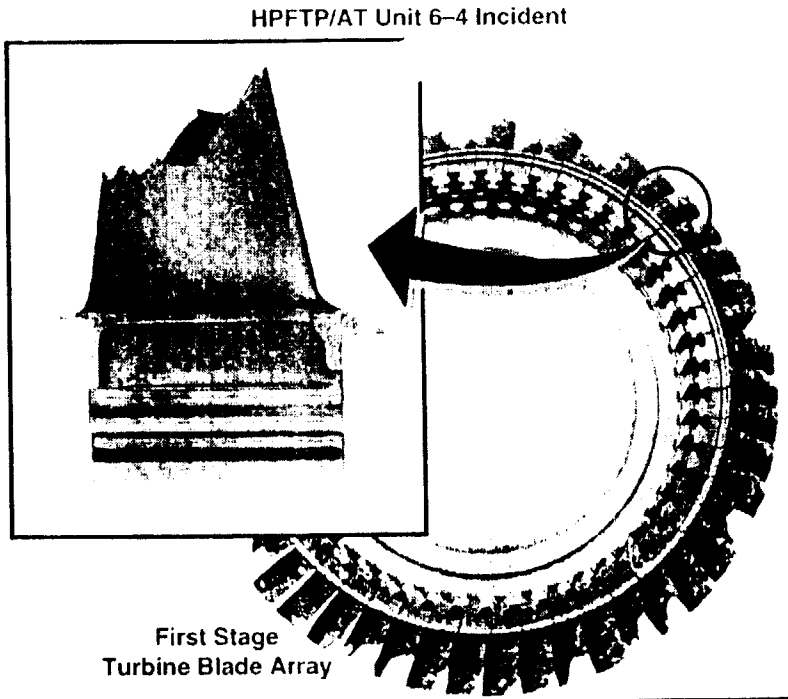


Pump-End Power Spectral Density Showing Subsynchronous



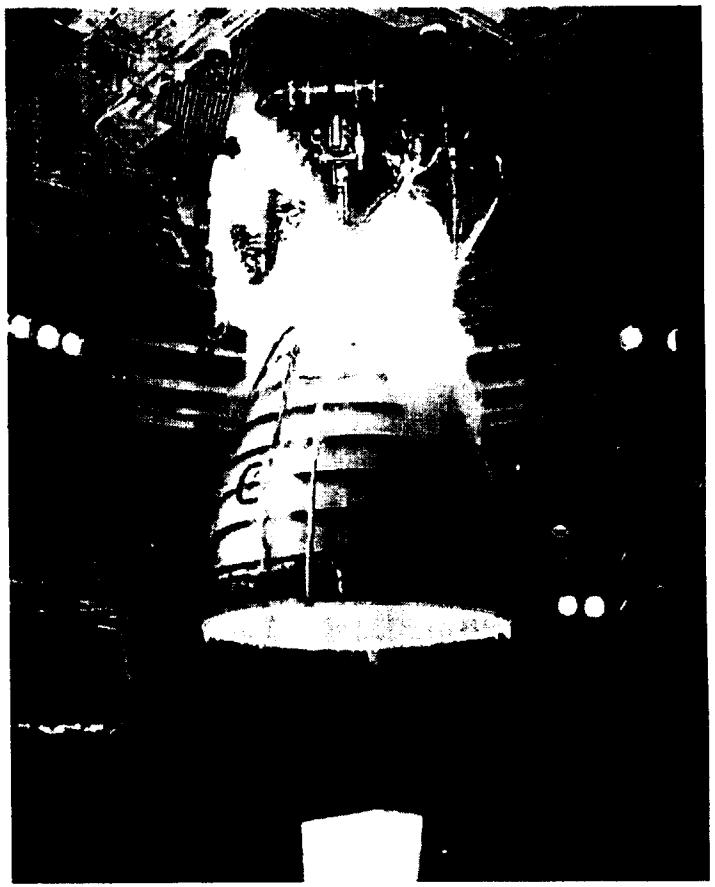
Pump-End Synchronous Vibration Levels



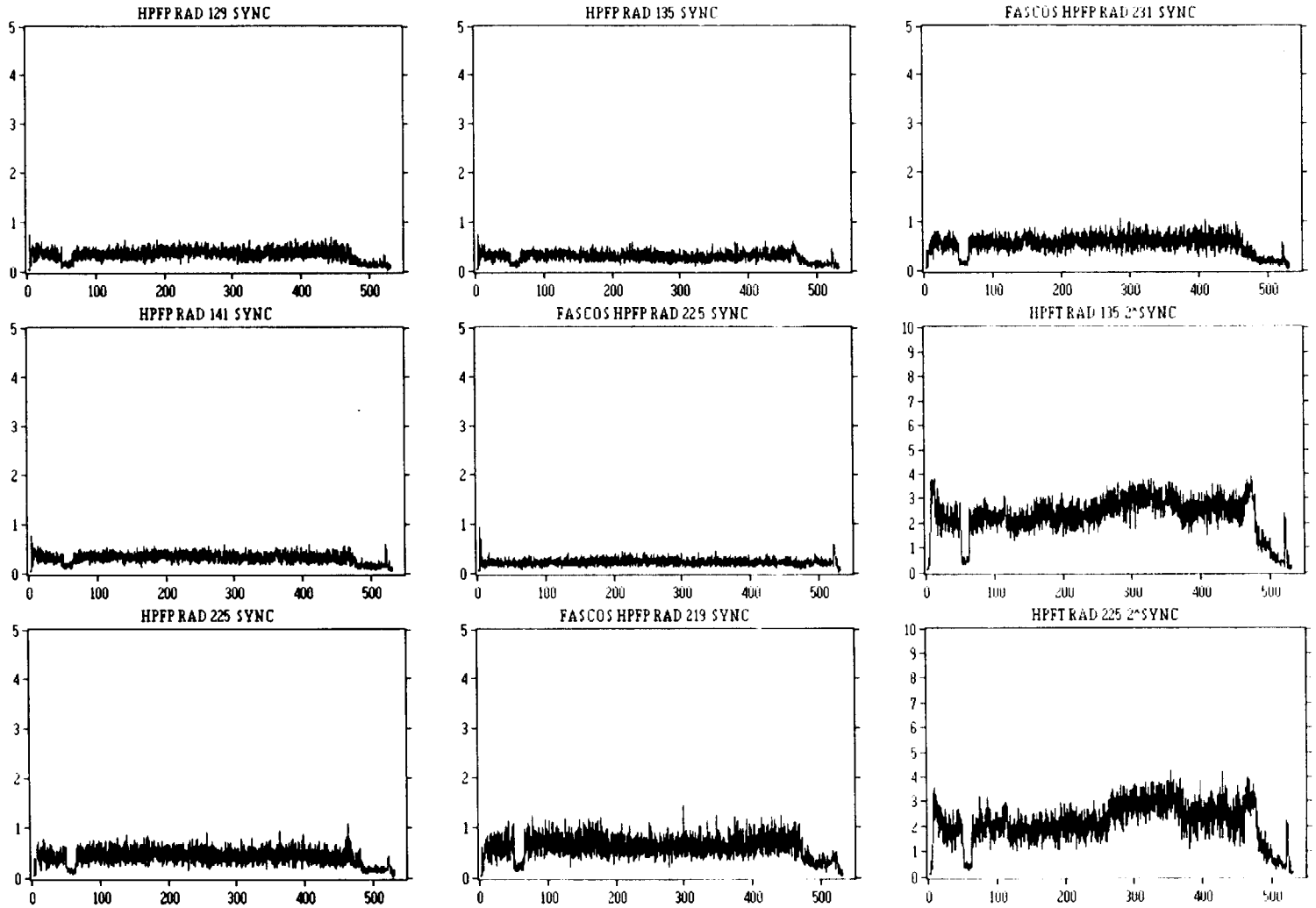


- **Operational History - Ground Testing**

  - 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



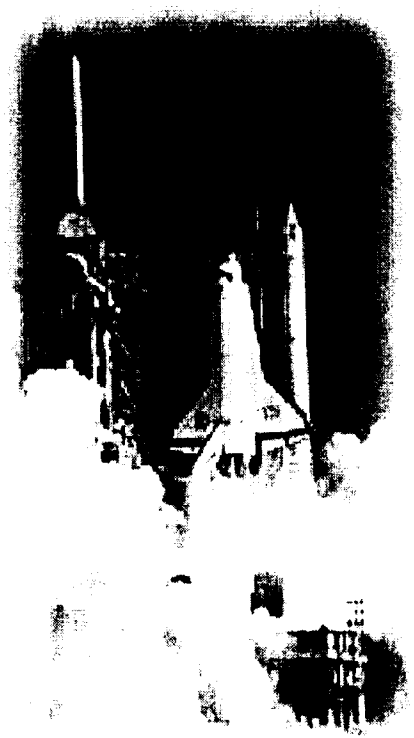
