Electrical Signature Analysis

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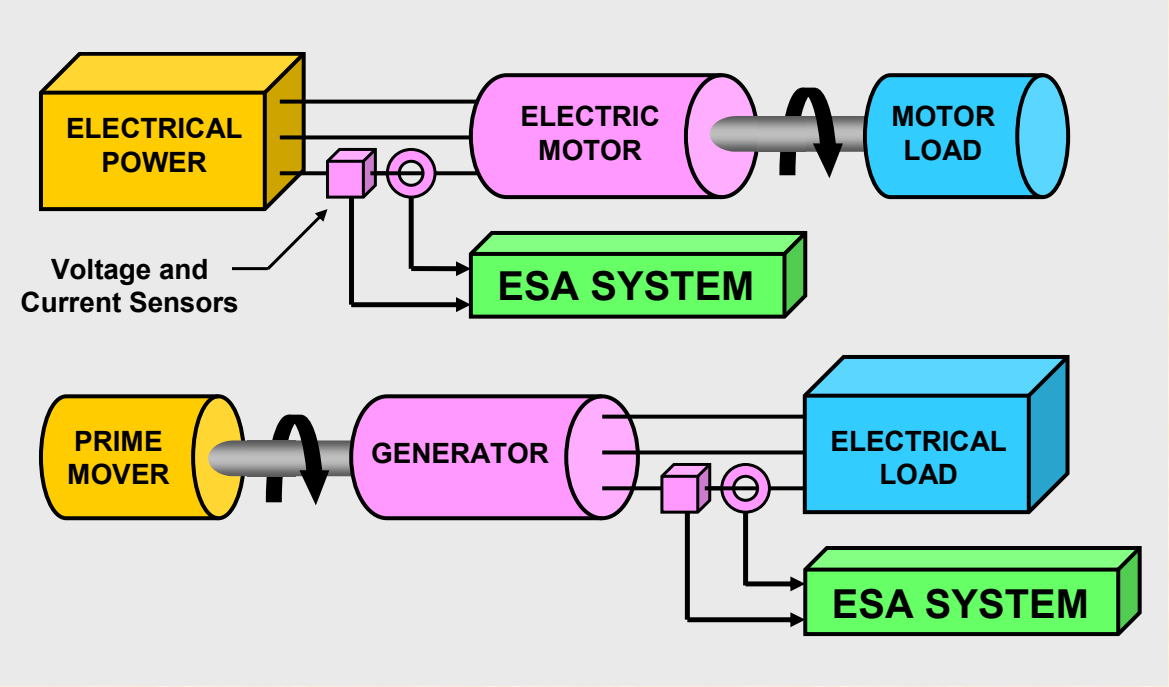
What is Electrical Signature Analysis?

- **Electrical Signature Analysis (ESA) describes a "toolbox" of non-intrusive techniques that have been developed by ORNL over the last 20+ years for monitoring the health of electro-mechanical equipment.**

- **The motor or generator of the system under test is used to provide the diagnostic signals, thus acting as a built-in transducer.**

- **Variations in electric current and/or voltage are analyzed and used to characterize the electrical and mechanical condition of the tested system.**



- **ESA can detect and diagnose degraded condition before any loss in performance is detected, and thus provides a powerful tool for condition-based maintenance.**

ESA is an Attractive Technology for Several Reasons

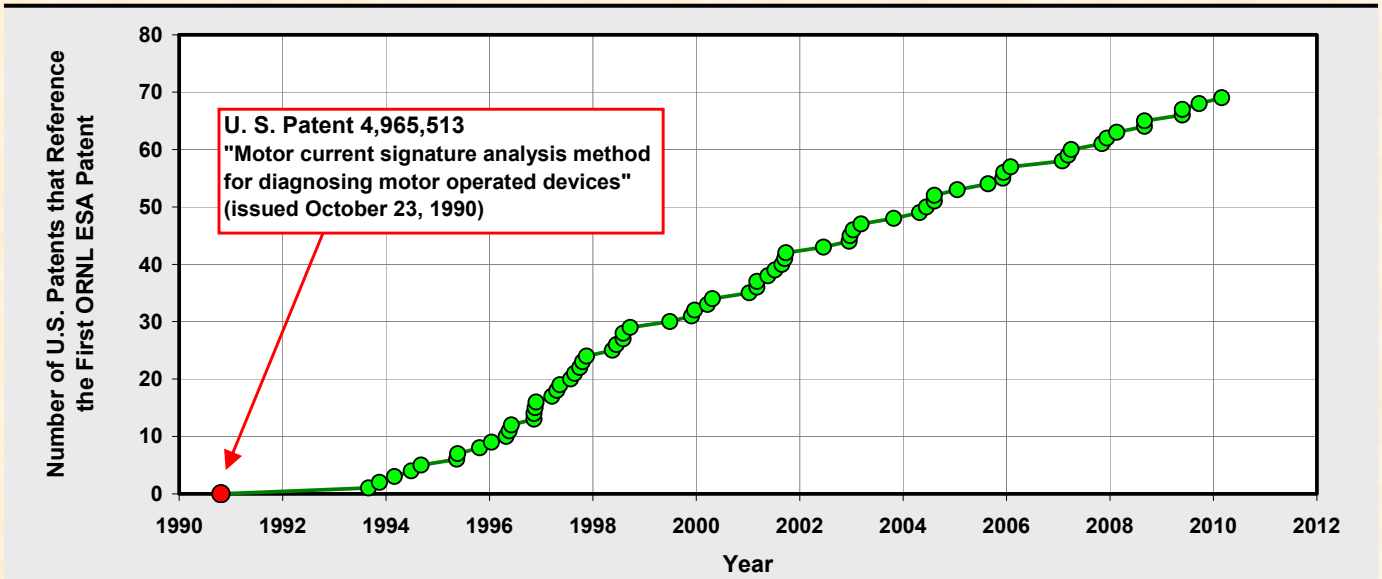
Benefits

- Non-intrusive and remote monitoring capability
- No equipment-mounted sensors required
- Applicable to high and low power equipment
- Large range of applicable analysis methods
- High sensitivity to a variety of disorders
  - degraded and misaligned motors and generators
  - worn bearings, gears, and belts
  - unstable process conditions
  - power system degradation

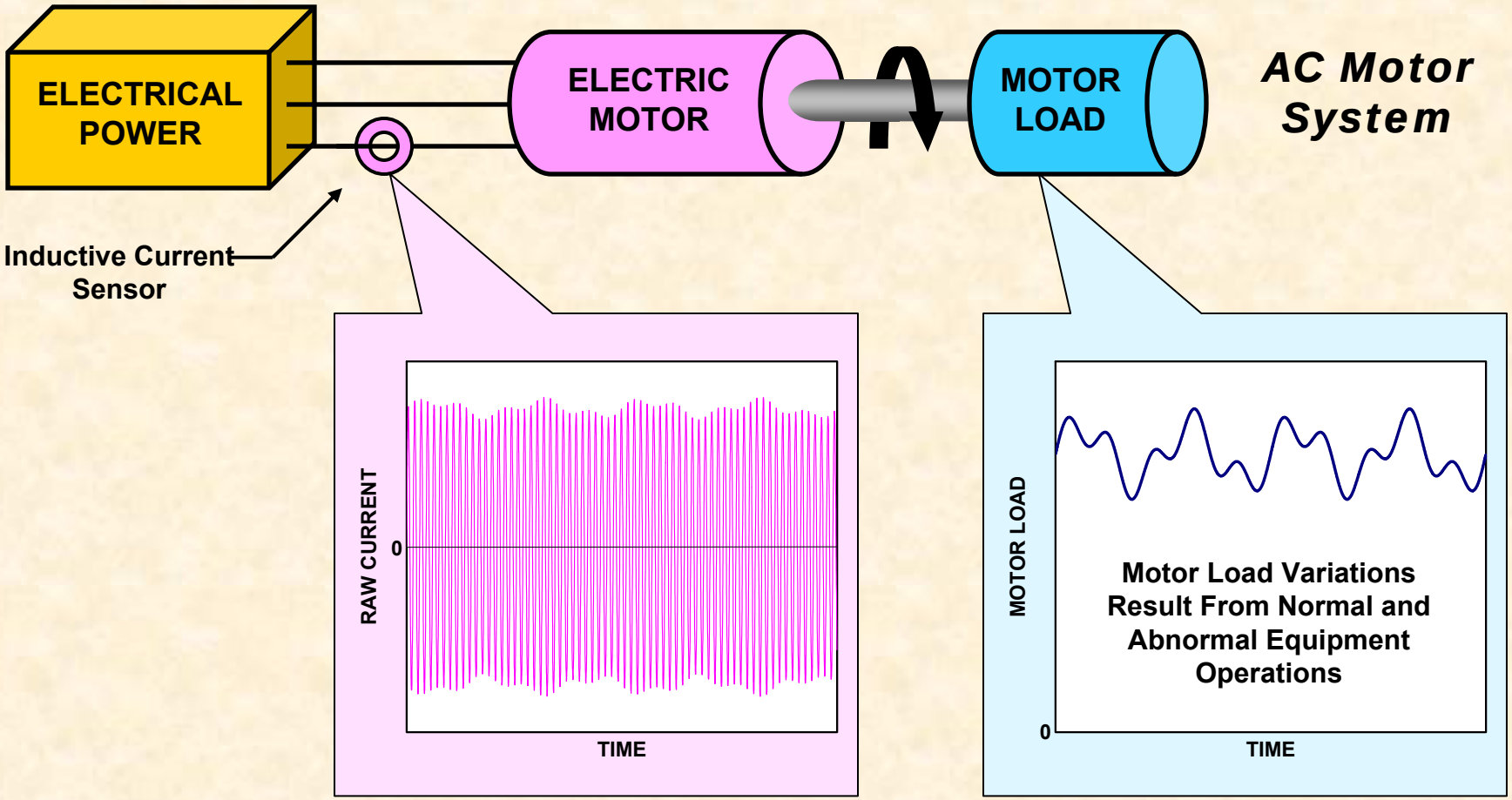
When to Use ESA

- On-line condition and performance monitoring
- Catastrophic failure prevention
- Improved safety and reliability
- Quality assurance and evaluation
- Energy conservation
- Condition based maintenance
- Diagnostic and prognostic testing
- Remaining life assessments

ESA is a Mature Technology

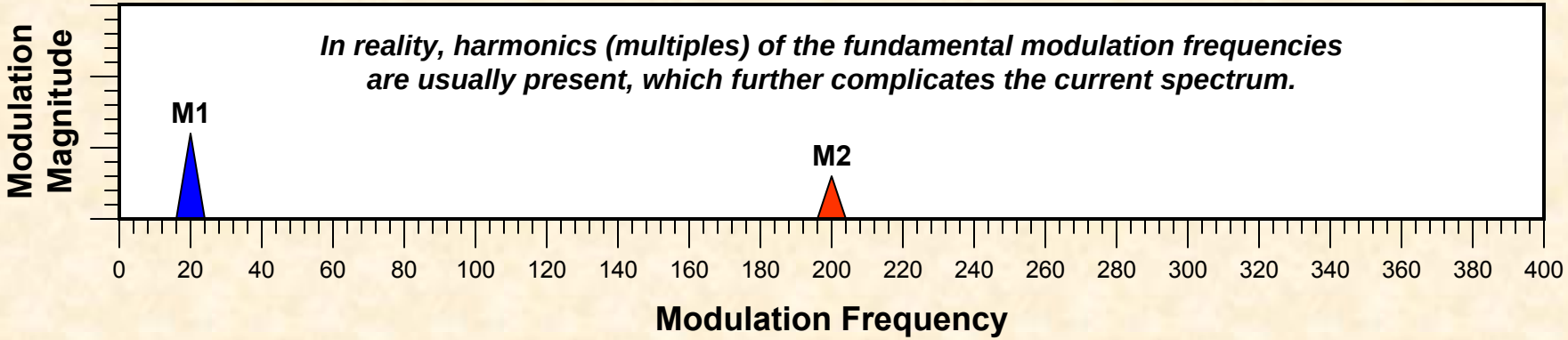


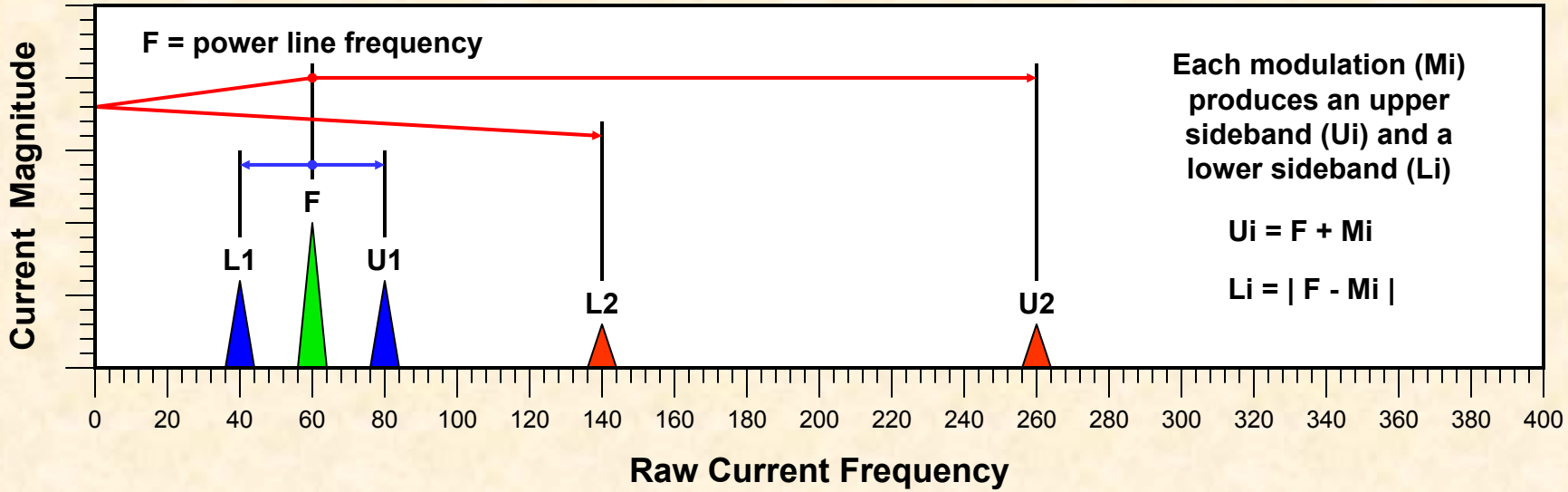
Motor Load Variations Are Directly Converted Into Electric Current Modulations



Electric Current Modulations Result in Sideband Components in the Raw Current Spectrum

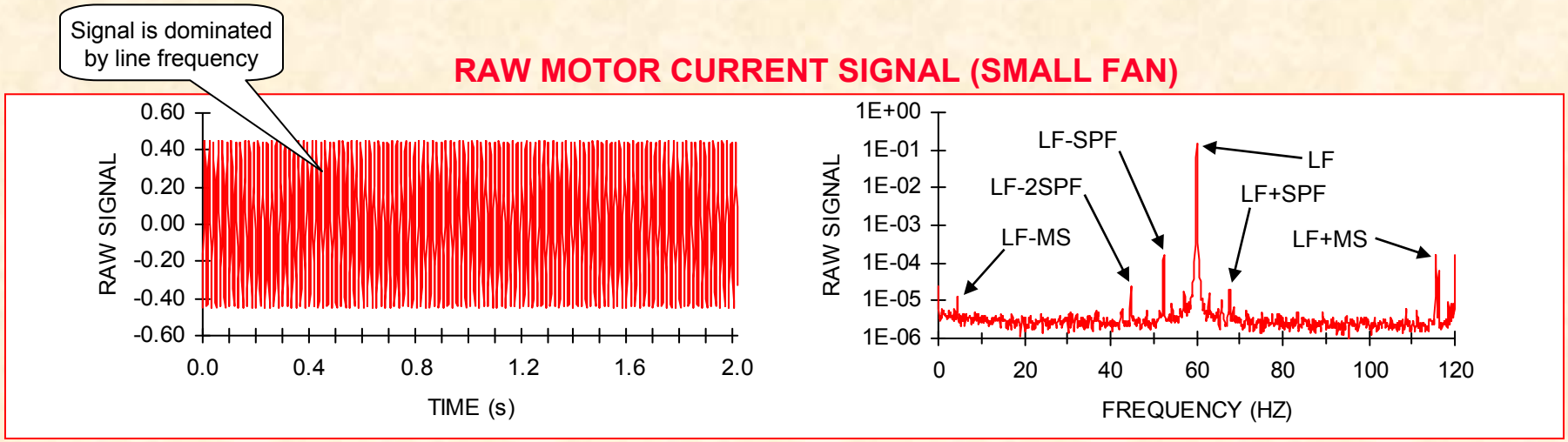
(In this example, two current modulations are shown: M1 and M2)*

