Advanced Monitoring to Improve Combustion Turbine/Combined Cycle CT/(CC) Reliability, Availability and Maintainability (RAM)

Semi-Annual Report

***Reporting Period* Start Date:** April 1, 2004

***Reporting Period* End Date:** September 30, 2004

Agreement Number – DE-FC26-01NT41233

Submitted by:

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Abstract

Power generators are concerned with the maintenance costs associated with the advanced turbines that they are purchasing. Since these machines do not have fully established operation and maintenance (O&M) track records, power generators face financial risk due to uncertain future maintenance costs. This risk is of particular concern, as the electricity industry transitions to a competitive business environment in which unexpected O&M costs cannot be passed through to consumers.

These concerns have accelerated the need for intelligent software-based diagnostic systems that can monitor the health of a combustion turbine in real time and provide valuable information on the machine's performance to its owner/operators. EPRI, Impact Technologies, Boyce Engineering, and Progress Energy have teamed to develop a suite of intelligent software tools integrated with a diagnostic monitoring platform that will, in real time, interpret data to assess the "total health" of combustion turbines. The Combustion Turbine Health Management System (CTHM) will consist of a series of dynamic link library (DLL) programs residing on a diagnostic monitoring platform that accepts turbine health data from existing monitoring instrumentation.

The CTHM system will be a significant improvement over currently available techniques for turbine monitoring and diagnostics. CTHM will interpret sensor and instrument outputs, correlate them to a machine's condition, provide interpretative analyses, project servicing intervals, and estimate remaining component life. In addition, it will enable real-time anomaly detection and diagnostics of performance and mechanical faults, enabling power producers to more accurately predict critical component remaining useful life and turbine degradation.

Executive Summary

Introduction

Power producers are justifiably concerned with the maintenance costs associated with the advanced combustion turbines (CTs) they are purchasing today. While more efficient and environmentally clean than previous models, some advanced CT models do not have fully established operation and maintenance (O&M) track records. And without accurate information upon which to base maintenance decisions, optimizing system life while minimizing costs can be extremely difficult for operators. As a result, power producers face financial risk due to uncertain future maintenance costs and turbine life. This risk is of particular concern in today's increasingly competitive business environment in which reserve margins are shrinking and unexpected O&M costs usually cannot be passed through to consumers.

These concerns have accelerated the need for intelligent software-based diagnostic systems that can monitor the health of a CT in real time and provide owners and operators with valuable information on machine performance. While commercial systems—ranging from time-history database/display systems to model-specific operation/performance monitoring systems—are available, they have limited diagnostic capability and their results typically require expert interpretation. To date, neither CT manufacturers nor owners have developed a comprehensive diagnostic monitoring system, primarily because of the cost and the need for historical data from many units operating over the entire commercial operating spectrum.

To meet this need, the Department of Energy selected EPRI to lead the development of a comprehensive suite of intelligent diagnostic tools for assessing the total health of CTs. The resulting Combustion Turbine Health Management (CTHM) system will improve the RAM of CTs in simple-cycle and combined-cycle configurations.

The CTHM system will be a significant improvement over currently available techniques for turbine monitoring and diagnostics. CTHM will interpret sensor and instrument outputs, correlate them to a machine's condition, provide interpretative analyses, project servicing intervals, and estimate remaining component life. In addition, it will enable real-time anomaly detection and diagnostics of performance and mechanical faults, enabling power producers to more accurately predict critical component remaining useful life and turbine degradation.

Project Objective

The objective of the proposed project is to develop new monitoring techniques for CT power generation in simple or combined-cycle configurations aimed at improving reliability, availability and maintainability (RAM) and overall performance/capacity factor. The project team will develop advanced, probabilistic and artificially intelligent performance and mechanical fault diagnostics algorithms, sensor validation and recovery modules, as well as prognostics for maintenance-intensive CT areas. The objective stated above will be achieved via the following tasks:

Task 1: Sensor validation, recovery virtual sensor module
Task 2: CT/CC performance diagnosis and prognostics
Task 3: CT/CC combustion process diagnostics.
Task 4: CT/CC stall detection and surge margin risk assessment
Task 5: CT/CC mechanical anomaly detection and fault pattern diagnostics
Task 6: CT/CC life limiting component prognostics
Task 7: CT/CC database management and health management integration
Task 8: Field validation
Task 9: Project management and reporting

Conferences and Publications

- The development work on the suite of DOE/EPRI CT diagnostics modules was presented at the EPRI Advanced Condition Assessment Technology for Power Plants Symposium, June 2-4 2004, in San Diego, CA.
- Papers on the Sensor Validation (ASME Paper GT2004-54079) and Performance Degradation and Fault Diagnostics (ASME Paper GT2004-54123) modules were presented at the ASME TURBO EXPO 2004 in Vienna, Austria, June 14-17, 2004.
- A draft revision to the Remaining Life Module topical report was completed on July 21, 2004. The revision included information on how the Remaining Life Module (RLM) could be integrated with the Combustion Turbine Performance and Fault Diagnostic Module (CTPFDM). Without the CTPFDM integration, some of the RLM inputs (e.g. firing temperature) would need to be calculated by another source.

Status

Activities during the current period of performance focused on the development and completion of the following three software modules:

- Remaining Life Module (RLM).
- Start-up/Combustion Process Diagnostics Module (SUDM).
- Vibration Fault Diagnostics Module (VFDM).

An update (Version 1.1) to the Remaining Life Module was released in April. The update included EPRI's Hot Section Life Management Platform (HSLMP) algorithms for the first stage rotating blades of a GE 7FA+ (MS7231) combustion turbine. Subsequent in-house testing revealed that some of the inputs for the EPRI HSLMP calculations were not being set properly by the RLM macros. These mistakes were corrected in Version 1.1. Also, Version 1.1 added 4 Excel trend charts that are automatically generated from the RLM results. The RLM User Guide, which was issued at the end of March 2004, was updated to reflect the changes in Version 1.1. Also, a draft EPRI technical report that describes the development and functionality of the Remaining Life Module was completed at the end of April.