- **Operational History - Flight**

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

  - During the flight, the RTVMS module:

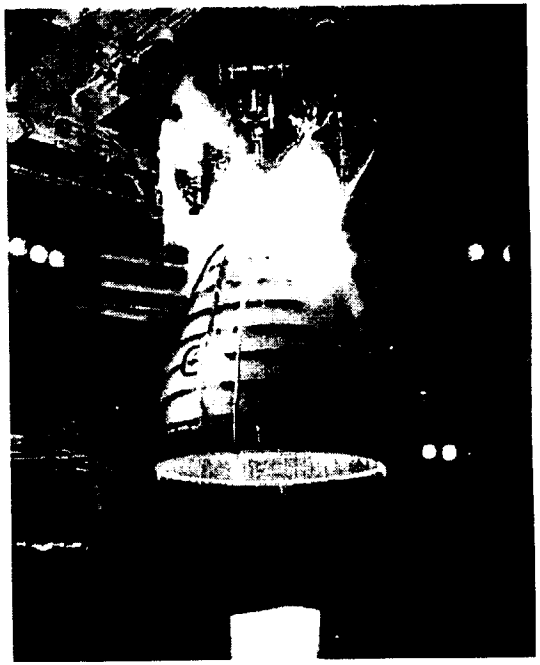
    - acquired data from 8 vibration measurements (one flight engine) at 10,240 samples/second
    - processed the digital data real-time
    - actively located and monitored the synchronous vibration responses for the HPOTP and HPFTP for flight duration
    - provided real-time discrete frequency and amplitude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

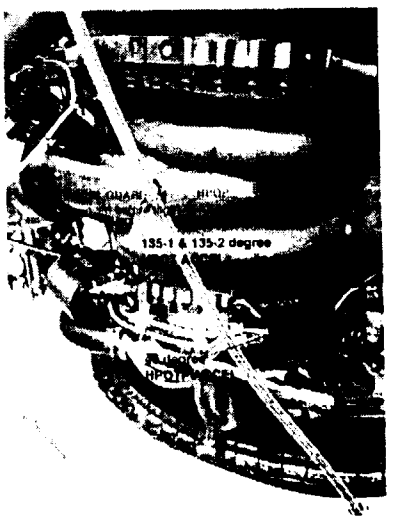
  - The RTVMS flight experiment proved the concept of high-speed vibration data acquisition and real-time processing in a flight environment.