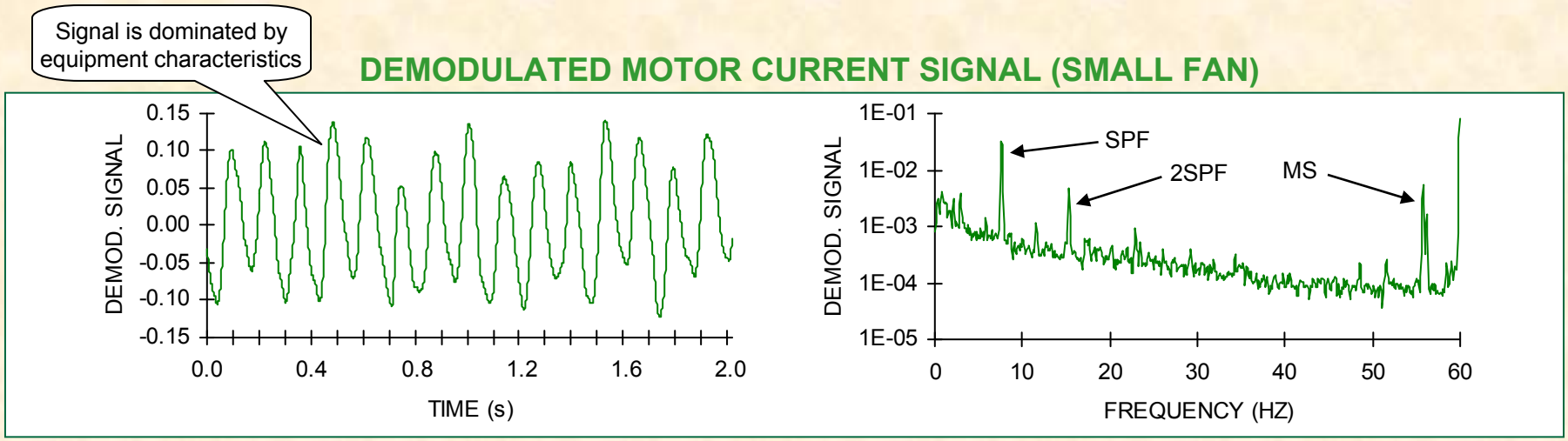




* For DC-powered devices, no line frequency is present; thus, load frequencies translate directly into electric current frequencies, and no demodulation is necessary.

These Modulations Can Be Easily Identified After *Demodulating* The "Raw" Current Signal

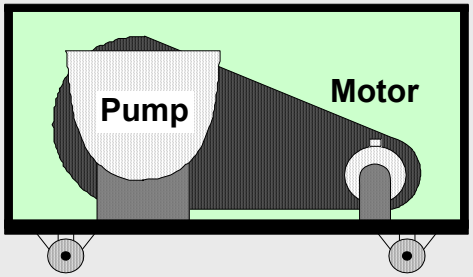




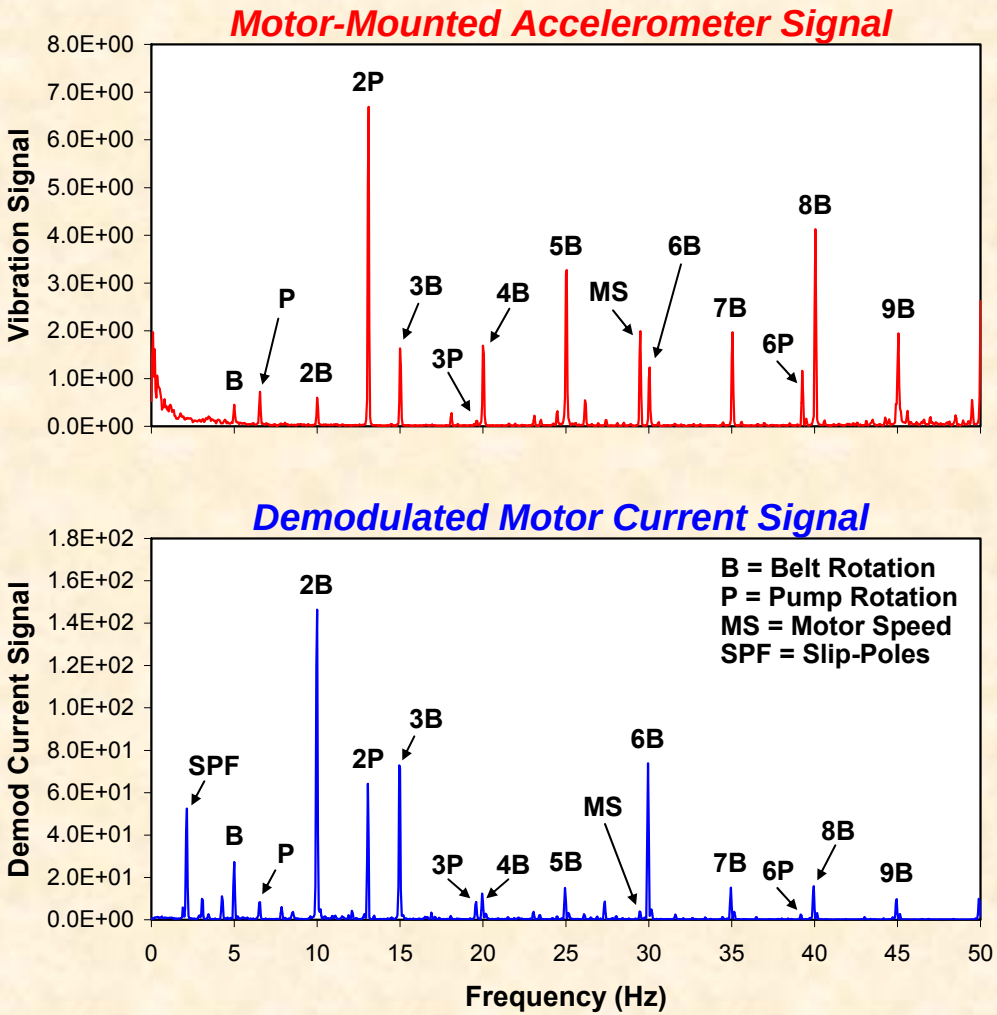
LF = LINE FREQ. (60 HZ) **MS** = MOTOR SPEED **SPF** = SLIP POLES FREQ. = NP(SS - MS) ; **SS** = SYN. SPEED, **NP** = # MOTOR POLES

Motor and Generator Electrical Signatures Can Provide Spectral Content Similar to An Attached Accelerometer

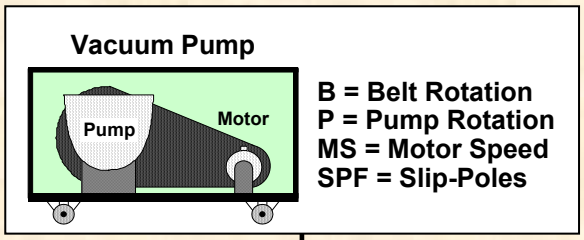
- **Periodic mechanical interactions between the motor, belt, and pump produce periodic vibrations <u>and</u> periodic modulations in running current.**
- **All key mechanical events are sensed by <u>both</u> the accelerometer and motor.**



Vacuum Pump

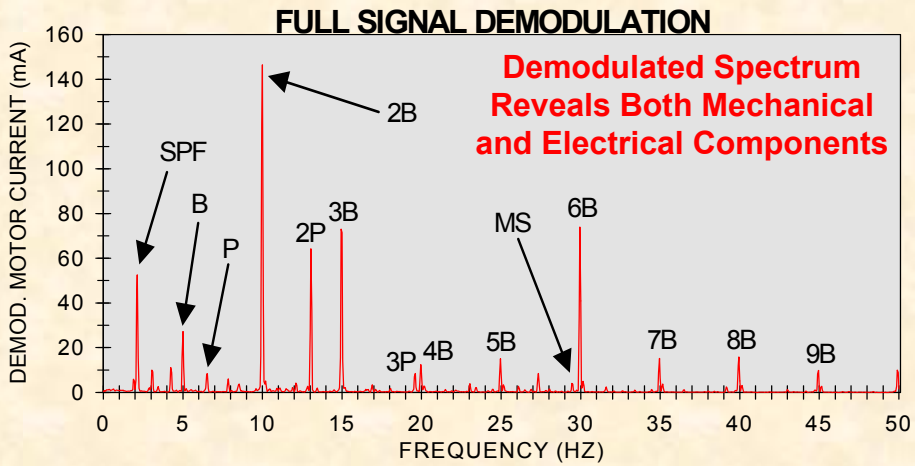


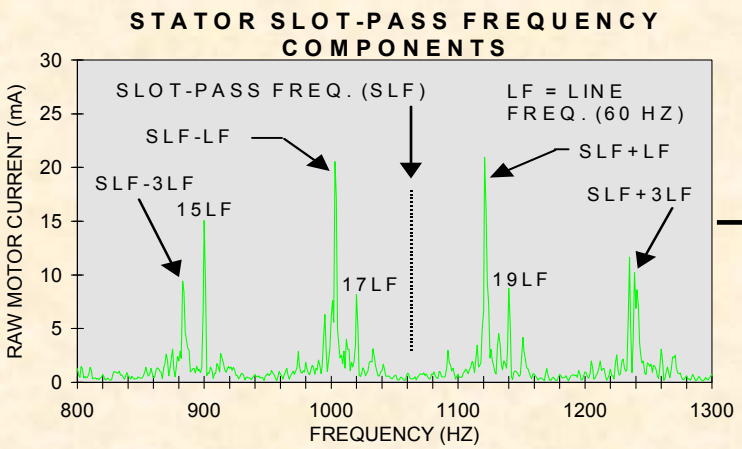
Filtering Techniques Can Help Separate Electrical and Mechanical Component Details



D

Band-Pass Filter (800 Hz to 1300 Hz)





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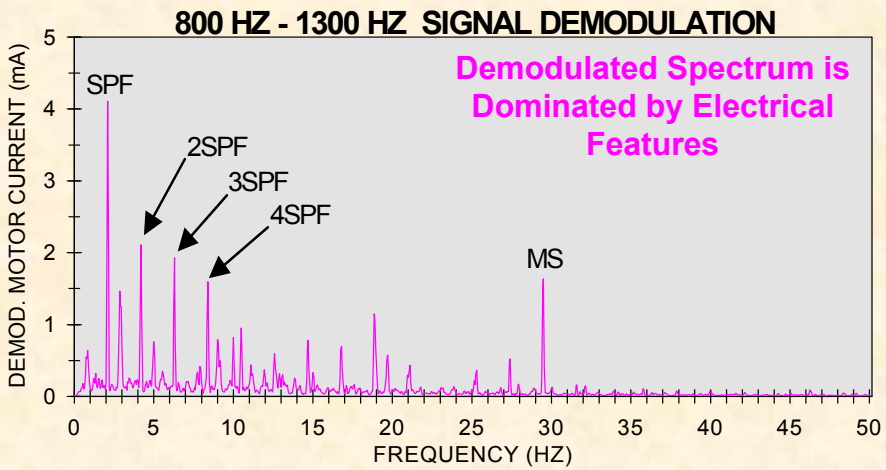
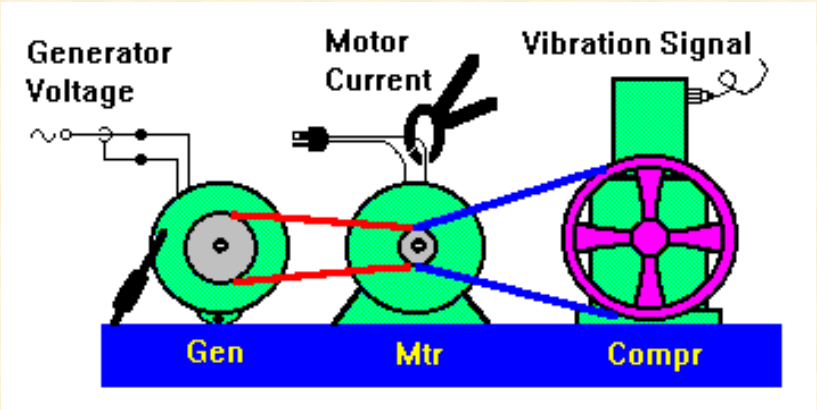
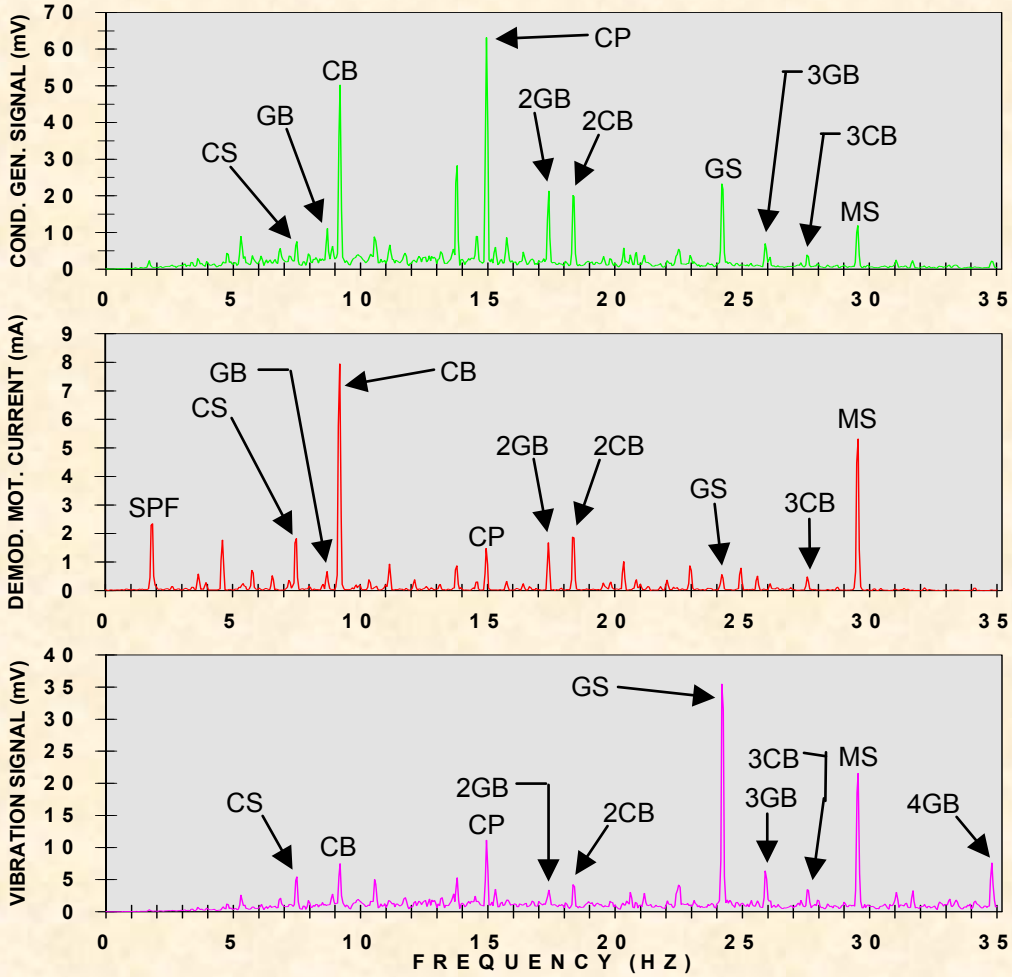


D = Signal Demodulator

Alternators And Generators Can Also Be Utilized As Transducers Of Useful Diagnostic Information

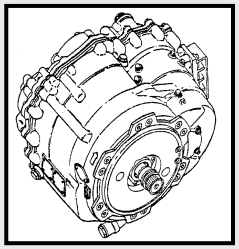


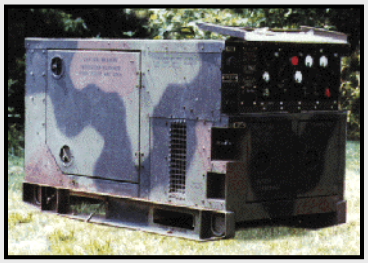
MS = MOTOR SPEED
SPF = SLIP-POLES FREQ.
GS = GENERATOR SPEED
GB = GENERATOR BELT ROTATION
CS = COMPRESSOR SPEED
CB = COMPRESSOR BELT ROTATION
CP = COMPRESSOR PISTON FREQ.