As work began on the functional specifications for the final two deliverables of the project, the combustion diagnostics and rotor dynamic anomaly modules, it was discovered that combustion dynamics and vibration spectra data would need to be available on the host site's PI data historian. This created a need for the host site to add signal-conditioning equipment to their PI data system, and EPRI requested that the DOE grant a no-cost, 90-day contract extension to allow time to complete the final two software deliverables. This contract extension revised the due dates for the combustion diagnostics and rotor dynamic anomaly modules to September 2004 and December 2004, respectively.

During the review cycle of the SUDM, it was decided to move forward with the development of a Microsoft Visual Basic application that would use the database functionality of Microsoft Access. However, it was later learned that the graphing capabilities in Access were not as sophisticated as those in Microsoft Excel, and consequently it was agreed to use Excel's charting capabilities to display the overlay charts that compared various runs. An alpha version of SUDM and a draft of the associated topical report were completed at the end of July. The beta version of SUDM was submitted to Progress Energy for beta testing and to the DOE for record in September 2004.

Several conference calls were held to review the various iterations of the Vibration Fault Diagnostics Module functional specification. Much of the comments revolved around the type and quantity of inputs that would be needed to perform an assessment, the desired analysis features, and the hardware and software that would be required to accommodate the capabilities of the module. Final agreement was reached on the functional specification at the end of August, and the VFDM hardware and software were ordered in early September. This new equipment will need to be installed and operational by the end of September so data collection can begin to support the module's deliverable date.

Approach

Introduction

Power generators are concerned with the maintenance costs associated with the advanced turbines that they are purchasing. Since these machines do not have fully established operation and maintenance (O&M) track records, power generators face financial risk due to uncertain future maintenance costs. This risk is of particular concern, as the electricity industry transitions to a competitive business environment in which unexpected O&M costs cannot be passed through to consumers.

These concerns have accelerated the need for intelligent software-based diagnostic systems that can monitor the health of a combustion turbine in real time and provide valuable information on the machine's performance to its owner/operators. Such systems would interpret sensor and instrument outputs, correlate them to the machine's condition, provide interpretative analyses, forward projections of servicing intervals, estimate remaining component life, and identify faults.

EPRI, Impact Technologies, Boyce Engineering, and Progress Energy have teamed to develop a suite of intelligent software tools integrated with a diagnostic monitoring platform that will, in real time, interpret data to assess the "total health" of combustion turbines. The Combustion Turbine Health Management System (CTHM) will consist of a series of dynamic link library (DLL) programs residing on a diagnostic monitoring platform that accepts turbine health data from existing monitoring instrumentation.

The CTHM system will be a significant improvement over currently available techniques for turbine monitoring and diagnostics. CTHM will interpret sensor and instrument outputs, correlate them to a machine's condition, provide interpretative analyses, project servicing intervals, and estimate remaining component life. In addition, it will enable real-time anomaly detection and diagnostics of performance and mechanical faults, enabling power producers to more accurately predict critical component remaining useful life and turbine degradation.

Program Goals, Research Objectives and Project Objectives

The goal of this proposed project is to improve the reliability, availability and maintainability (RAM) and overall performance/capacity factor of combustion turbines by developing advanced health monitoring and management techniques. The objective is to develop a suite of intelligent software tools integrated with a diagnostic monitoring platform that will, in real time, interpret data to assess the "total health" of combustion turbines.

Methodology

The project team will apply and adapt know-how developed under prior DOD/Navy/NASA programs aimed at advanced health monitoring of aviation gas turbines. The project team will develop advanced probabilistic and artificially intelligent performance and mechanical fault diagnostics algorithms, sensory validation and recovery modules, and prognostics for maintenance-intensive CT areas.

Description of the Technology

The Combustion Turbine Health Management System (CTHM) will consist of a series of dynamic link library (DLL) programs residing on a diagnostic monitoring platform that accepts turbine health data from existing monitoring instrumentation. The real-time CTHM application algorithms proposed are intended to produce a comprehensive array of intelligent tools for assessing the "total health" of a combustion turbine, both mechanically and thermodynamically. CTHM includes the integration of real-time anomaly detection and diagnostics of performance and mechanical faults in addition to the prediction of critical component remaining useful life and turbine degradation.

Advanced signal processing algorithms utilizing correlation and coherence detection are combined with artificial intelligence and model-based algorithms to provide comprehensive coverage of the critical CT failure modes of interest. Prognostic algorithms have also been developed that accept diagnostic system results, model-based remaining useful life predictions, operating/maintenance histories and historical RAM data to provide real-time predictions on reliability and degraded performance of key CT components. Through proper utilization of these health management technologies, timely decisions can be made regarding unit operation and maintenance practices.

The neural network algorithm operates by comparing the physical relationships between signals as determined from either a baseline empirical model or computer model of the turbine's performance parameters. The fuzzy logic based sensor validation continuously checks the "normal" bands (membership functions) associated with each sensor signal at the current operating condition. When a signal goes outside these membership functions, while others remain within, an anomaly is detected associated with those specific sensors. Finally, signal correlation and special digital filters are used to determine if even small levels of noise are present on a particular signal. These approaches are implemented in parallel and then combined in a probabilistic data fusion process that determines the final confidence levels that a particular sensor has either failed or has suspect operation.