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





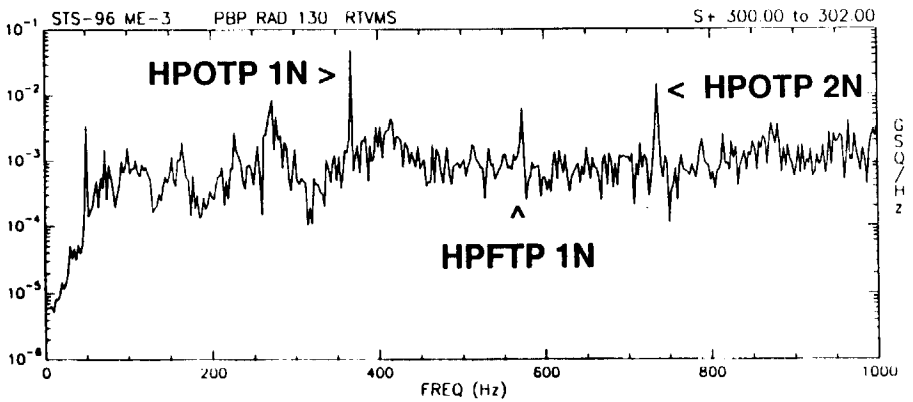
HTD-2 SSME RTVMS Results

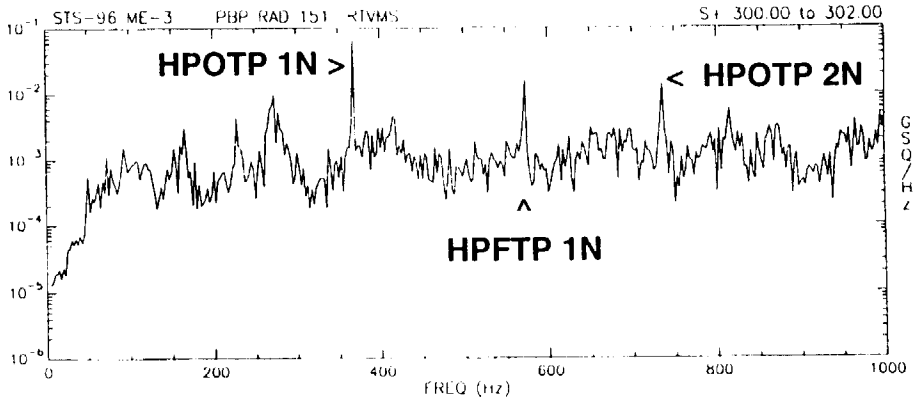
- Successful acquisition of accelerometer data at 10,240 samples/second per channel
  - Data was written to on-board flash storage.

- 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.

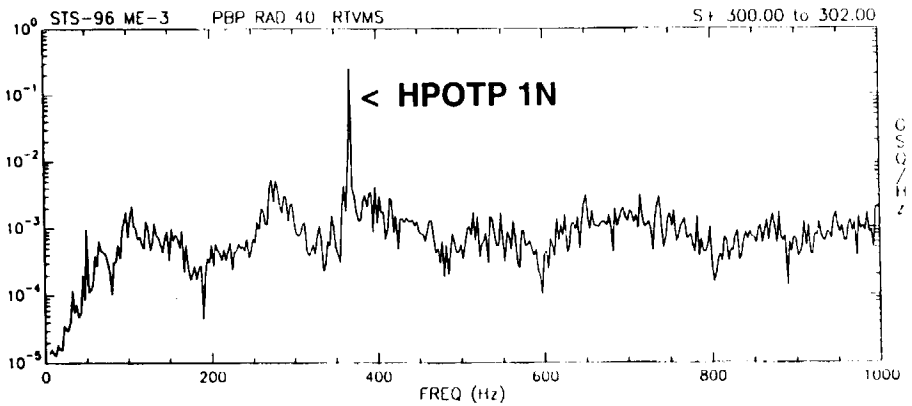
- The MSFC algorithm examined the frequency spectra real-time during engine operation for the synchronous frequency response.
  - Synchronous is the primary indicator of SSME turbopump rotordynamic health.
  - The algorithm accurately located synchronous for both high-pressure pumps
  - Synchronous was 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