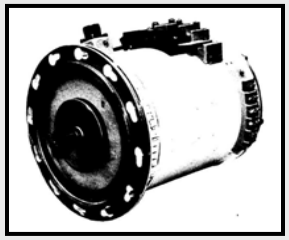


Since the Late 1980's, ESA Has Been Used by ORNL on a Wide Variety of Equipment

- ► Vacuum Pumps
- ● Coal Pulverizers
- ► Peristaltic Pump
- ● Air Compressors
- ● Textile Plant Motors
- ● Multi-Axis Milling Machines
- ● Variable Speed Motor Drives
- ● Diesel Engine Starter Motors
- ● NASA Propellant Control Valve
- ► Power Plant Pumps and Valves
- ● Navy Fire and Seawater Pumps
- ► Navy Aircraft Electric Generators
- ● Large Chillers, Blowers and Fans
- ► Helicopter Tachometer Generators
- ► Consumer Treadmills (gait analysis)
- ► Electric Solenoids and Fuel Injectors
- ► Army Tactical Quiet Generator (TQG)
- ► Gaseous Diffusion Plant Compressors
- ● Electric Vehicle Motors and Alternators
- ► Consumer Appliances and Power Tools
- ● Heat Pump and Air Conditioning Systems
- ● Army Prototype Ammunition Delivery Systems
- ► Commercial Aircraft Integrated Drive Generator
- ► Air Force Aircraft Fuel Pumps, Valves, and Actuators

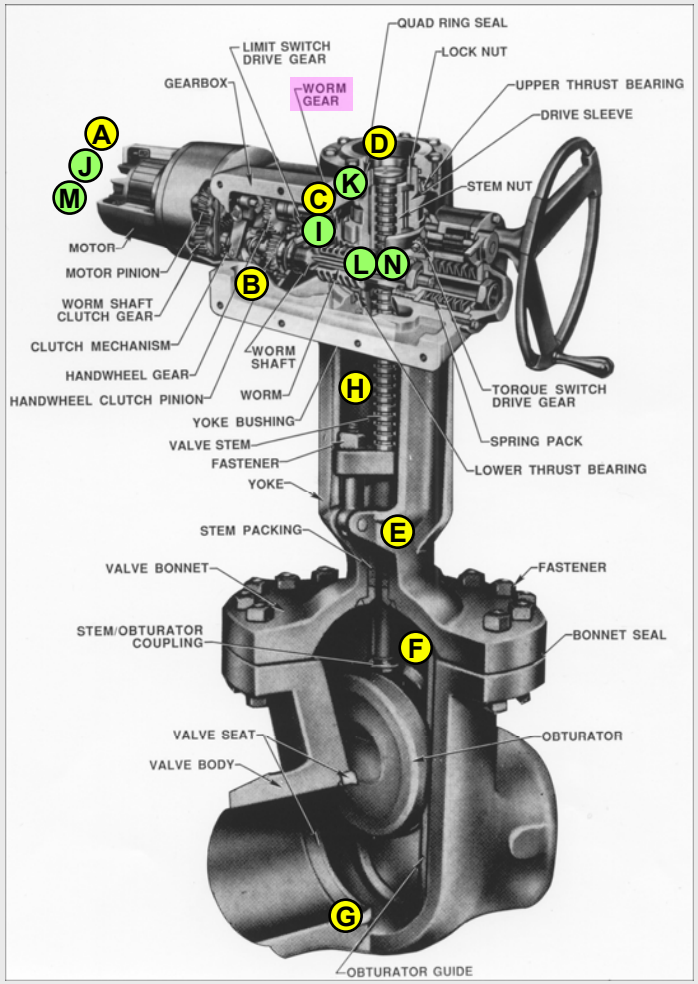




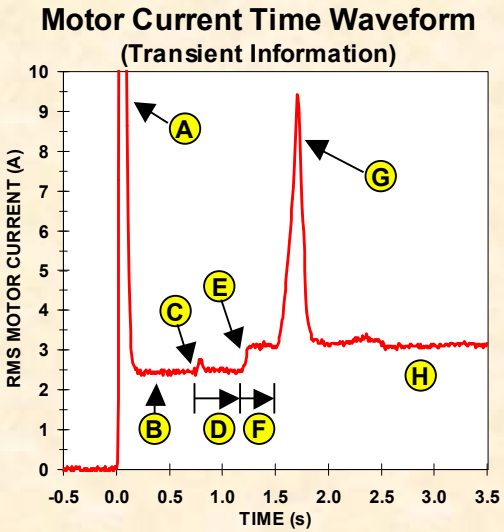


► Examples provided in this presentation

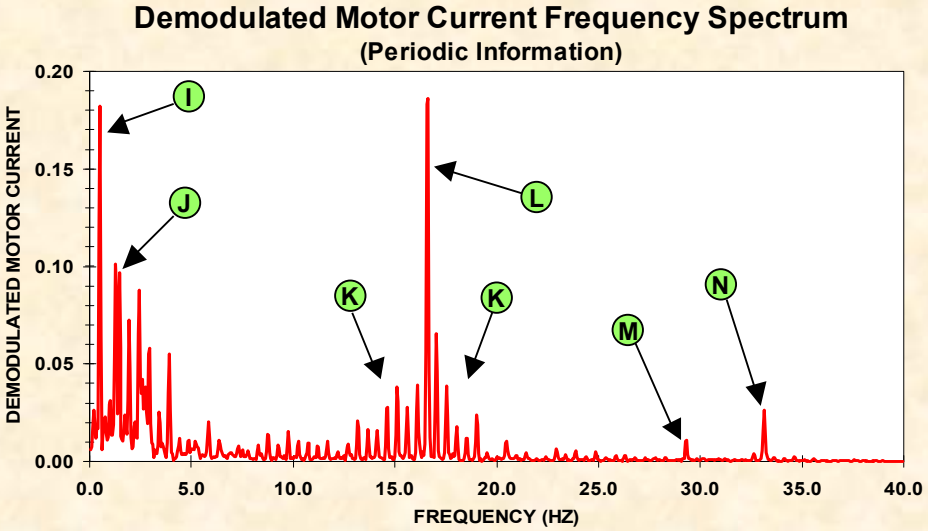
ESA Can Reveal Detailed Information at the Subcomponent Level



Motor-Operated Valve (MOV)

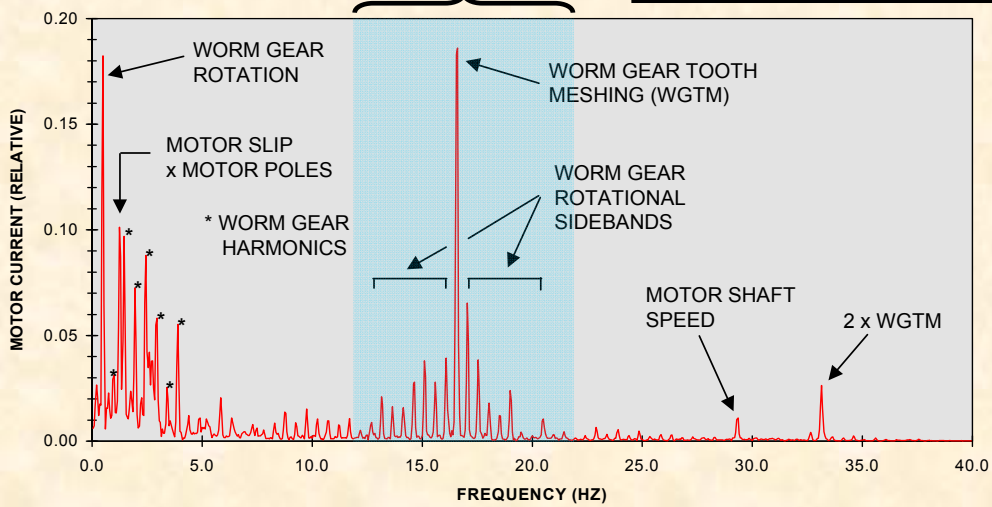


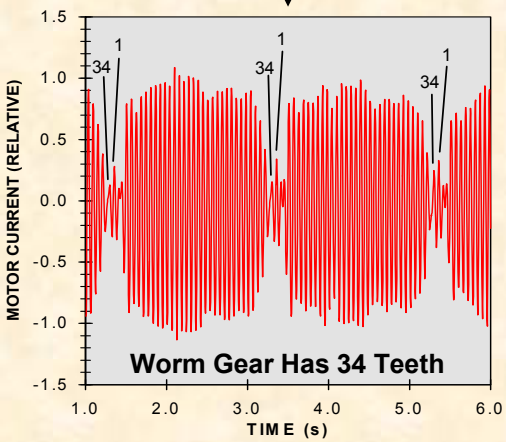
- (A) Motor inrush current
- (B) No - load current
- (C) Hammerblow current
- (D) Stem nut clearance time
- (E) Packing drag current
- (F) Stem coupling time
- (G) Unseating current
- (H) Total running current
- (I) Worm gear rotation
- (J) Motor slip
- (K) Worm gear rotation sidebands
- (L) Worm gear tooth meshing
- (M) Motor speed
- (N) Worm gear mesh harmonic



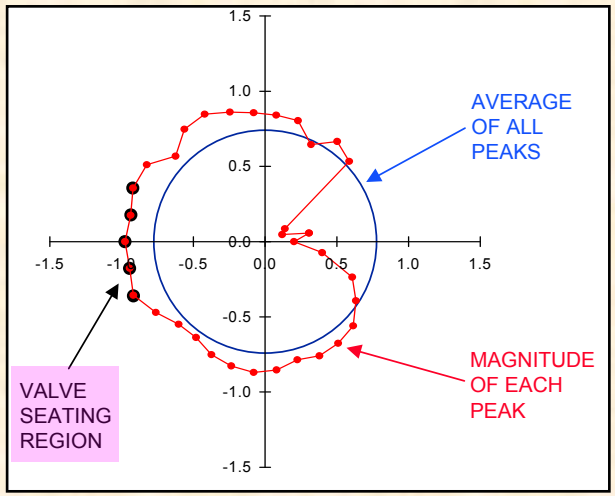
Filtering Techniques Can Separate Individual Component Details From The Overall Signal

Band-Pass Filter (12 Hz to 22 Hz)





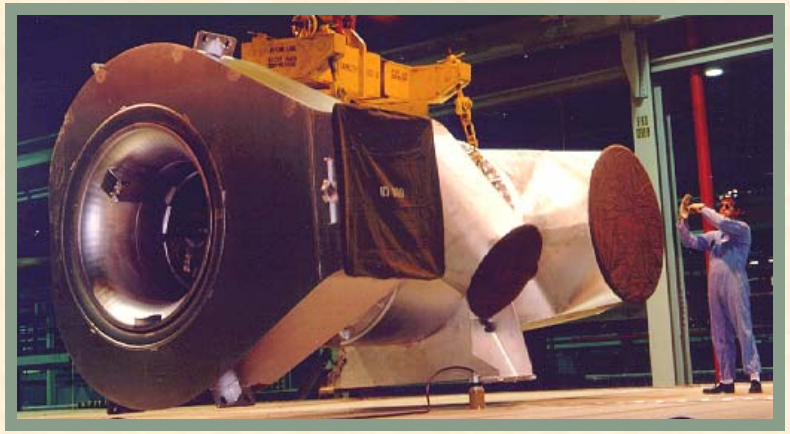
Convert Magnitudes To Polar Coordinates



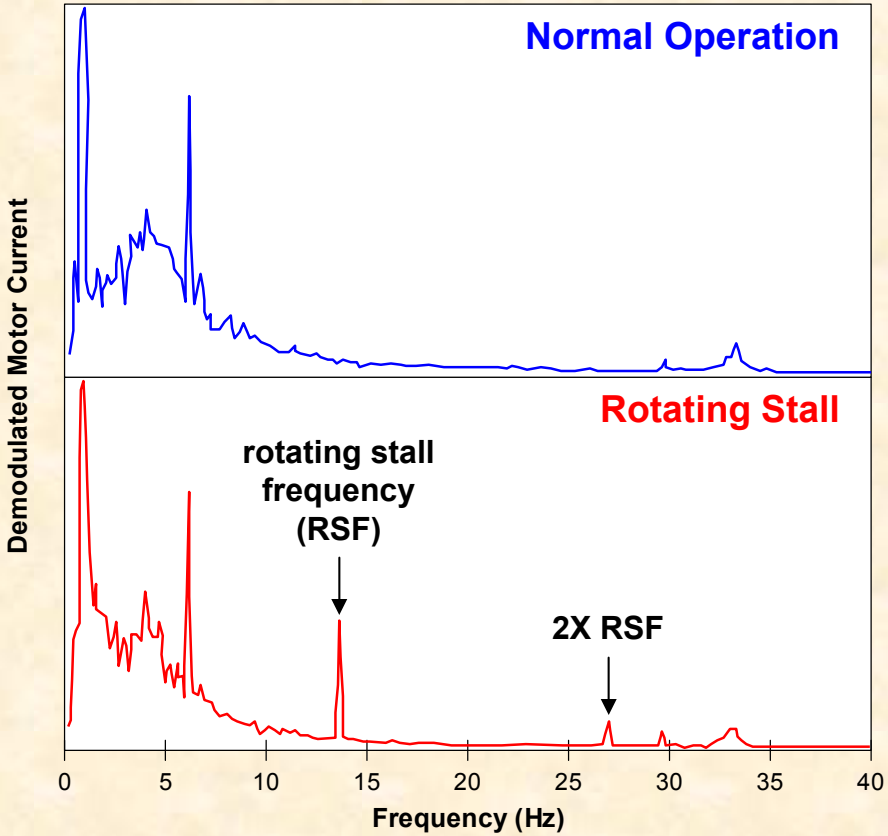
- **The polar graph reveals the worm gear mesh irregularities.**
- **Worm gear loading is particularly high when the gate valve closes. The region of the gear receiving these high loads is indicated in the graph.**

Damaging Aerodynamic Conditions, Such As Rotating Stall, Can Also Be Detected Using ESA

- **1700-hp axial flow compressors have been used in large numbers in U.S. Uranium Enrichment Plants.**
- **Certain process flow configurations can induce rotating stall, which quickly accelerates blade fatigue damage.**



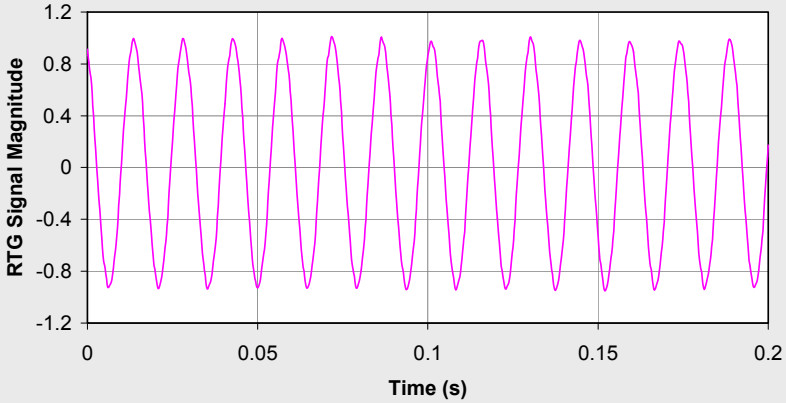
1700-hp Axial-Flow Compressor



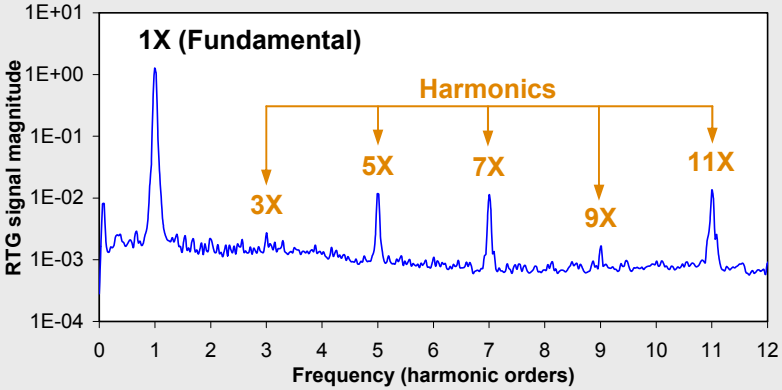
Demodulated Motor Current Spectra Obtained From the Control Room