The integration of prognostic technologies within existing diagnostic systems begins with validated sensor information on the engine being fed directly into the diagnostic algorithms for fault detection/isolation and classification. The ability of an enhanced diagnostic system to fuse information from multiple diagnostic sources together to provide a more confident diagnosis is emphasized along with a system's ability to estimate confidence and severity levels associated with a particular diagnosis. In a parallel mode, the validated sensor data and real-time current/past diagnostic information is utilized by the prognostic modules to predict future time-to-failure, failure rates and/or degraded engine condition (i.e., vibration alarm limits, performance margins, etc.). The prognostic modules will utilize physics-based, stochastic models taking into account randomness in operation profiles, extreme operating events and component forcing. In addition, the diagnostic results will be combined with past history information to train real-time algorithms (such as neural networks or real-time probabilistic models) to continuously update the projections on remaining life.

Once predictions of time-to-failure or degraded condition are determined with associated confidence bounds, the prognostic failure distribution projections can be used in a risk-based analysis to optimize the time for performing specific maintenance tasks. A process that examines the expected value between performing maintenance on an engine or component at the next opportunity (therefore reducing risk but at a cost of doing the maintenance) versus delaying maintenance action (potential continued increased risk but delaying maintenance cost) can be used for this purpose.

The difference in risk between the two maintenance or operating scenarios and associated consequential and fixed costs can then be used to optimize the maintenance intervals or alter operational plans. As key aspect of the proposed technical approach, this project will tap a unique resource of engine fault data developed under the Navy and Air Force with its resulting diagnostic knowledge base. This test cell engine fault data is unavailable for heavy frame machines and will require many machine-operating years to duplicate. The project substantially reduces its development costs and subsequent field validation by using experts and limited land-based CT data to modify the existing flight engine diagnostic database.

Anticipated Benefits

There is a great opportunity for power generation combustion turbines to become more reliable, operationally available and economically maintained through the use of enhanced diagnostic and prognostic strategies such as those presented in this proposal. The development and integration of enhanced diagnostic and prognostic algorithms that can predict, within a specified confidence bound, time-to-failure of critical engine components can provide many benefits including:

- Reduced overall life cycle costs of engines from installation to retirement
- Ability to optimize maintenance intervals for specific engines or fleets of engines and prioritization of tasks to be performed during the planned maintenance events
- Increased up-time/availability of all engines within a fleet
- Provides engineering justification for scheduling maintenance actions with corresponding economic benefits clearly identifiable
- Improved safety associated with operating and maintaining combustion turbine engines

The maintenance outage factors for the F/FA frame and the mature frame technology are significantly divergent, with CT core systems being the primary drivers with outage factors of 10.074% and 5.080%, respectively. The core combustion turbine system problems can be attributed to new-design introduction centered on inherent design flaws, manufacturing/assembly problems, and the combustion system. These design break-in issues will eventually be supplanted by service-imposed mechanical/electrical degradation and outage assembly problems. Diagnostic monitoring as an integral component of a proactive maintenance program should certainly meet mature fleet RAM performance. By avoidance of serious damage and improved maintenance scheduling, 2% availability points are achievable.

For each 500 MW combined cycle, this improvement represents 72,000 MWhr valued at $3M per year. For a 100 unit combined cycle fleet, or approximately half of the 30 GW new generation projected, a $300M per year cost-avoidance savings appears achievable.

DOE has long played an essential role in bringing high performance CTs with its enabling metallurgy into the U.S. generation mix. The higher performance and fuel savings certainly offset the higher maintenance costs when compared to conventional CTs. Yet concerns exist about the overall RAM capability of the fleet in light of shrinking reserve margins and higher gas prices. With DOE and EPRI, important maintenance engineering and management tools can be delivered on a timely basis that would otherwise take an additional 5 years to deliver.

These tools would be made available to all CT operators regardless of their EPRI membership status and direct contributions. Since all operators routinely calculate life consumption and perform hot section NDE, the introduction of new and improved validated methods will readily find acceptance with plant engineers and maintenance planners. Training courses and software maintenance fees would further support the expanded application and periodic necessary updating.

Discussion

The prior semi-annual report reviewed the completion of the Combustion Turbine Performance Degradation Module, the Combined Cycle Performance Degradation Module, and the Remaining Life Module.

During this report period, an update to the Remaining Life Module was completed in April 2004 in preparation for additional on-site beta testing at Progress Energy's Asheville CT location. Also, the Start-up/Combustion Diagnostics Module was delivered on August 30, 2004 to Progress Energy for on-site beta testing.

The final focus of effort during this period of development has centered on the development of the Vibration Fault Diagnostics Module.

Start-up/Combustion Process Diagnostics Module

The SUDM is a low-cost, easy-to-use software tool that operators can use to diagnosis problems that arise during the start-up phase of a Combustion Turbine (CT). The SUDM should be particularly useful for CTs in peaking or cycling service that start and stop frequently and are relied upon to provide power on short notice. Reliable starting is an important characteristic for CTs in peaking service, and therefore a tool that can help operators detect starting problems before they impact reliability should provide significant value. The SUDM facilitates the diagnosis of problems by comparing the start-up trends versus time from one start to another. By comparing the trends of a CT that may have equipment health issues to the trends from a start when the machine was known to be in good condition, it is possible to identify potential problems.

Background

The SUDM is a computer program that facilitates the comparison of trends from one CT start to another. Start trends such as those shown in Figure 1 can be compared to trends from a different start-up on the same CT or from a start-up on a different CT. Trends can be plotted against time or against other important turbine parameters such as rotor speed or fuel flow.