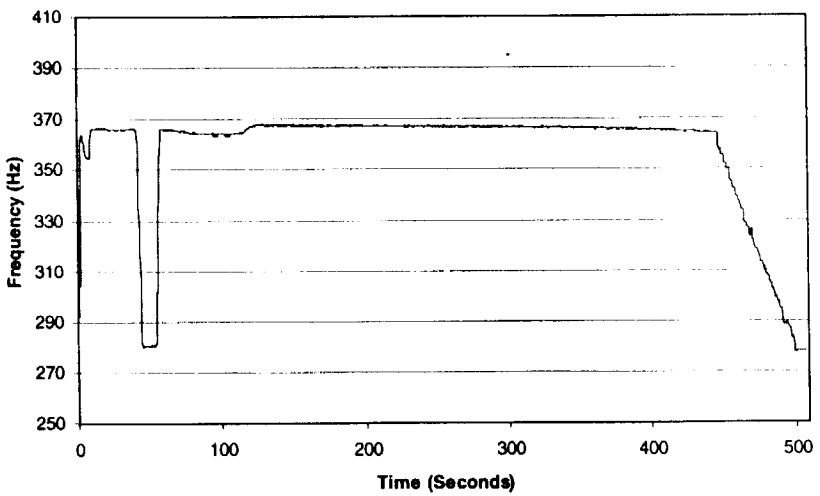


***** Note: The synchronous response is labeled as "1N".***

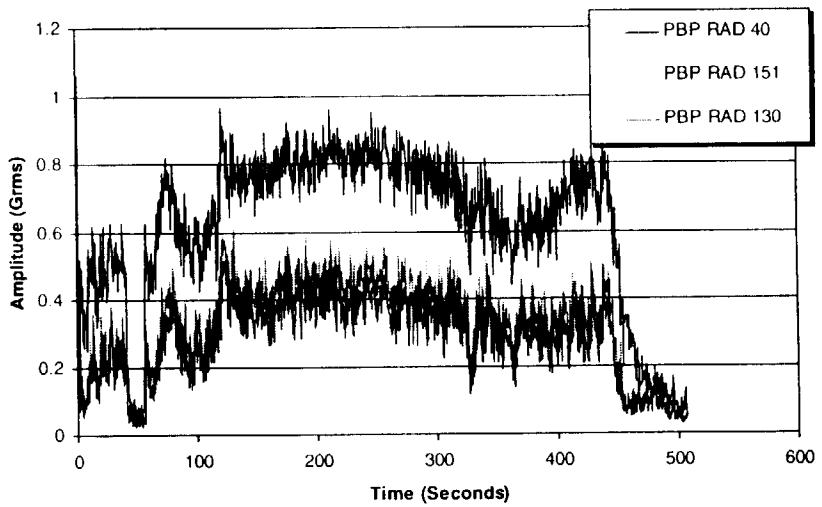


HTD-2 RTVMS HPOTP Tracking Results
STS-96 SSME Position 3

RTVMS HPOTP Synchronous (Speed) Frequency Tracking

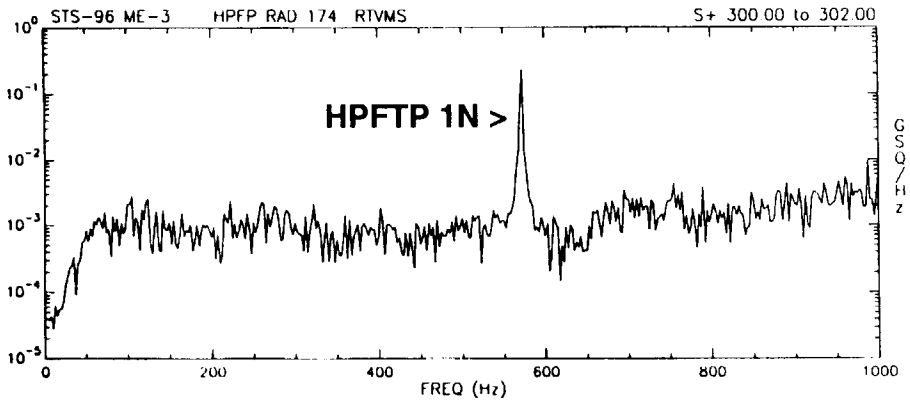


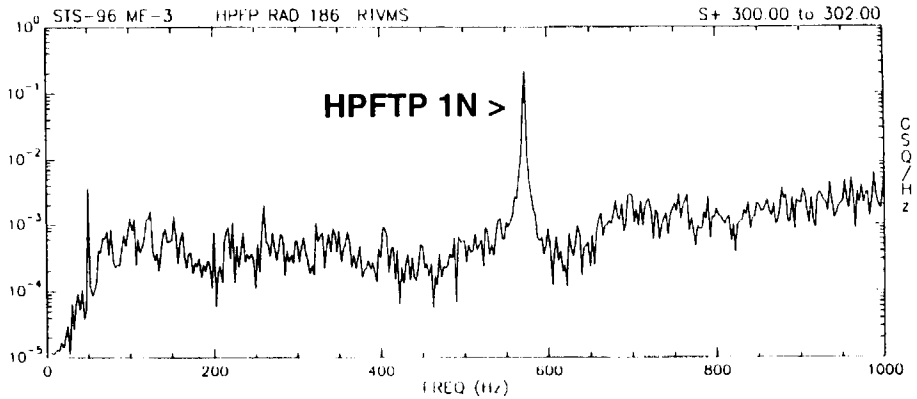
RTVMS HPOTP Synchronous Amplitude Trackings