Tachometer Output Signals Can Contain Useful Diagnostic Information

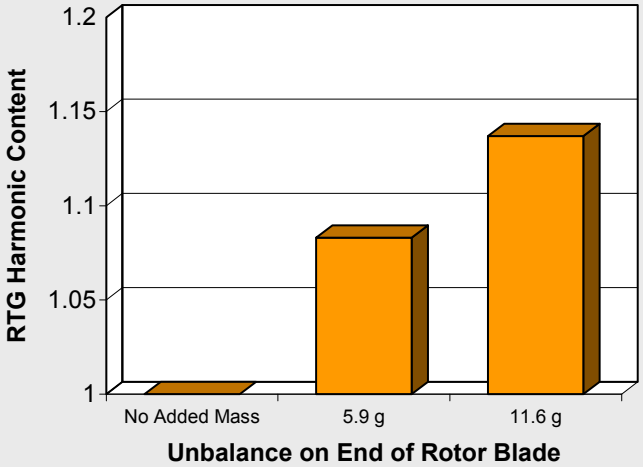
Bell Jet Ranger Helicopter



Rotor Tachometer Generator (RTG) Signal

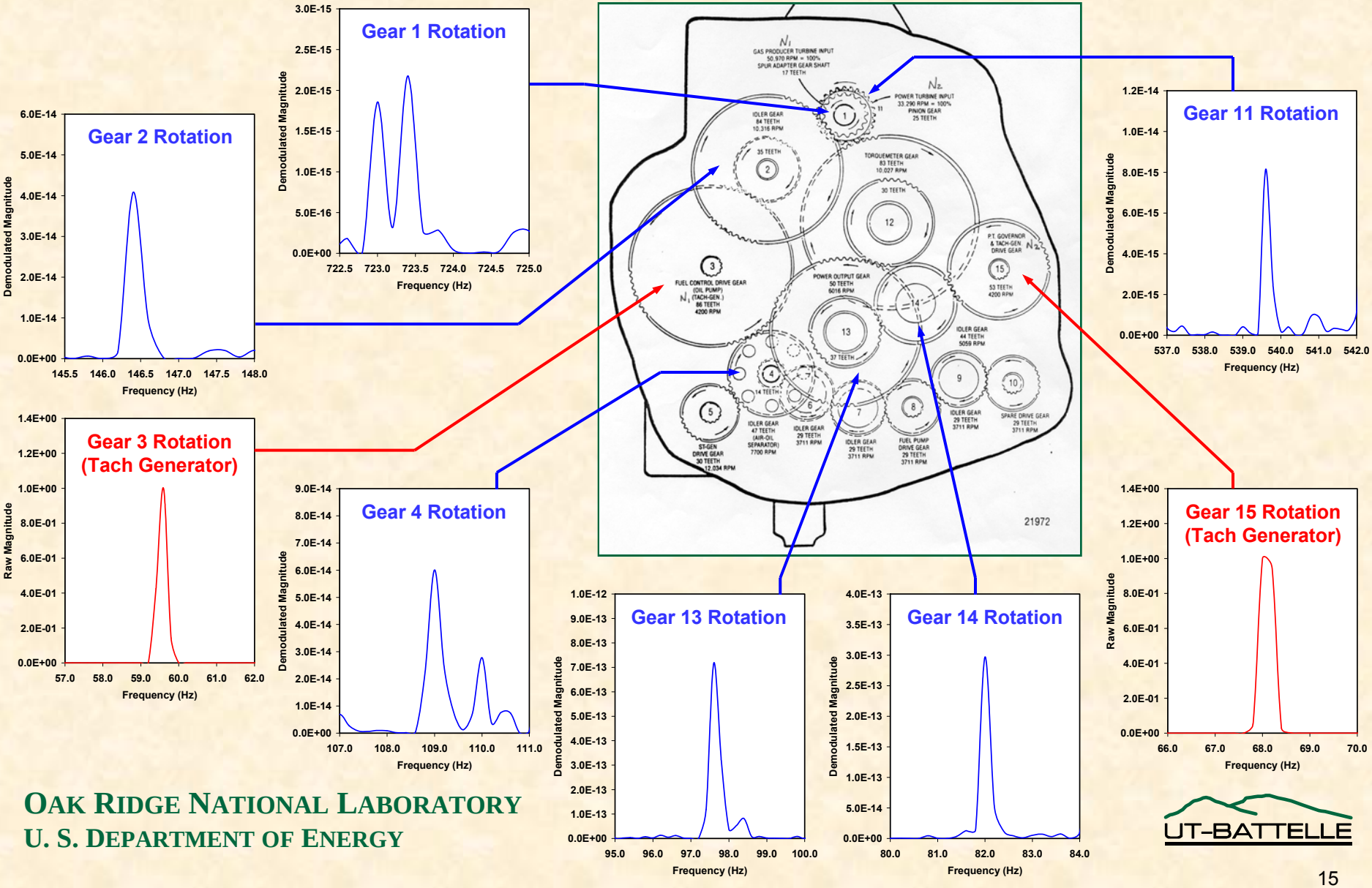


RTG Signal Spectrum, Showing Harmonics



Rotor Unbalance vs. RTG Signal Harmonics

The Helicopter's Turbine Tachometer Generators Provide Information on Gear Train Components

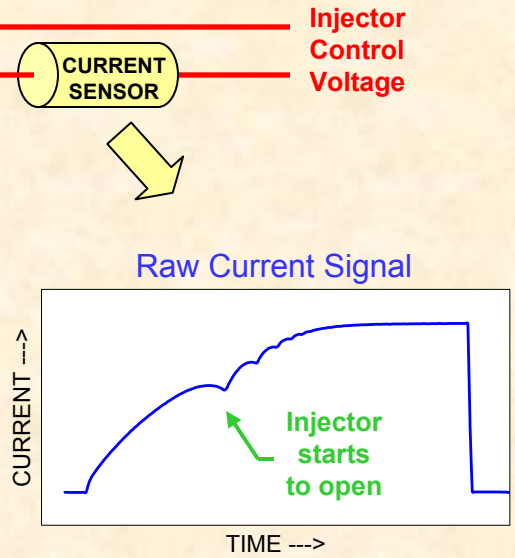


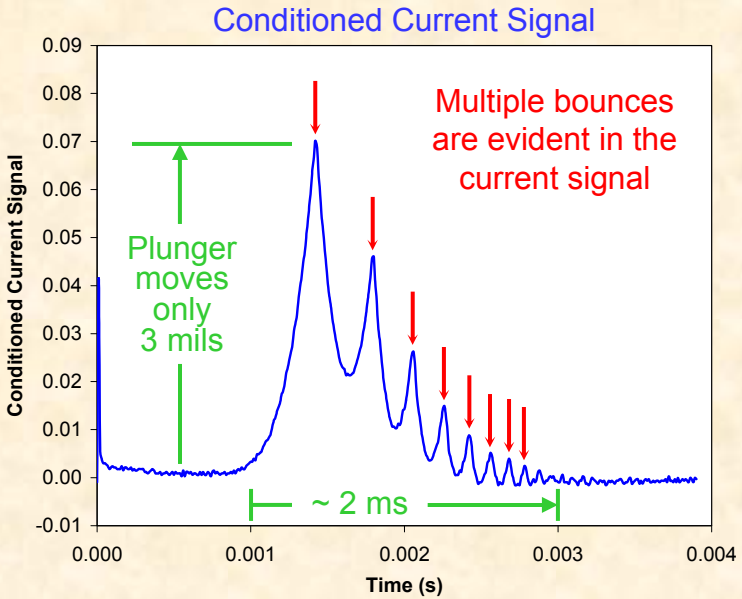
ESA Can Be Used to Monitor the Performance And Condition Of Solenoid-Operated Devices

(Example: Automotive Fuel Injector)

- **ESA methods can differentiate between effects due to changes in injector temperature, voltage, and supply pressure.**
- **ESA methods have been successful at detecting injector outlet port plugging.**
- **ESA offers a quick, inexpensive method for checking the quality of newly-manufactured injectors.**
- **ESA can be the basis for new, non-intrusive test equipment for engine maintenance shops.**

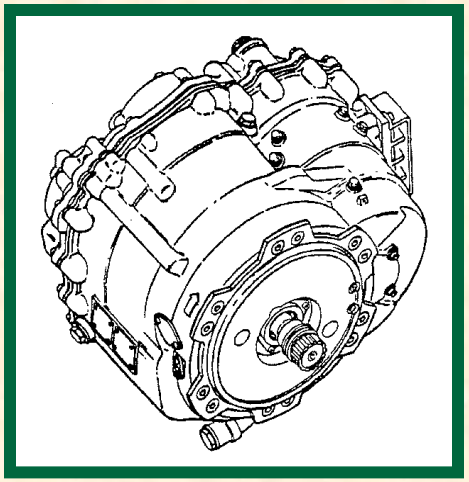
Fuel Injector



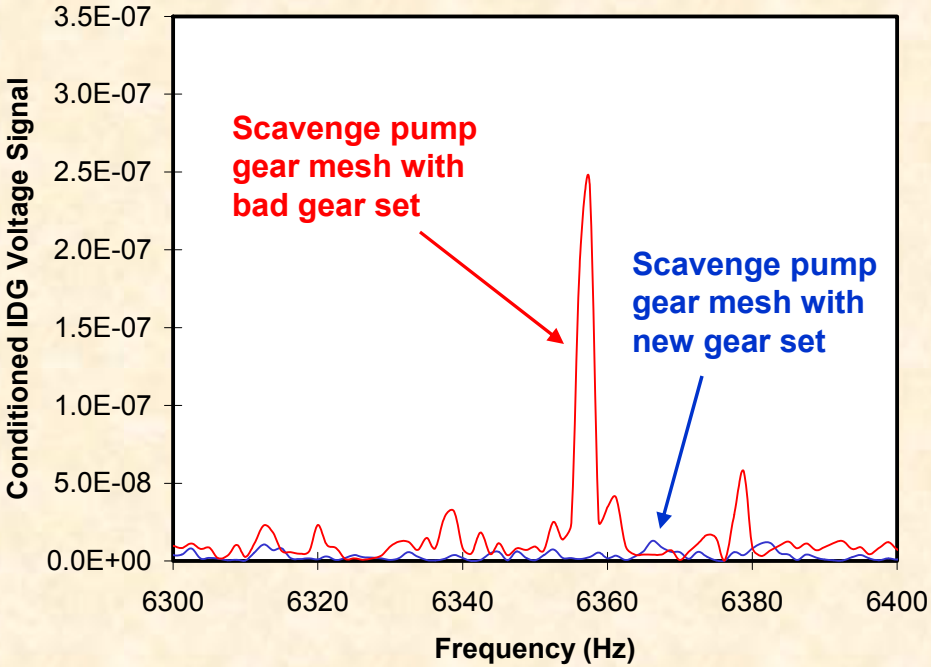


ESA Has Detected Mechanical Degradation In a Commercial Aircraft Integrated Drive Generator (IDG)

- **IDGs provide power for devices in the passenger cabin such as reading lights and microwave ovens.**
- **On certain aircraft, IDGs fail at the rate of four per year. Each IDG costs $250K to replace.**
- **The primary failure mode is seizure and destruction of scavenge, drive pump, and axial gears on the IDGs main shaft.**
- **Even at very low generator electrical loads, ESA can detect gear problems before they fail.**



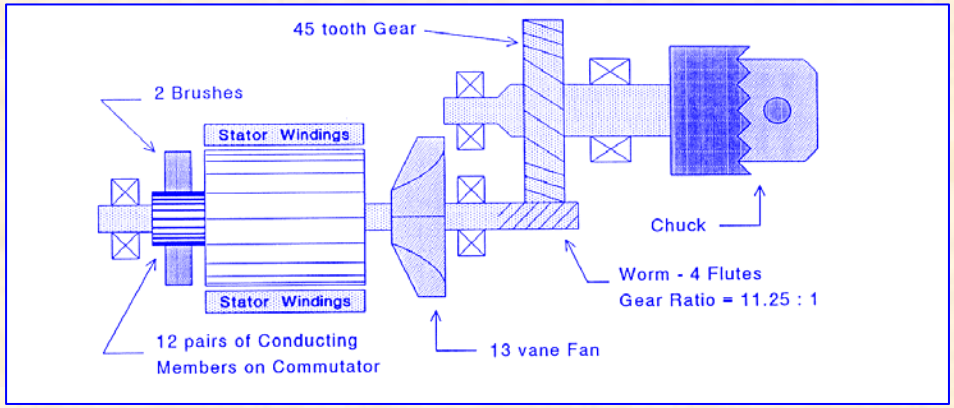
Aircraft Integrated Drive Generator (IDG)



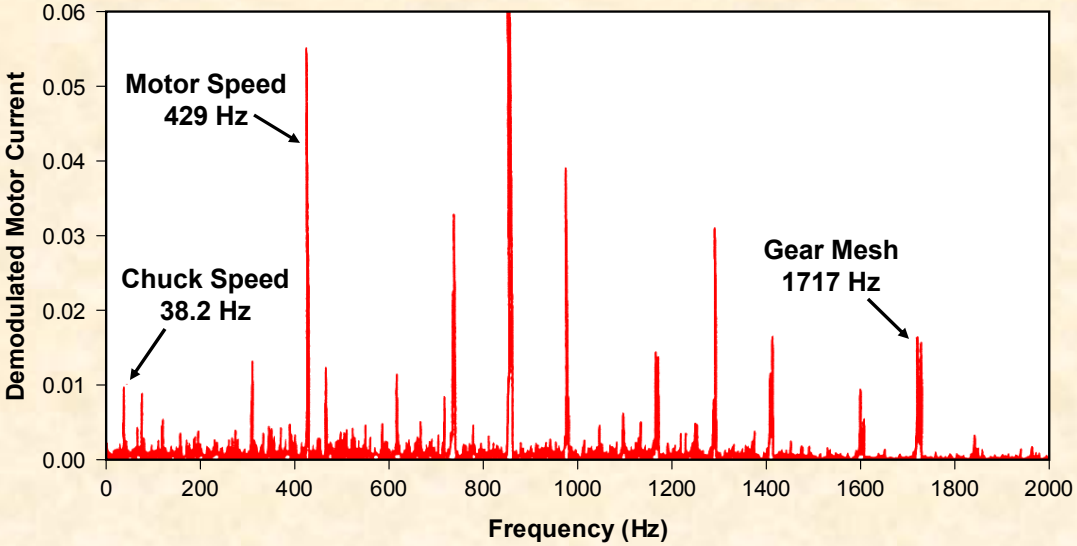
Several Power Tools and Consumer Appliances Were Also Examined to Show the Versatility of ESA

(Example: Power Drill)

- **Drill frequency components were observed with ESA.**
- **Relationships were established between vibration magnitudes and ESA parameters for different levels of motor unbalance.**