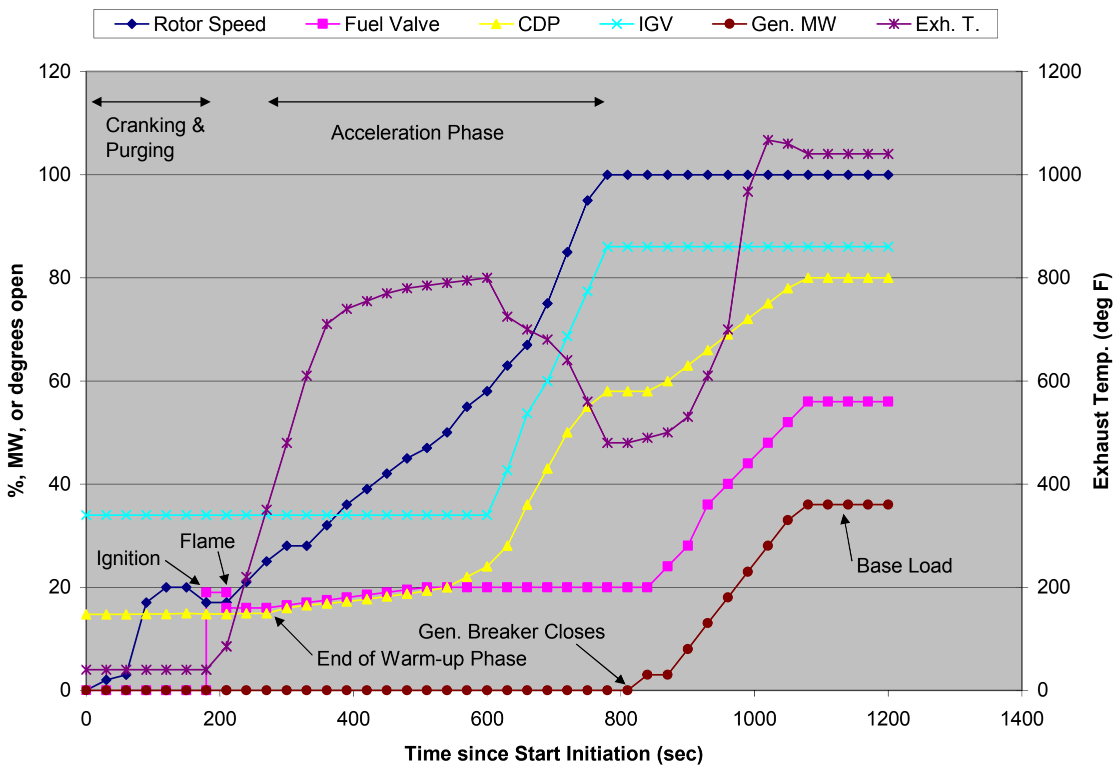

Figure 1 – A representative time history trend chart for a CT start-up.

The SUDM can maintain a database of trends of key parameters collected during the various start-ups of a CT. A user can then compare the trends of the most recent start-up or start-ups to a baseline trend that was obtained when the CT started successfully. A user has the ability to define different baselines for different types of operation (e.g., fast starts and normal starts, natural gas starts and distillate starts, cold weather starts and warm weather starts, cold CT starts and warm CT starts, etc.).

The SUDM works "look back" mode after a start-up is completed rather than in "real time" during a start-up. The reason for this is that most start-up sequences are completely automated leaving very few actions for the operator to take which can influence the success of a start. In addition, many of the sequences during a start-up take place so quickly that there would be no time to react.

Program Design

SUDM operates in Windows 2000 and Windows XP using Microsoft Office 2000 or 2002 applications. SUDM, with two exceptions, is "self-contained" software meaning no other software programs will need to be installed on the user's PC in order to use SUDM. The two exceptions are the PC will also have to have:

- Excel 2000 or 2002
- OSI's PI Datalink 2.0

PI Datalink is an Excel add-in for accessing data from a PI database. It is assumed that the PI database server will be installed on a separate computer.

SUDM has been developed using Microsoft's Access 2003 with royalty-free runtime license provided with Microsoft Visual Tools for Office 2003.

Program Overview

SUDM has five basic functions:

- Start-up data retrieval via PI DataLink to an Excel spreadsheet
- Start-up data import from an Excel spreadsheet into a Microsoft Access Database file
- Plotting trend charts for a single start-up
- Creating "overlay" trends charts for comparing trends from two start-ups
- Database administration functions (e.g., deleting starts, renaming starts, etc.)

Vision

By comparing trends from recent start-ups against trends from a start when a CT was known to be in good condition, it is possible to detect and diagnose problems before they impact starting reliability.

In many deregulated markets there is an added financial incentive for maintaining high starting reliability. If a CT owner makes a bid to deliver power at a certain time and at a certain price and that CT fails to start at the appointed time, the CT owner must purchase the amount of power it agreed to provide from the spot market. If the spot price is higher than the CT owner's bid price, the difference must be absorbed by the CT owner. Concerns about getting "caught with their plants down" have actually caused some CT owners in marginal power markets to decline to bid into the market even when it would appear to be attractive to do so.

EPRI's SUDM is meant to be a simple tool that can assist CT engineers in diagnosing start-up related problems. The simple premise is that a CT engineer can identify at least one "good start" which can serve as the "gold standard" by which all other starts are judged. In this report such as start is referred to as a "reference start".

To facilitate a comparison between starts, SUDM allows the user to "overlay" the trend lines of the start of interest (the "analyzed start") on top of the trend lines of the reference start. In many cases the trend lines will use time as the x-axis, but there are situations in which other parameters such as rotor rpm such will provide additional insight. For example, vibrations are typically a function of rotor speed. Consequently, when comparing the vibrations from an analyzed start to the vibrations of the reference start, it would make sense to base the overlay plot on rotor rpm. That way the user can compare the vibration levels at the same rpm levels.

Problems to Look For During Start-ups
A typical gas turbine starting sequence can be grouped into the following phases:

- Cranking & Purge
- Ignition
- Warm-Up
- Acceleration
- Synchronization

The starting sequence begins with the Cranking & Purge phase. During this phase the turbine rotor is turned entirely by a starter motor of some type - usually an electric or diesel motor. Once the rotor reaches a pre-determined speed (well below the rated speed of the engine) a purge timer begins. The purpose of the purge time is to ensure that sufficient volumes of fresh air have passed through the turbine and its exhaust system in order to lower the concentration of any combustible gases to well below their lower flammability limits. This will prevent an explosion in the exhaust system when the CT lights off.