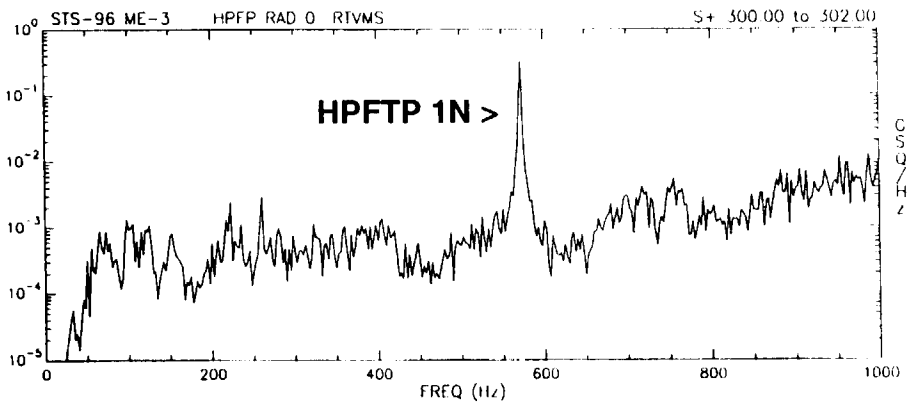


HTD-2 RTVMS HPFTP Tracking Results

STS-96 SSME Position 3



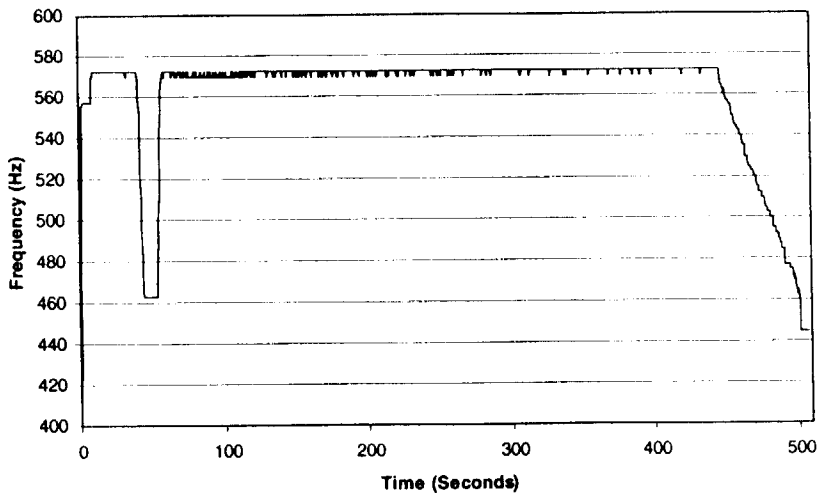




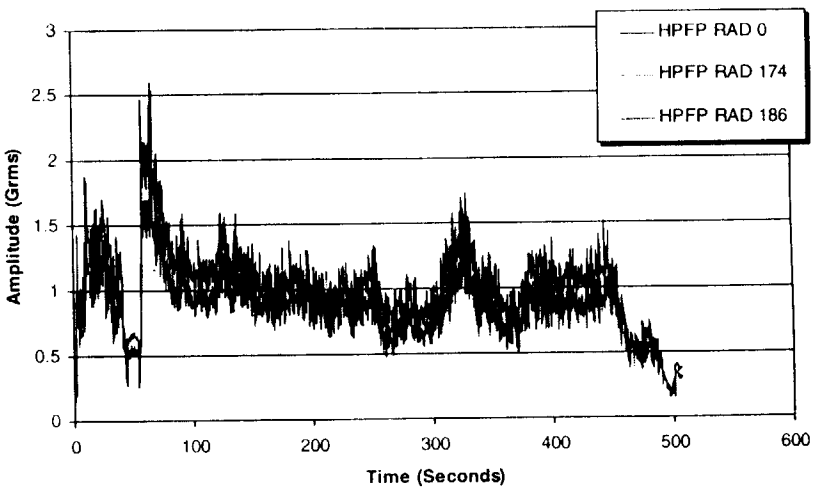
***** Note: The synchronous response is labeled as "1N".***