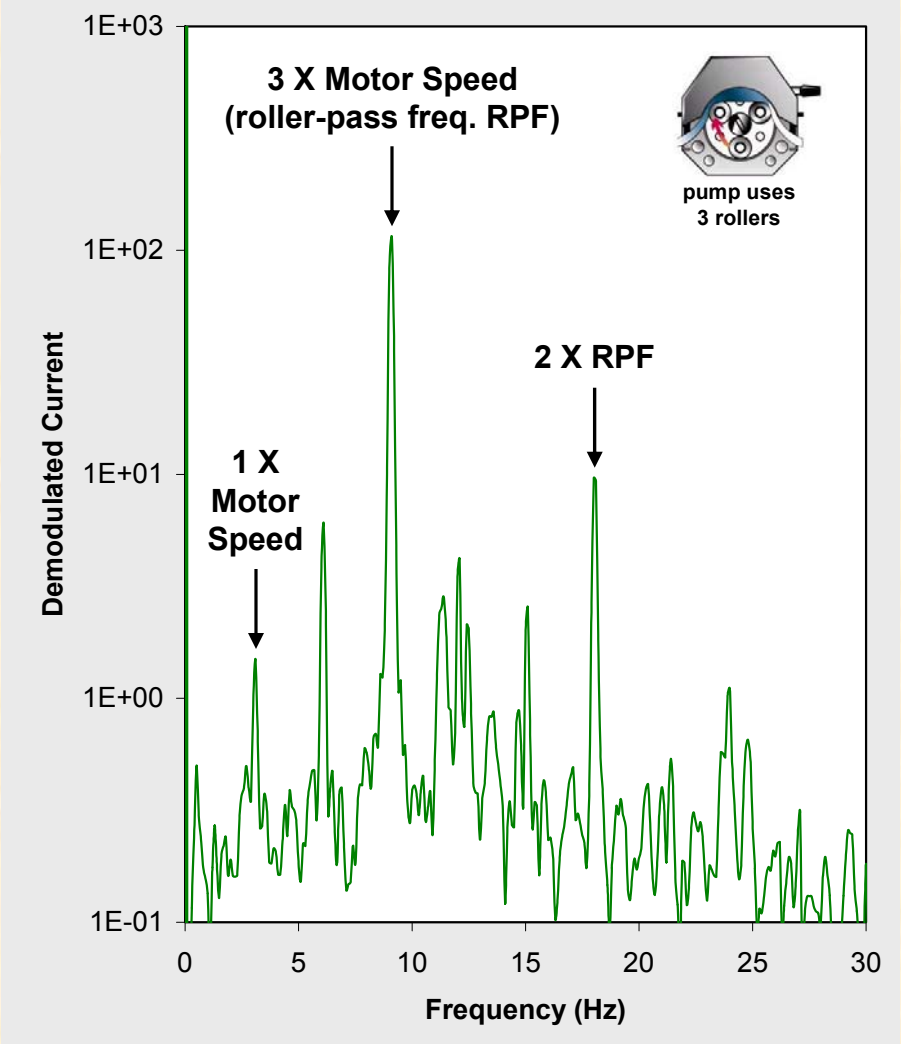


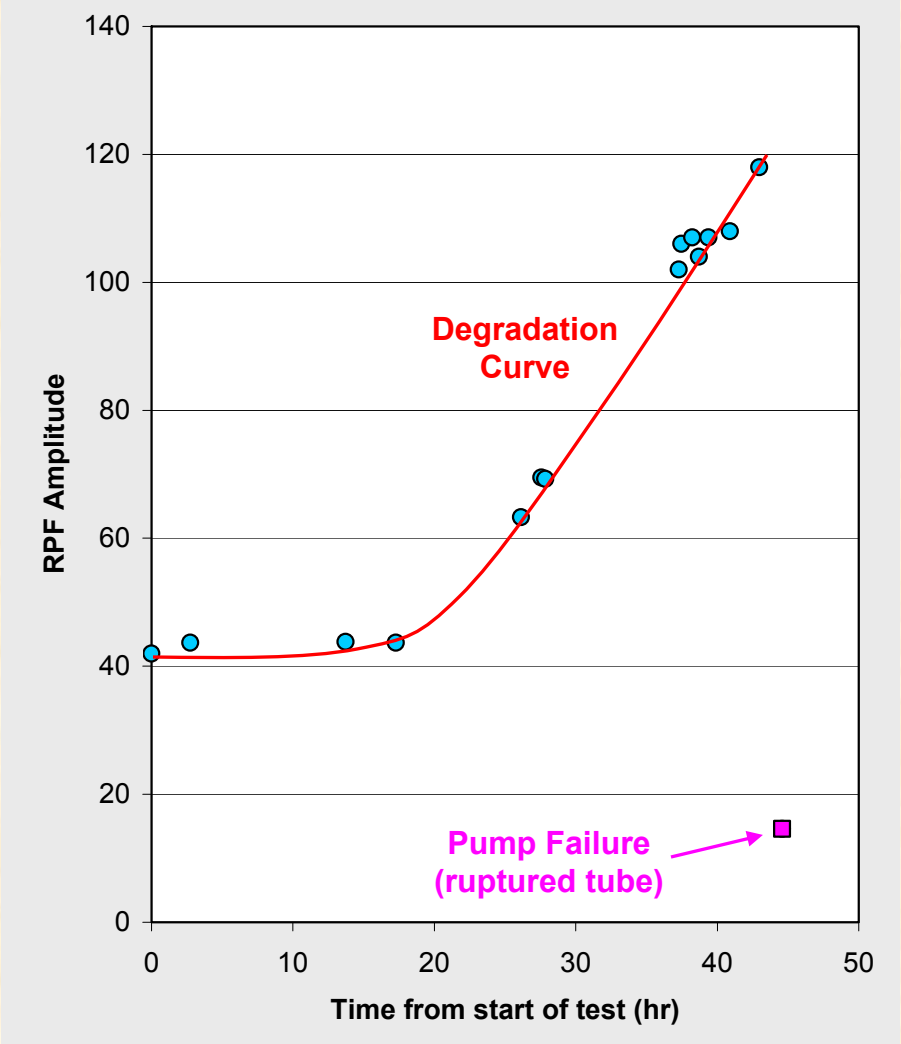
Power Drill



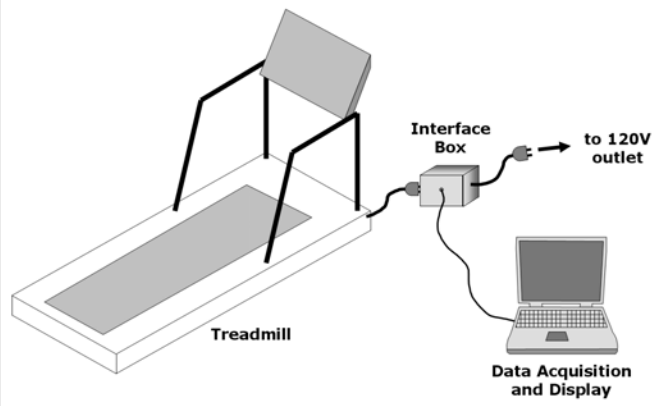
ESA Can Detect Changes in Component Condition Before Failure

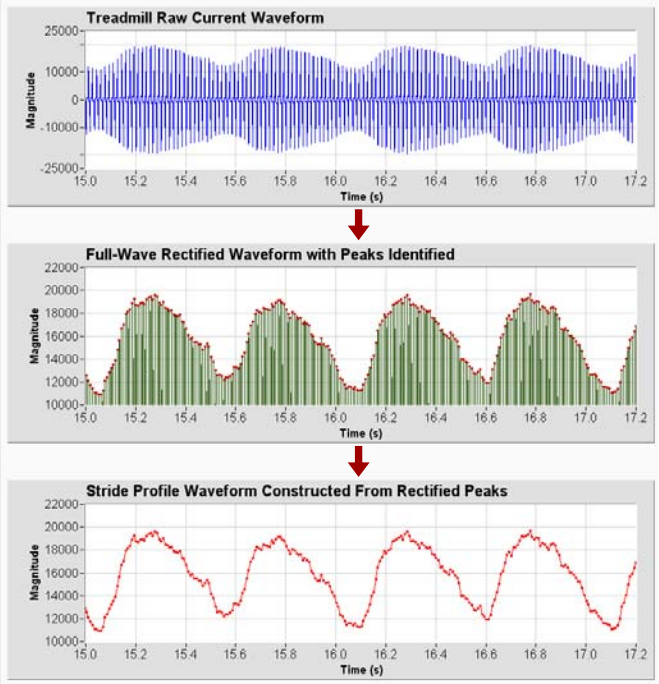
(Example: Peristaltic Pump)

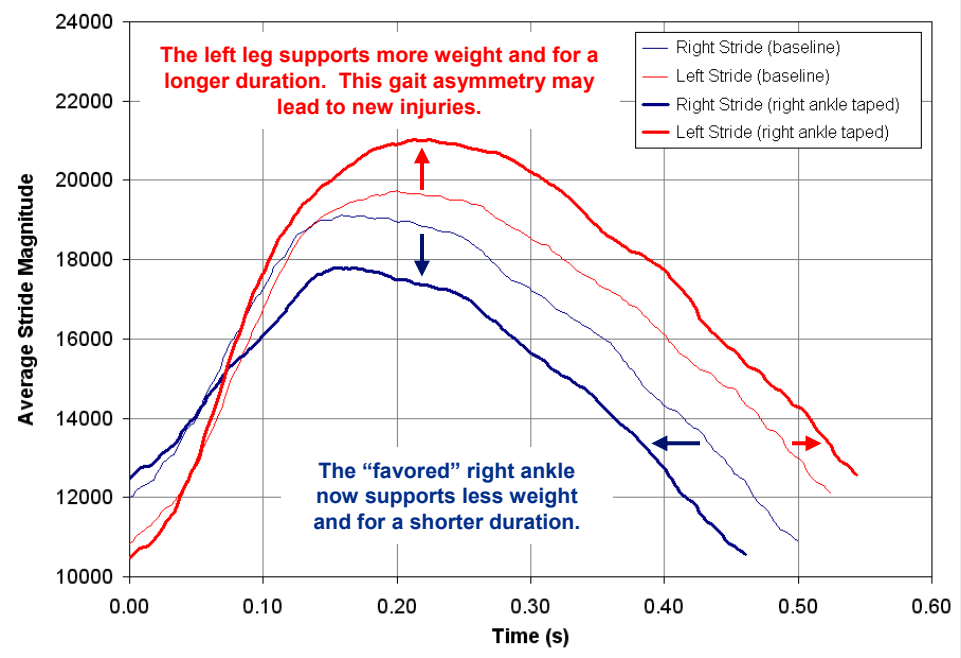




We Are Now Evaluating ESA as a Gait Analysis Tool







Effect of Taping the Right Ankle on the Gait Signature

Possible Applications Include:

- **New tool for helping the physical therapist establish or re-establish optimal gait symmetry and efficiency in geriatric populations, people with foot, leg, and hip injuries (sprains or strains), post-surgical cases, etc.**
- **New tool for aiding the design and evaluation of various braces, prostheses, athletic shoes, etc.**

ESA Was Recently Demonstrated by ORNL to be An Effective Tool for Monitoring the Condition Of C-141 Aircraft Fuel Pumps

C-141 Starlifter

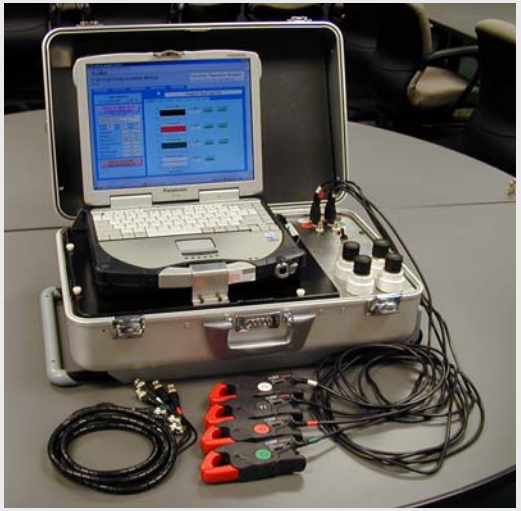
Main Fuel Pump

Aux Fuel Pump

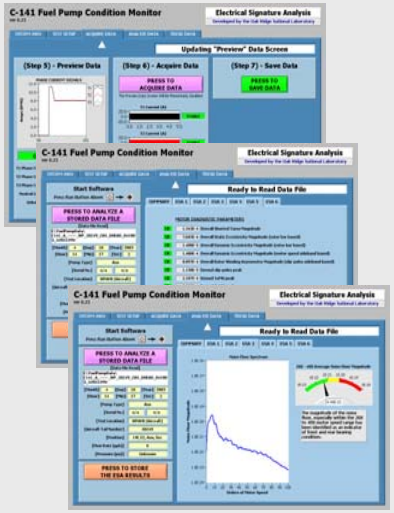
- Each C-141 has 20 centrifugal fuel pumps that are driven by 3-phase electric motors.
- Fuel pump failures had accounted for over 4000 hours per year of aircraft unscheduled downtime.

- Using ESA, fuel pumps can be tested while still installed in the aircraft and submerged in fuel.
- Motor current signals are obtained using clamp-on current probes.

- This work culminated in the development of a portable fuel pump condition monitor (FPCM).



Fuel Pump Condition Monitor (FPCM)



Virtual Instrument ESA Software

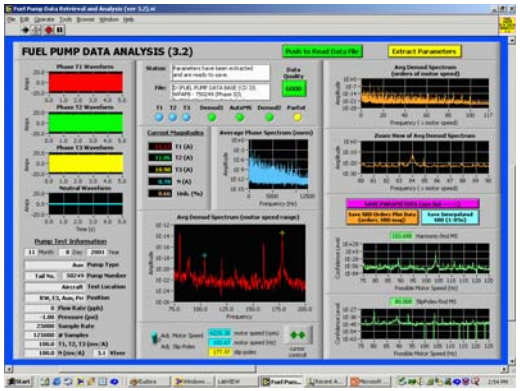
The Development Of The C-141 Fuel Pump Condition Monitor (FPCM) Required The Following Steps:

Test Fuel Pumps

- Tests performed at WPAFB, OC-ALC, and Oak Ridge
- Pumps were tested in good condition and with known defects

Analyze Data

- Signal processing (filtering, demodulation, etc.)
- Signature analysis (waveform, frequency spectrum, etc.)
- Relationships between the signatures and pump condition were discovered and exploited



Electrical Signatures Contain Many Identifiable Features

Develop Hardware and Software

- Suitcase-style enclosure
- Signal conditioning electronics
- "Virtual instrument" software

Complete The Prototype

- Rugged
- Portable
- Reliable
- Easy to use

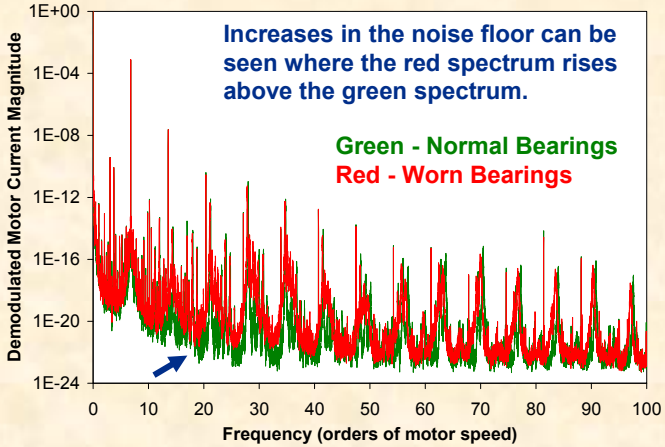
Fuel Pump Condition Is Determined In A Few Seconds

The Diagnostic Methods Used In The C-141 FPCM Exploit The Electrical Signature Differences Between Good And Degraded Equipment

Example: C-141 Fuel Pump Bearing Condition Detection

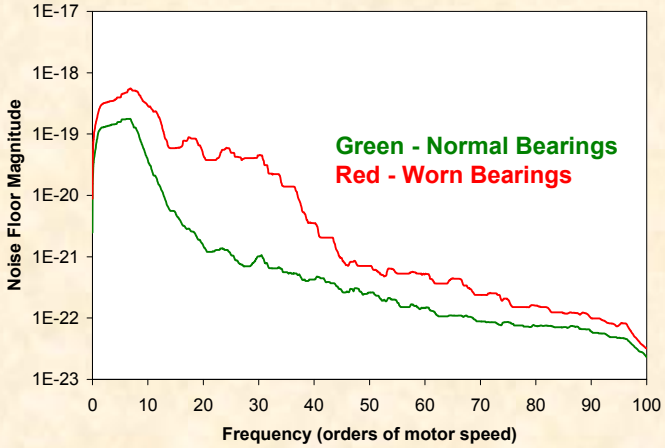
1 Identify Feature

By analyzing the signatures of many fuel pumps, it was discovered that increased bearing wear led to an elevated spectral "noise floor."