Once the purge timer has expired, the starting sequence enters the Ignition phase. In this phase the CT control system adjusts the fuel control valve to a pre-determined percent open position, while the fuel stop valve remains closed. The control sequencer then energizes the spark plug or igniter in the combustion section of the CT and opens the fuel stop valve to allow fuel to begin flowing to the combustion section. The sequencer as starts an ignition timer. The flame eyes within the combustion section must report back with a positive flame signal before the ignition timer expires or the start will be tripped (i.e., fuel stop valve closed, igniter de-energized, trip purge sequence started).

If the flame eyes do report back a positive signal before the ignition timer expires, then it the starting sequence enters the warm-up phase. The purpose of the warm-up phase is to minimize the thermal shock of a start on the hot section of a gas turbine and the downstream equipment. Typically the warm-up phase will last on the order of 60 seconds. Because heat is being released in the combustor, the CT is exerting some work on the rotor and the rotor will speed up. To limit the rate of acceleration during the warm-up stage, the fuel control valve will actually close off some compared to its value during ignition. In Figure 1 the change in fuel control valve position is seen as a step function at the end of the Ignition phase.

Once the warm-up timer has expired, the starting sequence enters the Acceleration phase. During this phase the turbine rotor speeds up until it approaches the rated speed of the engine. Fuel flow is increased with a ramping function. The rate of acceleration is monitored and the fuel ramp can be temporarily halted if the acceleration rate reaches the OEM's limit. As seen in Figure 1, the exhaust temperature increases rapidly during this phase and then falls as air flow through the turbine increases. The starter motor also disengages during the Acceleration phase when the rotor speed reaches a pre-set level.

Once the rotor speed reaches is rated 100% value, the starting sequence enters the Synchronization phase. During the phase the control system adjusts the turbine speed and generator exciter current to match the frequency, phase, and voltage of the grid. Once all three parameters are synchronized, the generator breaker closes and the generator is connected to the grid. At that point the CT is operating at its "full speed, no load" (FSNL) condition. This is usually defined as the end of the starting sequence; however, the CT then has to be ramped up to the load level that is desired

Potential problems can appear in each phase, and the SUDM reference start overlay technique can be used to identify those problems. Some examples are provided in this sub-section.

Slow to Reach Purge Speed
As a starter motor degrades, the time it takes for the rotor to come up to purge speed will increase. If the overlay chart of rotor speed versus time shows a slower rate of increase for the analyzed start compared to the reference start, this could be an indication of problems with the starter motor. For example, in Figure 2, "Start3" took 90 seconds longer to reach the purge speed when compared to the other two starts examined. This could be a sign that the starter motor on this turbine has degraded and needs maintenance.

However, it could also be an indication of increased friction within the CT itself. If a CT is slow to reach its purge speed, the user should also examine an overlay chart of vibrations versus rotor speed over the range from 0 rpm to the purge speed. If the vibrations from the analyzed start are significantly higher, this is an indication that the fault lies within the CT and not with the starter motor.

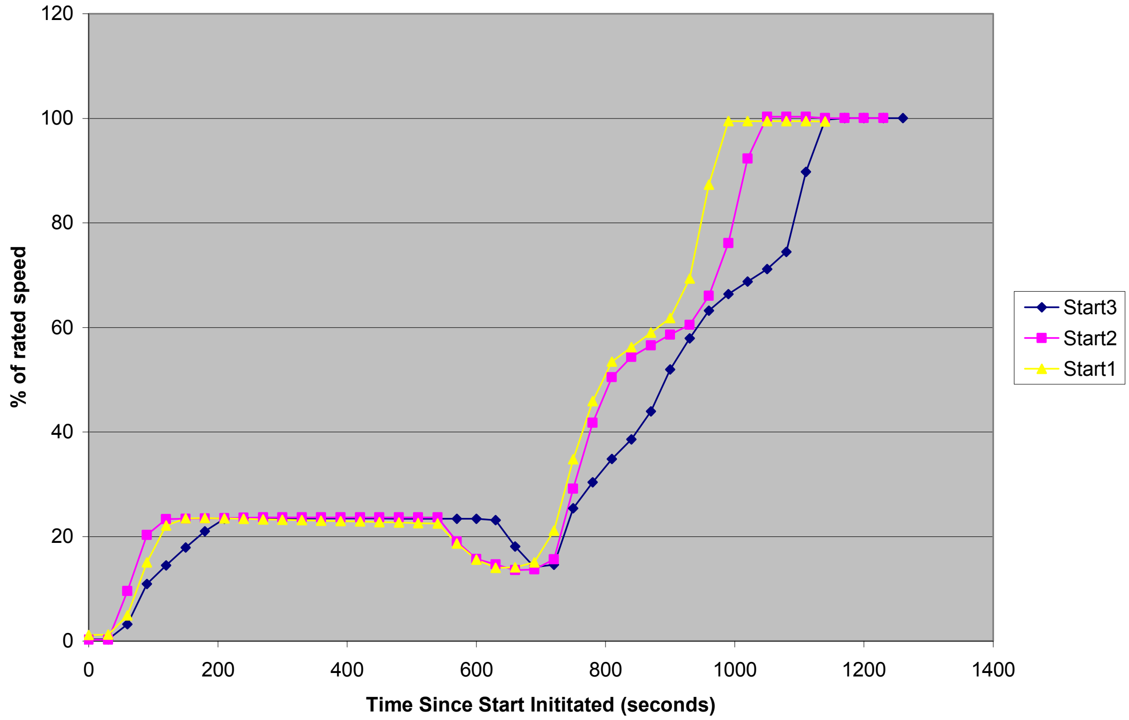

Figure 2 – Overlay trend chart showing rotor speed versus time for three starts on the same machine.