HTD-2 RTVMS HPFTP Tracking Results
STS-96 SSME Position 3

RTVMS HPFTP Synchronous (Speed) Frequency Tracking

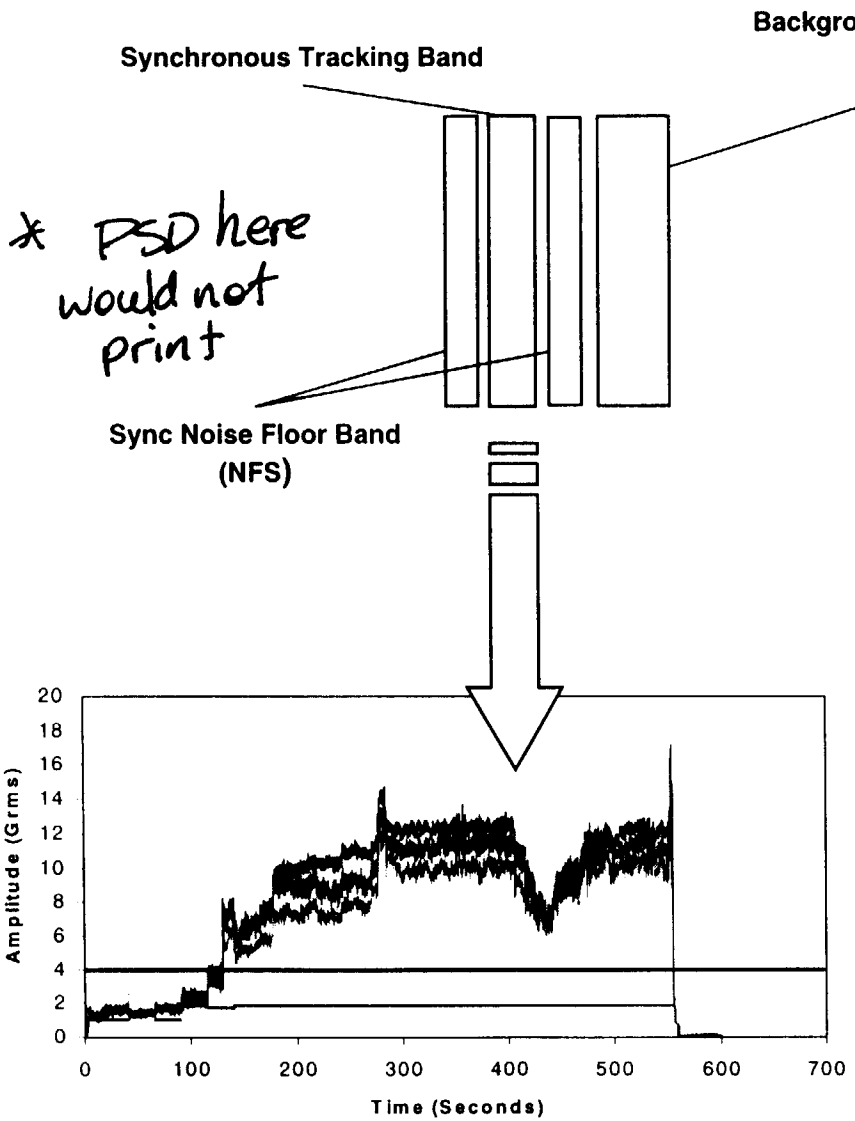


RTVMS HPFTP Synchronous Amplitude Trackings



- **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.