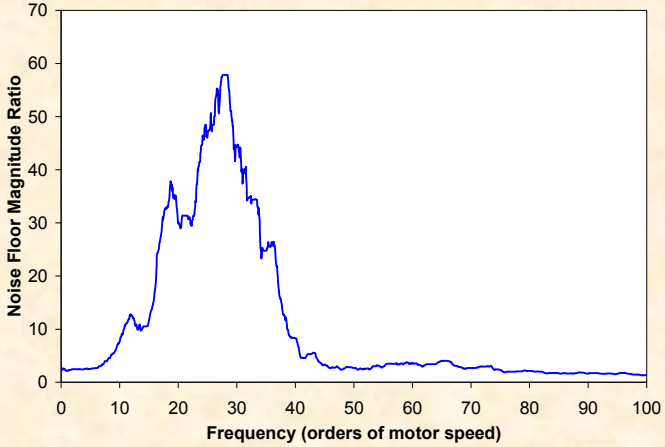
2 Enhance Feature

Further processing the spectral data enhances the noise floor differences.



3 Define Correlation

The noise floor is seen to increase by greater than an order of magnitude within a particular motor speed range.



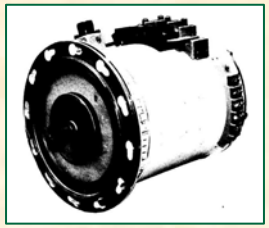
4 Final Result

This discovery led to the development of a powerful new tool for monitoring the condition of bearings used in C-141 fuel pumps <u>after</u> the pumps are installed and submerged in fuel.

ESA Testing Has Also Been Performed On A Navy P-3C Electric Generator

- For these tests, the P-3C generator was connected to a constant electrical load. Output current signals were recorded using clamp-on current probes and a digital audio tape recorder.

- The generator is a 3-phase, 400 Hz, 115 VAC, 60 kVA (20 kVA/ph), air cooled machine. According to the *Product Specification Sheet*, the relationship between operating speed and output frequency is:

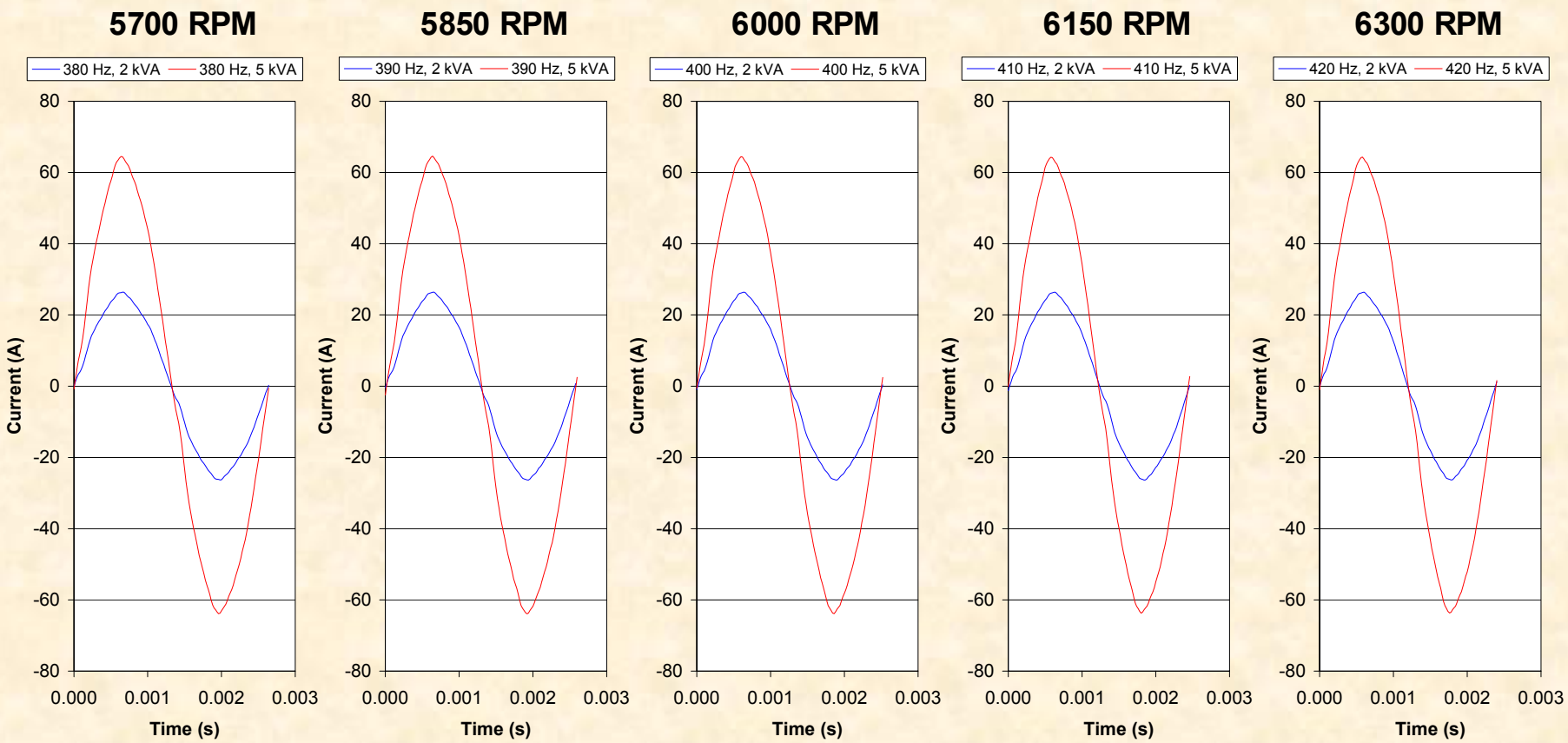


Speed (RPM)	Speed (Hz)	Output Frequency * (Hz)
5700	95	380
6300	105	420

* Output frequency is four times the running speed

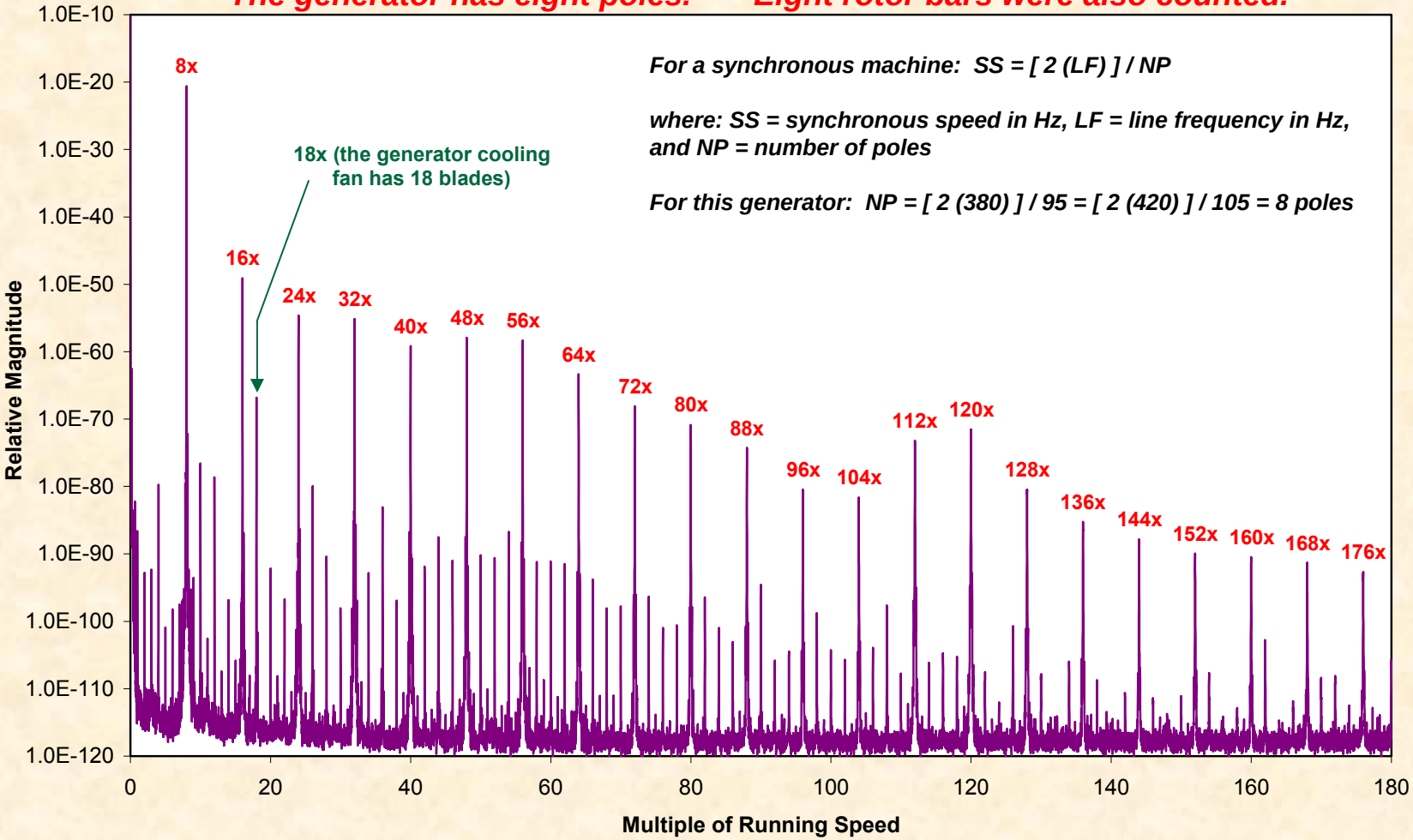
- During testing, the frequency of the generator's output voltage varied from 380 Hz to 420 Hz in 10 Hz increments. Running loads were set at 2 kVA/ph (10% of rated), 5 kVA/ph (25% of rated) and 10 kVA/ph (50% of rated).

Generator Speed And Running Load Determined The Frequency And Magnitude Of The Current Waveform

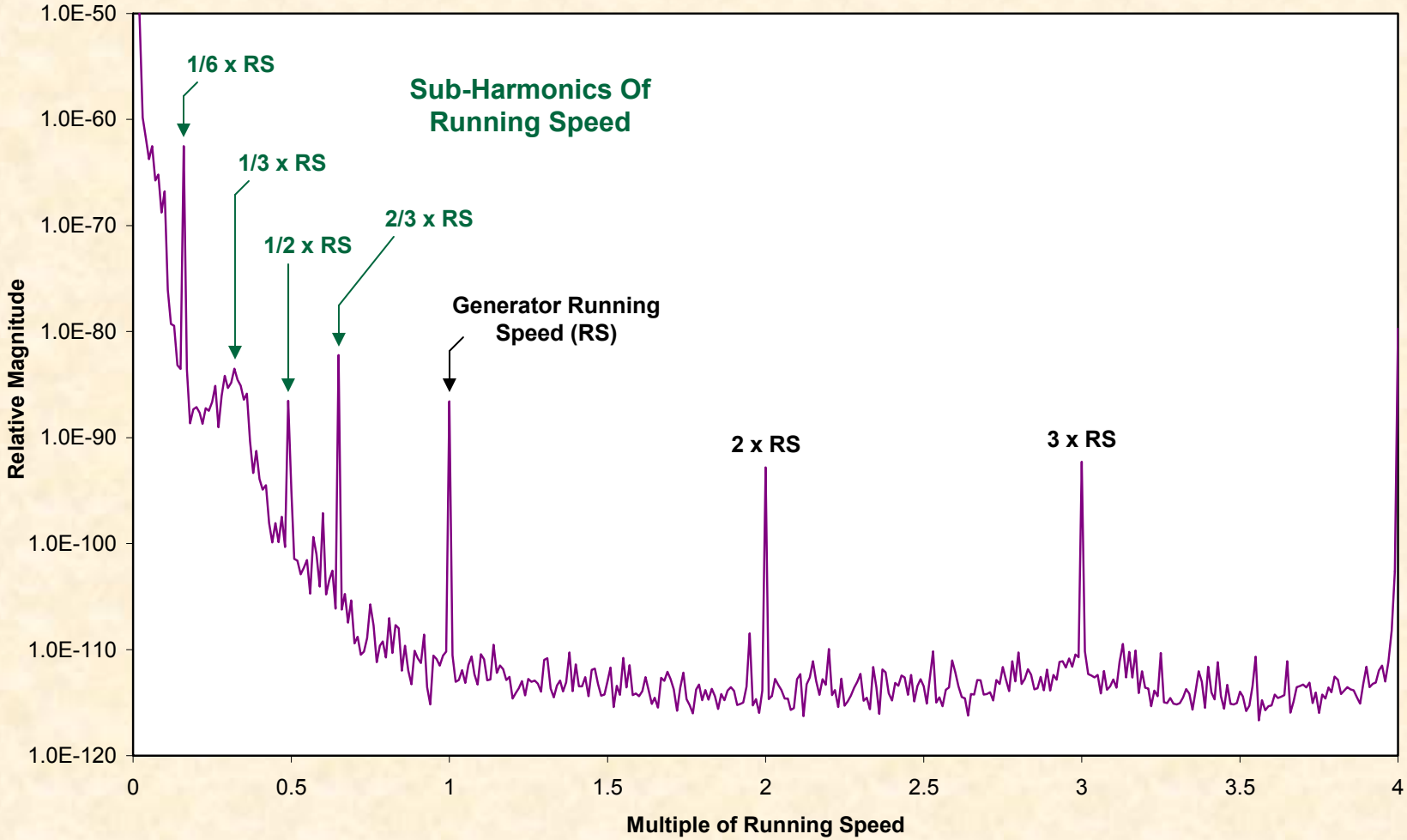


The Most Dominant Spectral Peaks Were At Multiples Of Eight Times Generator Speed

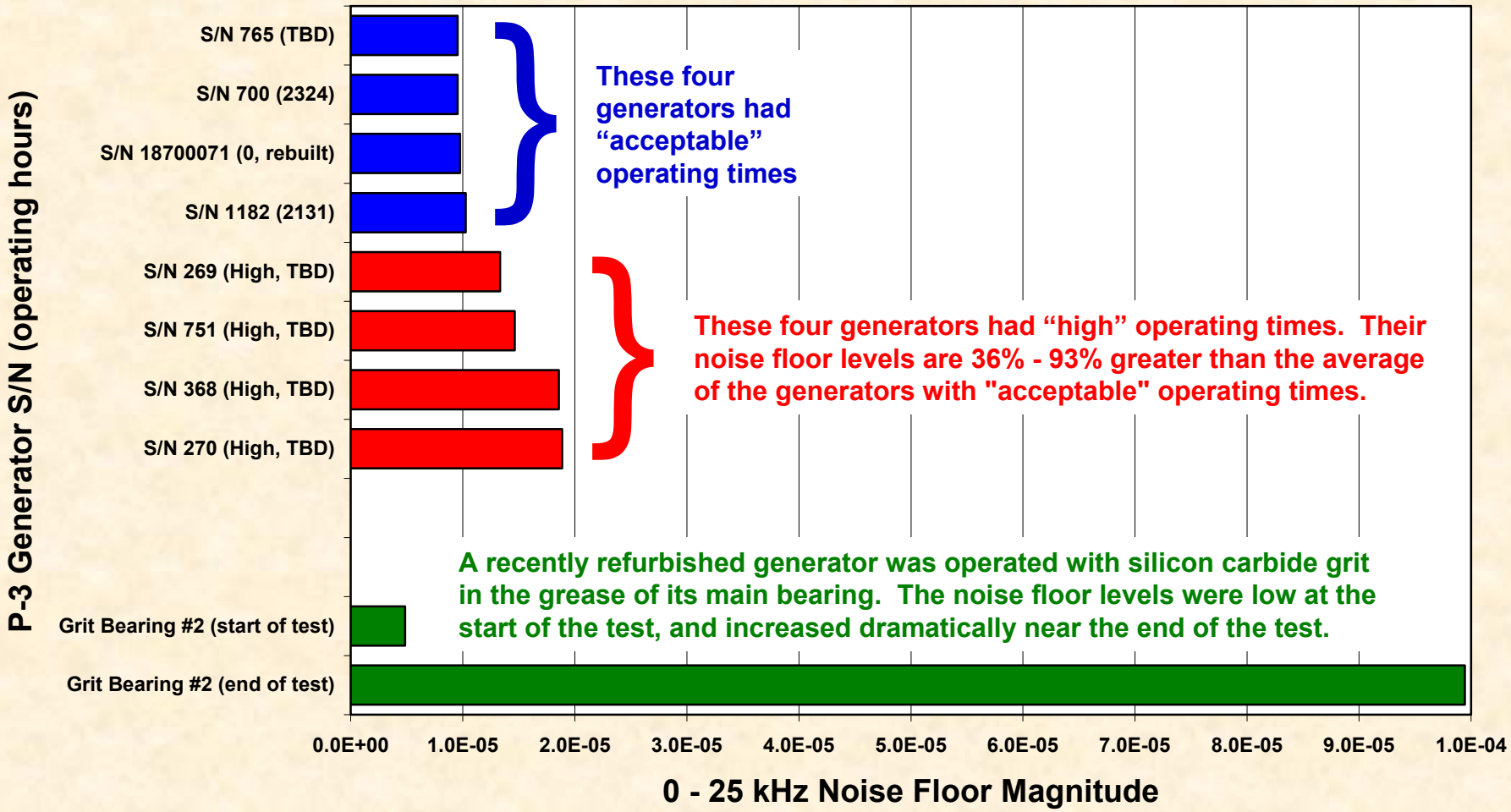
The generator has eight poles. ***Eight rotor bars were also counted.***