Failure to Light-off
At least two possible scenarios could lead to a tripped start caused by a failure to light-off during the Ignition phase. The first scenario is a failure of the flame eye to detect an actual flame. The second scenario is an actual failure to light-off.

The difference between the two scenarios can easily be determined by examining an overlay chart of the trends of the fuel valve position (FSR) and exhaust gas temperature (EGT) versus time. If EGT ramps up as quickly in the analyzed start as it did in the reference start, then the problem lies in the flame detector. On the other hand, if the EGT does not ramp up at all or the ramp is delayed or slower than the reference, this is an indication of a true failure to light-off. The root cause of the problem could be the ignitor or the fuel nozzles, or the fuel supply system.

There is no need to wait until a CT has a tripped start to detect an imminent failure to light-off. Since the FSR value drops as soon as a positive flame is detected, one can use the time between the point that the FSR reaches its ignition value and the point that it is reset to the warm-up value as an indicator of the length of time to reach a positive flame signal. If this time in an analyzed start is significantly longer than the reference start (and is approaching the user should examine the EGT trends and determine whether the flame eye is slow to detect a real flame or a real flame is slow to appear. Maintenance actions can be determined accordingly.

Slow to Accelerate
If a longer acceleration phase is needed to get the CT up to 100% speed, this could be a sign of several potential problems. Among these are:

- Degraded starter motor
- Rubbing
- Fouled Compressor
- Faulty Compressor Bleed Valve

The first two problems can be evaluated in the same manner as outlined in the previous section titled, 'Slow to Reach Purge Speed.' A fouled compressor can be detected with an overlay chart of compressor discharge temperature (CDT) versus compressor discharge pressure (CDP). Ideally the ambient temperature should be similar for both the reference start and the analyzed start, but even if it is not, if the slope of the CDT line for the analyzed start is steeper than the slope of the reference start, this is an indication of reduced compressor efficiency.

A faulty compressor bleed valve could result in the valve not fully closing when it is supposed to. If this happens, some of the turbine's power, which would be accelerating the rotor, will be wasted by compressing air that is bled off. Detection of this problem may be difficult unless the bleed valve has a position sensor with feedback to the control system that can be trended. Typically the bleed valve is adjusted based on rotor speed, so a trend chart versus speed would be the best choice for detecting deviations from the reference start.

A second method for detecting a leaking bleed valve is to monitor the air temperature downstream of the valve. Some CTs have a thermocouple in the air bleed line specifically for this purpose. In other CTs the bleed air is routed back to the inlet duct of the turbine. For CTs with that set-up, the deviation between ambient temperature and compressor inlet temperature can be used as an indicator of bleed valve leakage.

High Exhaust Gas Temperature Spread
If the difference between the hottest and coldest thermocouple in the CT exhaust exceeds the OEMs guidelines, the protection system will trip the unit to avoid damaging the engine. High exhaust gas temperature spreads are caused by a variety of problems, but the two most common are fouled fuel nozzles and unequal combustion liner air flow (caused by cracks in the liner or out-of-spec manufacturing). For CTs burning liquid fuel, sticky check valves in the liquid fuel lines are also a frequent cause of high spreads.

In order to prevent a start from being tripped by high EGT spread, it is important to monitor the EGT spread from each start. Since the trip value for EGT spread is typically a function of the average exhaust gas temperature, the most meaningful overlay chart would plot EGT spread versus average EGT. If the trend line for the analyzed start is getting close to the trip values, maintenance should be planned for the fuel nozzles. If switching out the fuel nozzles does not cure the problem, the combustion liners should be inspected.

Degraded DLN Fuel Nozzles
Start-up operation is very taxing on dry, low NOx fuel nozzles. Often the nozzles operate in non-premixed mode or with a pre-mixed flame very close to the tips of the nozzles during start-up. This can damage the fuel nozzles and cause the orifices of the nozzles to be enlarged.

An enlarged orifice will allow more fuel flow at a given supply pressure. Consequently, an overlay plot of fuel manifold pressures versus fuel flow can reveal a damaged fuel nozzle (this is also true for non-DLN fuel nozzles).

Detecting an enlarged fuel nozzle orifice is also a safety issue. The fuel valve position at ignition is set to provide the proper amount of fuel to allow a combustible fuel-air mixture to be present in the combustor. If the nozzle orifices are enlarged, more fuel will flow at the ignition setting and could result in a fuel-air mixture that is too rich for light-off. However, once cooling air flows are added to the mixture, it could fall back within the fuel's flammability limits and pose a danger of explosion if it finds a hot spot.

Module Development

Several potential options were considered for the structure of the SUDM. First, building the module in an Excel spreadsheet was considered. This is the method that was used for the Remaining Life Module (RLM) and Combustion Turbine Performance Fault Diagnostic Module (CTPFDM). However, because of the large number of start-up data sets which could potentially be used in SUDM, it was determined that Microsoft's database software package, Access, would be a better choice for SUDM.

Since many users will not necessarily have Access already installed on their PCs and since they may not be familiar with Access' commands, it was decided to develop a self-contained executable program, which contained the capabilities of Access, but had simplified commands and options. The program was developed using Microsoft's Visual Tools for Office 2003. The executable automatically opens a specific Access 2003 database file named SUDM.mdb.

While the ideal design would have allowed the user to extract data directly from a PI database into the SUDM database, it was learned that the PI database supplied with most GE turbines does not allow any third-party program to query it. Consequently, PI data must be extracted using Excel and the PI DataLink Add-In. Once the data is saved as an Excel file, it can be imported into SUDM.mdb. To make this process easier, a macro was built into SUDM that starts Excel and imports a pre-defined set of tags into Excel. More information on this macro is provided in the SUDM user manual.