The Normalized Spectrum Also Revealed Several Sub-Harmonics Of Generator Running Speed



A Relationship Was Found Between The Operating Hours Of The Generator And The Magnitude Of The Output Voltage Spectral Noise Floor



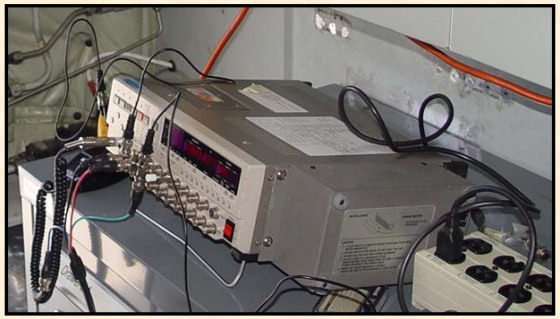
ESA Testing Was Also Performed On Several KC-135 Aircraft Components At The Tennessee Air National Guard (TN-ANG) Base In Knoxville

- **Fuel boost pumps (3).**
- **Fuel override pumps (2).**
- **Stab trim actuator, driven by the primary AC motor, and by the autopilot DC motor.**
- **Servo actuator for elevator trim tabs.**
- **Fuel shut off valves (6). Four were powered initially by the emergency batteries, and then by a ground power unit through a transformer-rectifier circuit.**

Electric Current Data Were Obtained Quickly and Efficiently

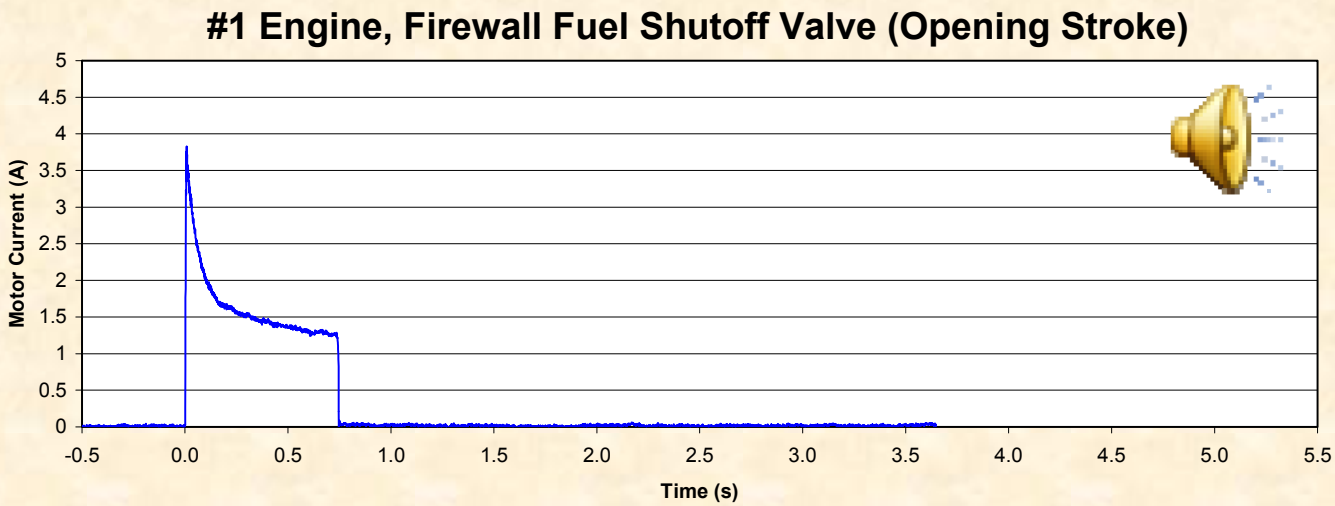
- **Clamp-on current probes were used to provide signals, which were then recorded on a digital audio tape recorder for off-site analysis.**
- **Multiple data sets were collected on all systems in less than two hours.**
- **A rough estimate of time needed for collecting data on all 12 KC-135 fuel pumps would be 30 minutes, and the aircraft would not have to be in a special configuration to do so.**

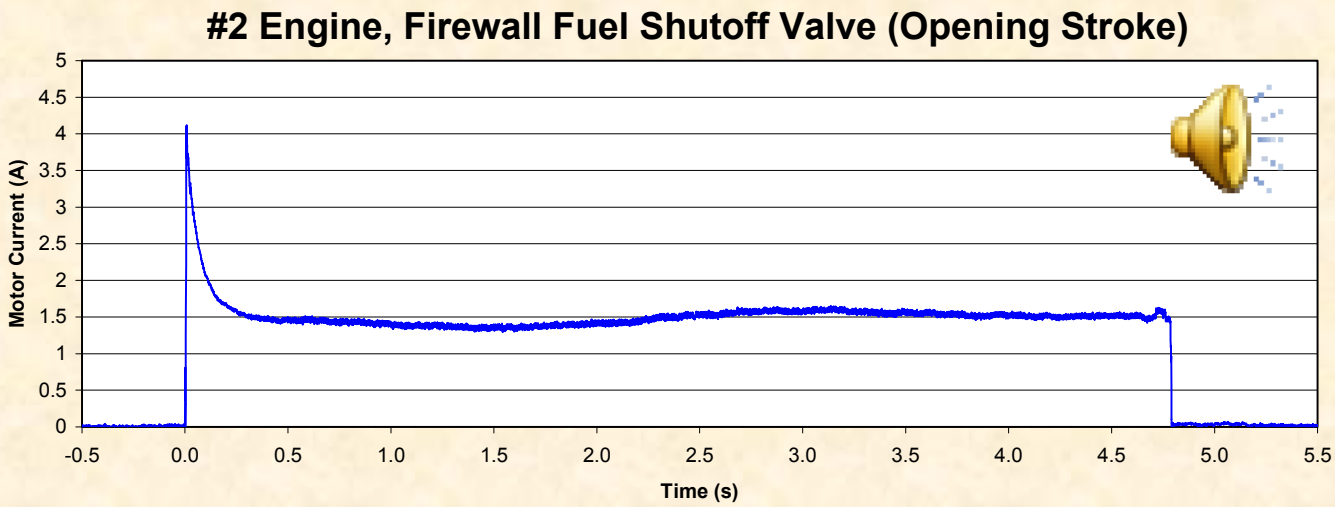
Clamp-On Current Probes



Digital Audio Tape (DAT) Recorder

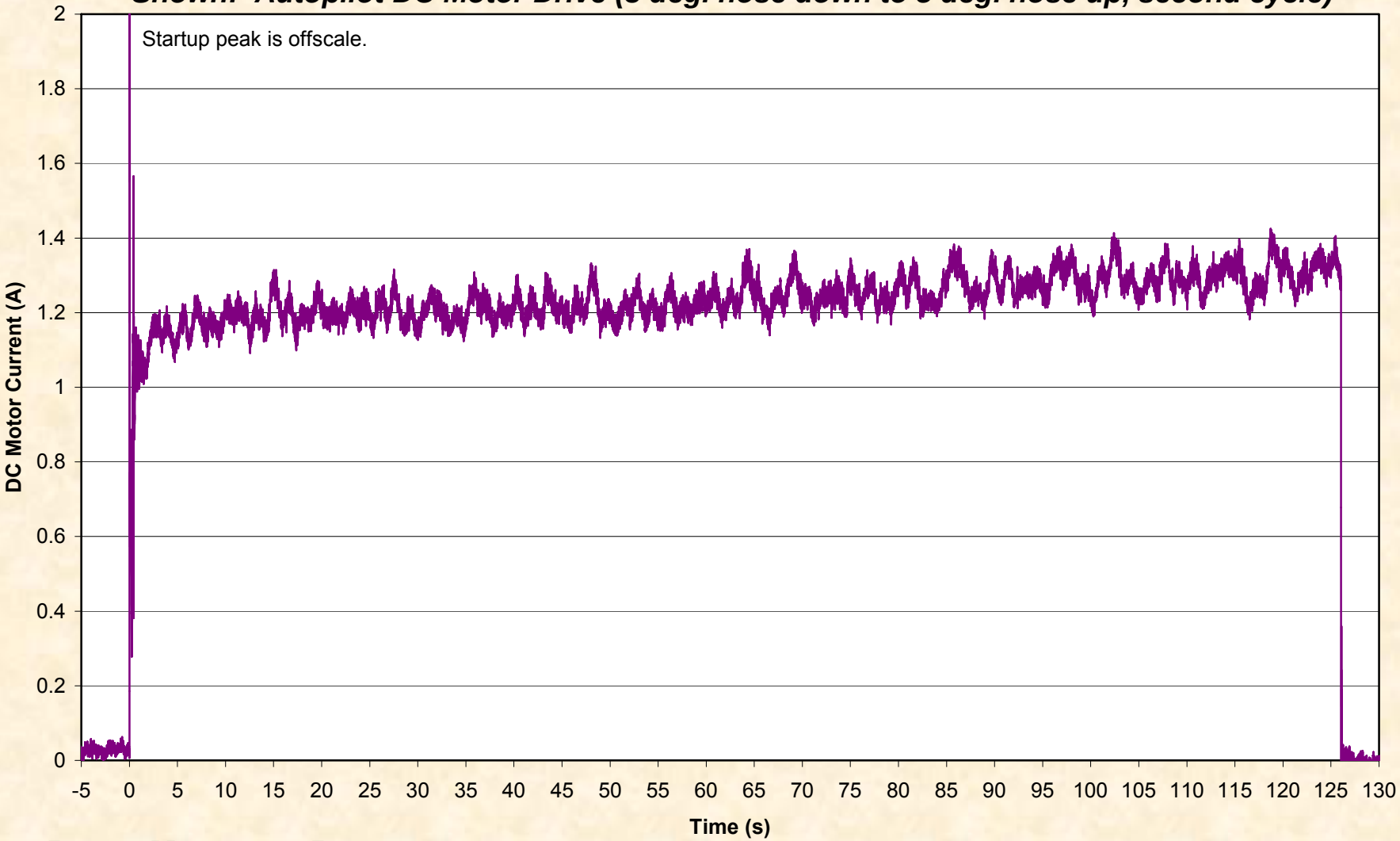
Significant Differences In Fuel Shutoff Valve Stroke Times Were Observed





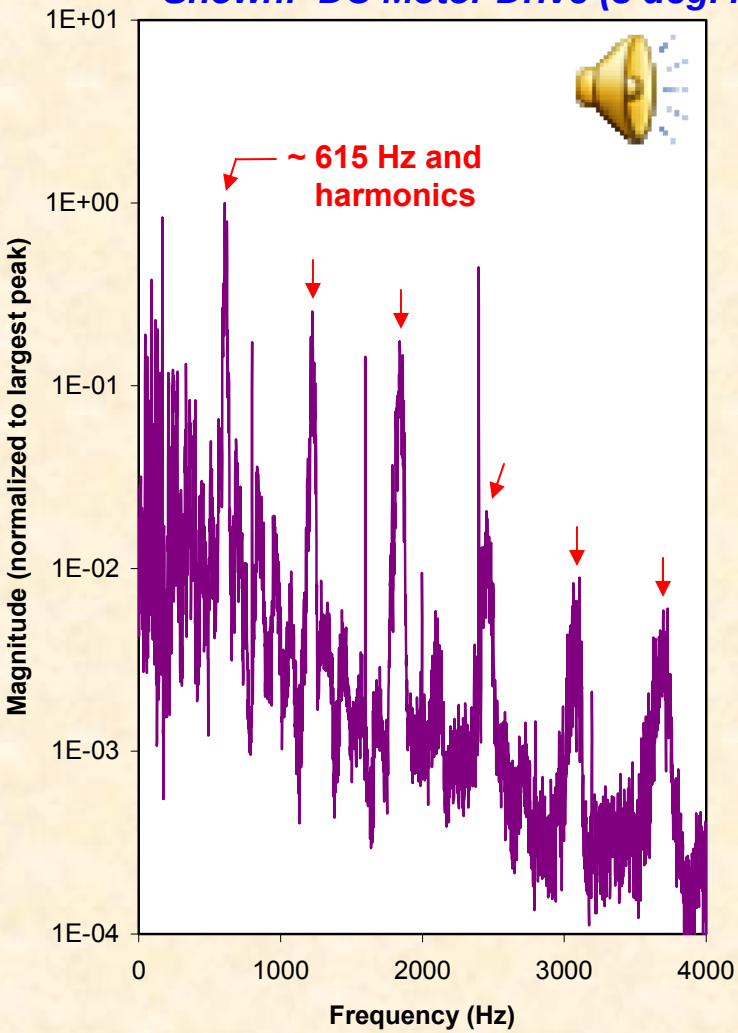
Variations Were Observed In The Stab Trim Actuator (STA) Running Current Magnitudes

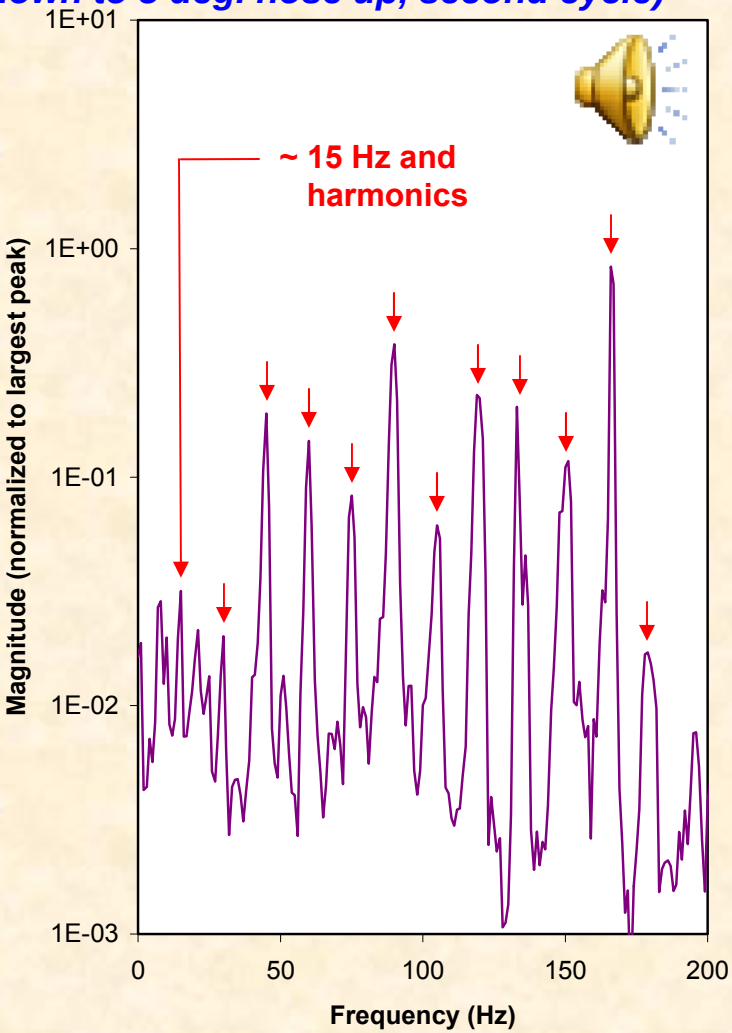
Shown: Autopilot DC Motor Drive (3 deg. nose down to 5 deg. nose up, second cycle)