An unexpected issue arose once development of the program was started. The charting capabilities of Access are different (and less sophisticated) from those in Excel. It proved impossible to create meaningful overlay charts using the Access charting package. To overcome this drawback, a macro was created in SUDM that causes overlay charts to be created in a new Excel spreadsheet using the Excel X-Y chart type. While this is again less than ideal, it does provide the important overlay charting tool, and it is hoped that future versions of SUDM will be able to generate overlay charts within Access.

Vibration Fault Diagnostics Module

Mechanical faults (i.e. bearing, rotordynamic, and structural) can be detected and classified from vibration sensors placed at specified locations on the turbine using feature-based diagnostic techniques. Domain knowledge associated with particular vibration fault frequencies, fixed frequency ranges, per-rev excitations, and structural resonances will be extracted from the vibration spectrums acquired from the Frame 7FAs. For a particular type of combustion turbine, these spectrums are used to develop a knowledge base from which fuzzy logic membership functions and rulebases are developed for diagnosing mechanical faults.

Overview

The Vibration Fault Diagnostics module will aide personnel in detecting incipient mechanical fault conditions and planning appropriate maintenance actions. The envisioned system will utilize high bandwidth data to extract low bandwidth feature data. This low bandwidth feature data, in addition to being posted to the PI Historian, will be utilized by the diagnostic reasoner to identify actionable failure modes. The vibration diagnostic module will be comprised of two components: an analysis component that extracts features and a display component that presents the features.

The analysis component will reside on a dedicated computer and interact with the existing vibration monitoring system, extract relevant features, identify actionable failure modes, and post the results to PI Historian. To eliminate the necessity of operator interaction to control its operation, the analysis component will remain on at all times. Upon detection of CT operation and the availability data, analyses will be initiated every second. Output of these analyses will be low bandwidth feature data reflecting the current health assessment from the current data snapshot. Output from the analyses will be displayed on a simple user interface, viewable on the computer's monitor, as well as being posted to the PI Historian system. A simple schematic of the system is shown in Figure 3.

The display module will extract data, created by the analysis component, from the PI Historian and display them in the control room for easy monitoring. These displays will simplify and present the extracted features in an intuitive manner. In addition any actionable failure modes will be clearly displayed.

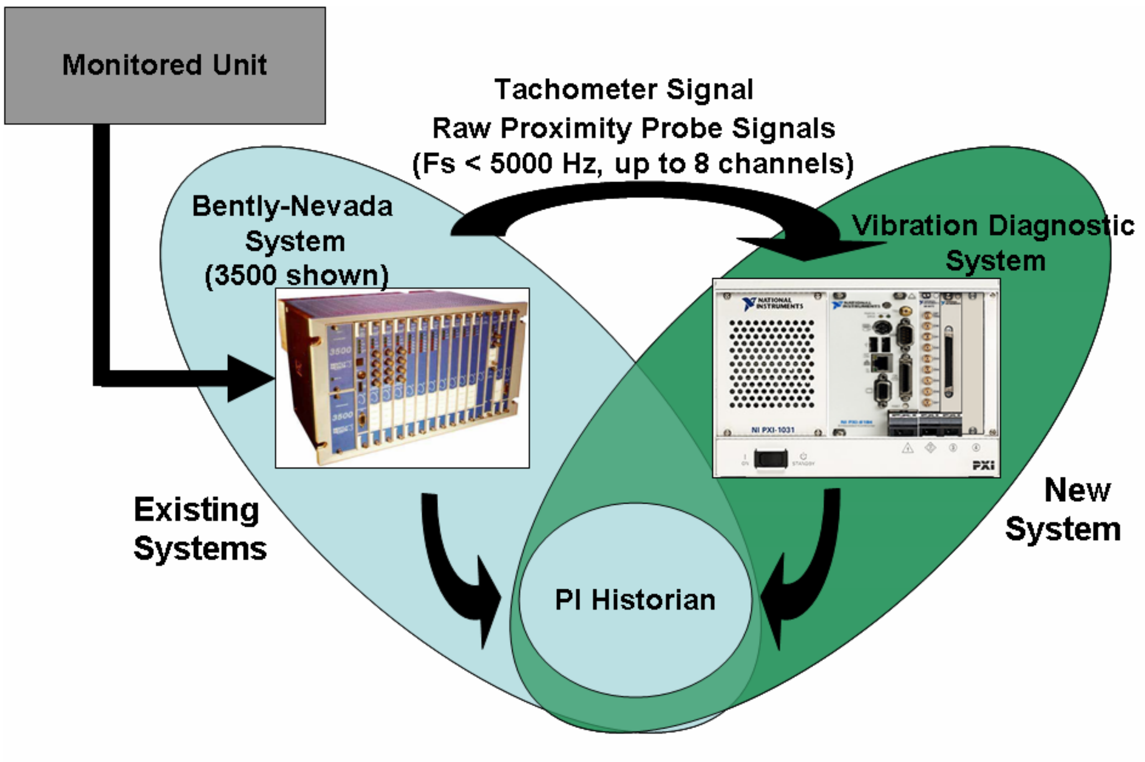

Figure 3 – Vibration Diagnostic Module Hardware Schematic

Work Scope and Schedule

The schedule for the continuing and proposed work is given in Figure 4. Work on the various software components should be completed by mid-October, meeting the first major milestone. Delivery of the first generation software is expected by the end of the calendar year.