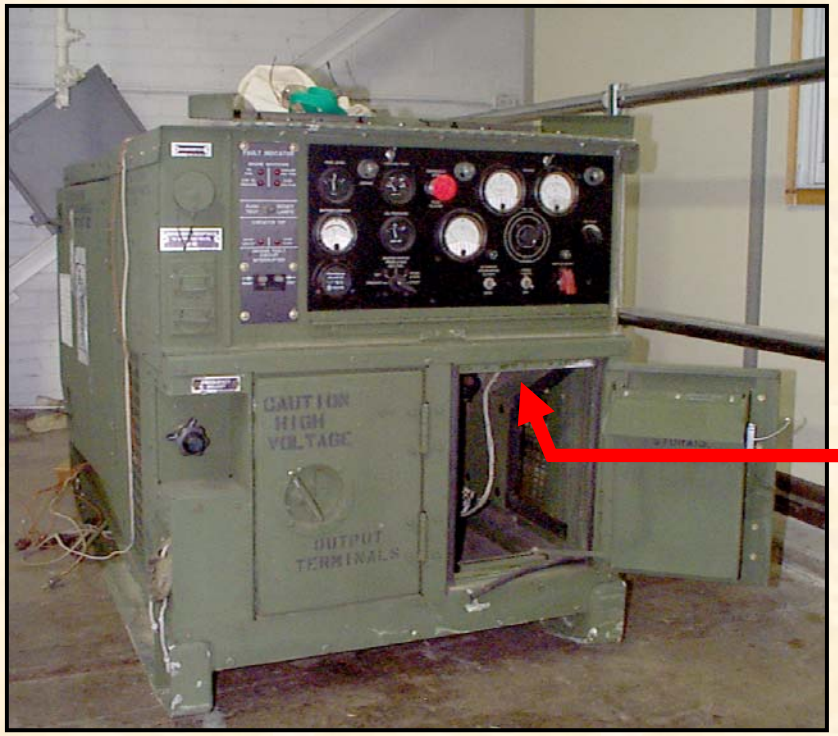
The STA DC Motor Current Spectrum Contained Many Peaks Having Potential Diagnostic Value

Shown: DC Motor Drive (3 deg. nose down to 5 deg. nose up, second cycle)

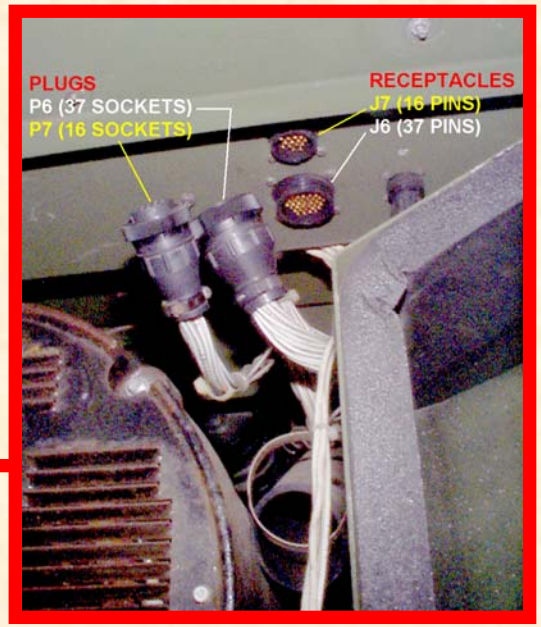




In 2000, ORNL Devised a Way To Extract Useful Diagnostic Signals From an Army 10 kW Tactical Quiet Generator (TQG)



10 kW Tactical Quiet Generator



The diagnostics cable was inserted between P6 and J6 and between P7 and J7.

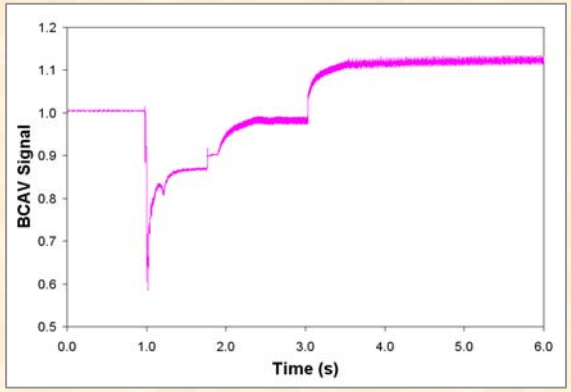
Diagnostics Cable

Based on the wiring diagrams for the TQG, a custom cable was designed and installed.

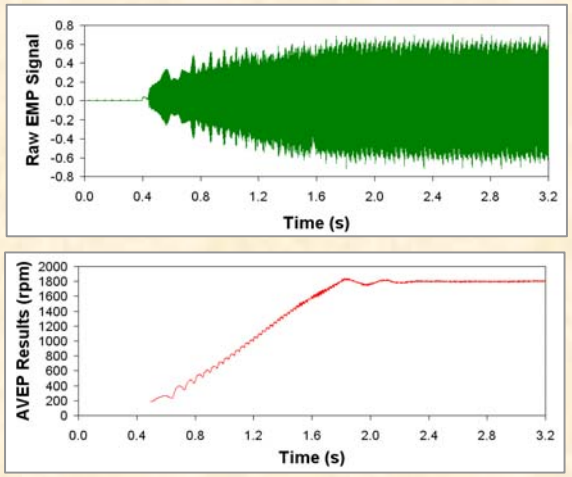
The TQG Diagnostics Cable Permitted Several Useful Parameters To Be Monitored

Monitored Parameters

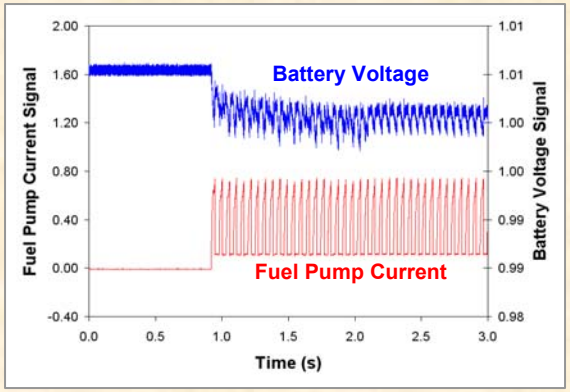
- Ph A Current
- Ph B Current
- Ph C Current
- Battery-Charging Alternator Voltage
- Battery-Charging Alternator Current
- Fuel Level Sender Output
- Coolant Temperature Sender Output
- Oil Pressure Sender Output
- Fuel Pump Current
- Auxiliary Fuel Pump Current
- Engine Speed Sensor Output
- Generator Voltage Output



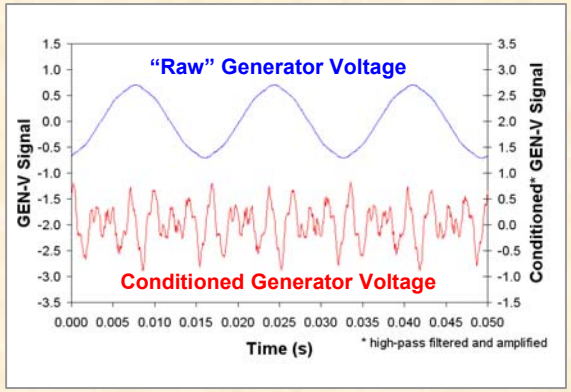
Battery-Charging Alternator Voltage



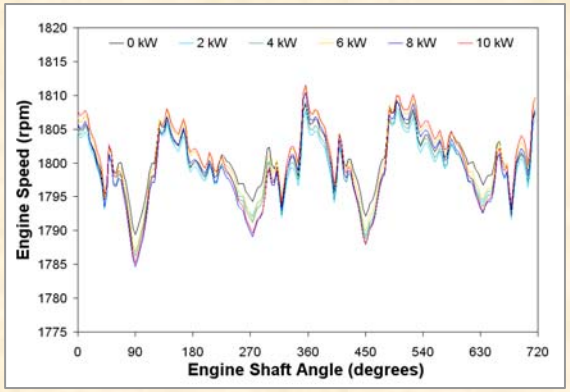
Engine Speed - Startup



Fuel Pump Current and Battery Voltage



Generator Voltage



Engine Speed - Steady State

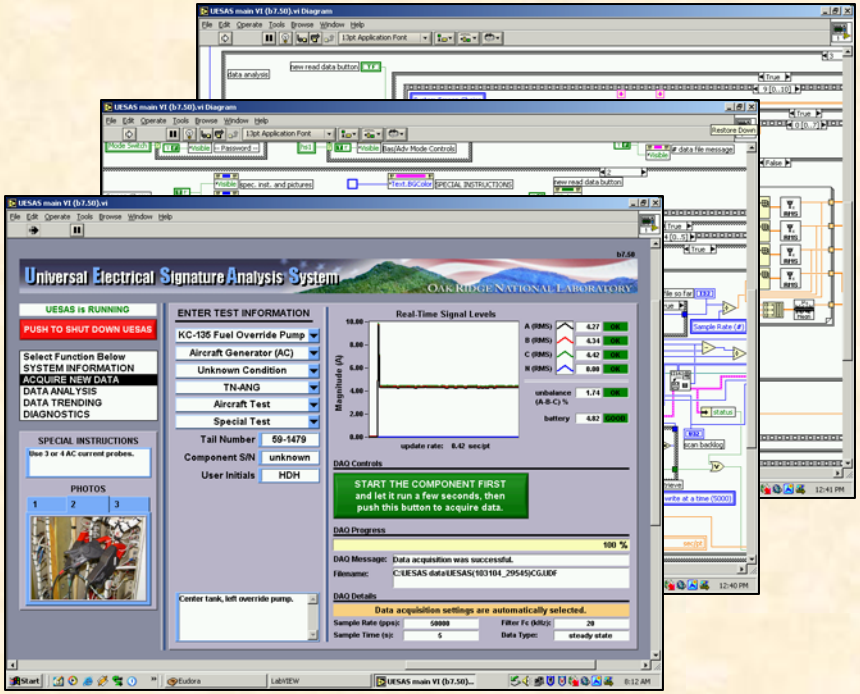
Due To The Large Variety Of ESA Applications, We Developed A Multi-Purpose, ESA-Based Diagnostic System

Universal Electrical Signature Analysis System (UESAS)
Constructed by DCS Electronics, Inc. in Maryville, TN

- **Dynamic virtual controls whose attributes change based on user input**
- **Both basic and advanced modes for different skilled users**
- **Multi-channel data acquisition and analysis**
- **Software-controlled anti-alias filters and self-diagnostic test capabilities**
- **Easily updated system instructions, including test setup menus and photos**
- **Real-time signal level and battery condition displays**
- **A novel audio conversion feature for qualitative analysis**
- **ESA time and frequency displays**
- **Automatic AC current probe calibration check and DC current probe zero bias and polarity correction**
- **A one-button automatic report generator**
- **42-page Users Manual**

Unlike The FPCM Which Was Optimized For Fuel Pump Use, The UESAS Was Designed To Monitor The Condition Of Many Electro-Mechanical Components And Systems

Signal Conditioning Electronics Are Modular And Programmable

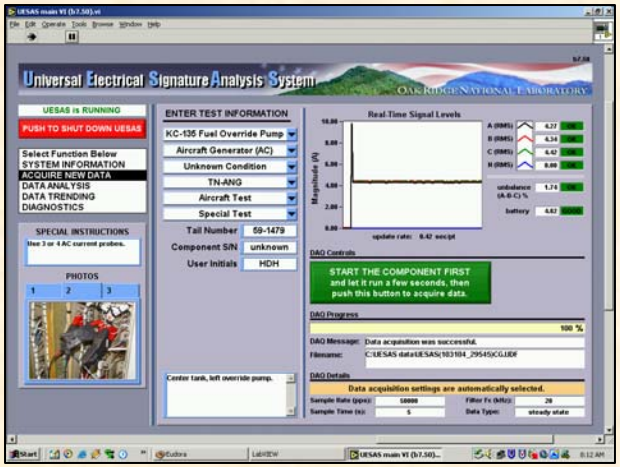


Software Has Been Developed To Allow New Components To Be Tested Without Major Software Revisions

This Example Illustrates How The UESAS Can Be Used To Acquire Test Data, Analyze The Data, And Print A Test Report

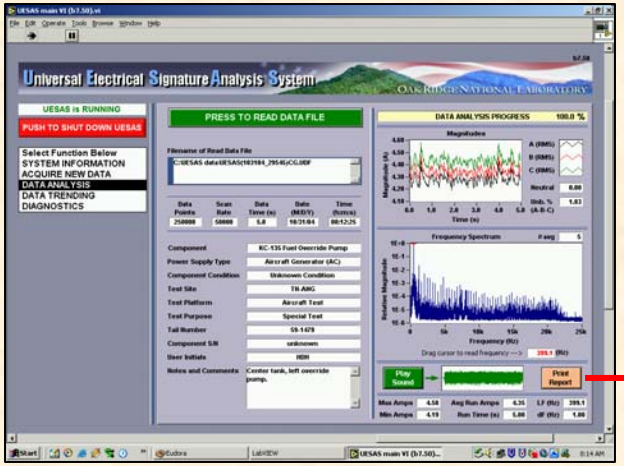
1 Acquire Data

- Data acquisition is guided by menus to ensure that all important information is recorded.
- Sample rate, sample time, and filter settings are automatically set based on the component selected.

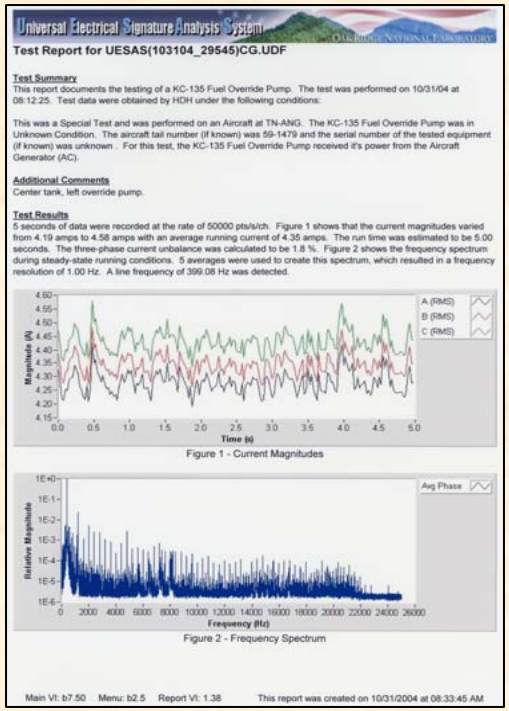


2 Analyze Data

- Data analysis can be performed immediately after data acquisition, or at a later time.
- The data obtained by the UESAS will be used by ORNL to develop software for enhanced diagnostic testing.



3 Print Test Report



The content and format of the UESAS test report can be modified by ORNL to meet the specific needs of the user.

Conclusions:

- **Electrical Signature Analysis (ESA) exploits the intrinsic abilities of electric motors and generators to act as transducers, by converting mechanical speed and load variations into electrical signal variations that can be analyzed by an assortment of methods.**
- **ESA can detect and diagnose degraded condition in a wide variety of electro-mechanical systems before any loss in performance is detected, and thus provides a powerful tool for condition-based maintenance.**
- **ESA provides non-intrusive monitoring capability that can often be performed remotely.**
- **Motor and generator electrical signatures can provide spectral content similar to an attached accelerometer, but without the requirement of equipment-mounted sensors.**

Conclusions, continued:

- **ESA is highly sensitive to a variety of disorders, such as: degraded and misaligned motors and generators, worn bearings, gears, and belts, unstable process conditions, and power system degradation.**

- **ESA can be used for many purposes:**
  - **On-line condition and performance monitoring**
  - **Catastrophic failure prevention**
  - **Improved safety, reliability, and operational readiness**
  - **Quality assurance and evaluation**
  - **Energy conservation**
  - **Condition based maintenance**
  - **Diagnostic and prognostic testing**
  - **Remaining life assessments**

- **Since the late 1980's, ESA has been used by ORNL in a wide variety of consumer, industrial, and military applications. Some of this work culminated with the development of portable ESA-based condition monitoring systems.**