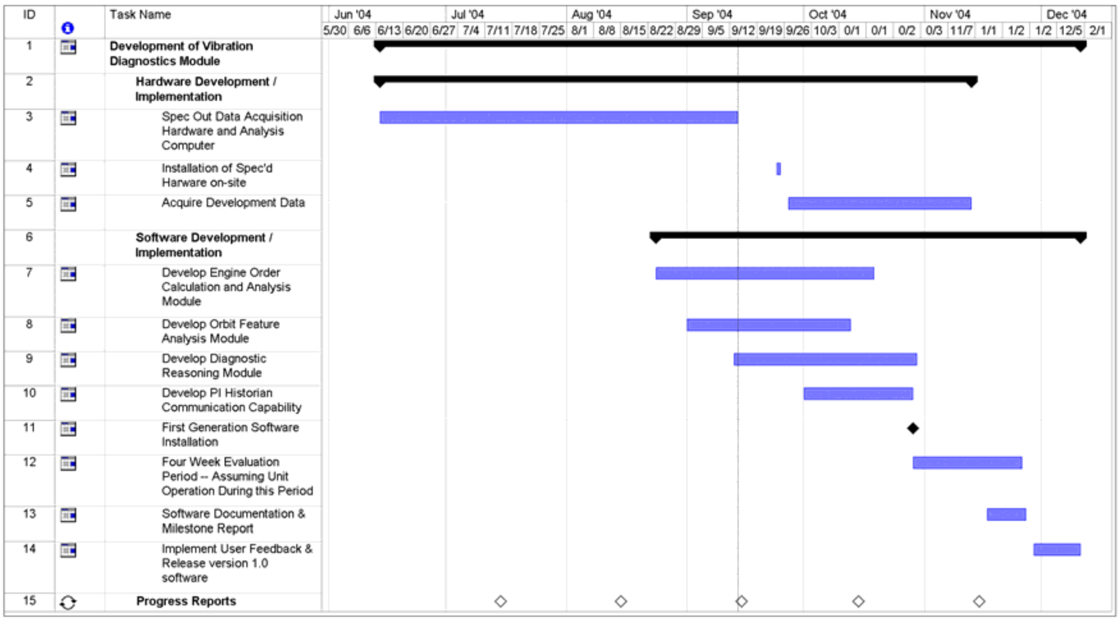

Figure 4 – Schedule

Hardware Specification

The data acquisition system for this project is a standalone autonomous device consisting of a dedicated computer running the developed software and a data acquisition card collecting the data. This configuration offers the most flexible solution, allowing easier communication with the Bently-Nevada system and PI Historian. In addition using a standalone fully operational computer in a PXI (PCI eXtension for Instrumentation) form factor affords flexibility in the system placement. Although the PXI based computer is more expensive than a basic desktop computer, the PXI system is ruggedized for operation in hostile environments. The diagnostic computer can be placed in any convenient location including outside of the control room.

Hardware Components

The system is comprised entirely of commercial off the shelf (COTS) components from National Instruments™. There are three primary hardware components: the host computer, data acquisition cards, and a common chassis. Below is a summary of the components:

Host Computer

A National Instruments™ PXI-8184 embedded controller has been selected as the host computer. The developed software will be deployed and run on this standalone computer. This Windows-based fully functionally ruggedized computer is capable of communication with the Bently-Nevada system and with PI Historian.

Data Acquisition Card

A National Instruments™ PXI-4472 dynamic signal acquisition board has been selected as the data acquisition board for this project. This card is capable of simultaneously sampling eight channels with a dynamic range of 110 decibels at 24-bit resolution and is well suited for vibration measurements. All eight channels will be used to acquire proximity probe data from the four probes on the turbine and the four probes on the generator.

Tachometer Data Acquisition Card

Since the 4472 board has all channels "full," an additional card is required to acquire the tachometer signal. A National Instruments™ PXI-6221 multifunction data acquisition card has been chosen for use in acquiring the tachometer signal. This 16-bit card is capable of acquiring up to 16 channels at speeds up to 250,000 samples per second. The current configuration will utilize only one of the 16 channels, leaving 15 channels for further expansion. One drawback of this card is there is no built-in antialiasing filters (as the PXI-4472 does), though this should not greatly effect the tachometer signal acquisition.

Common Chassis

A National Instruments™ PXI-1031 is a rugged and compact chassis that encloses and powers the above host computer and data acquisition card. Its dimensions are 10.12 x 7.50 x 8.38 (WxHxD in inches). The chassis will have two available slots for additional data acquisition cards if there is a need for additional channels.
Since each CC may be a different make or model, each unit must have its own CC model data files, which define the expected performance of the engine. Similarly, each CC will have different operating results, so each unit must have its own results files.

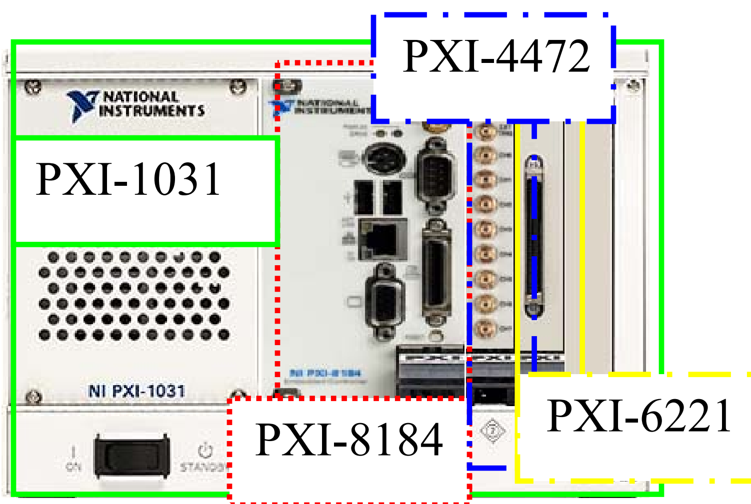

Figure 5 – Vibration Fault Diagnostic Module Hardware

Signals
The vibration diagnostic module will accept up to eight channels of raw high bandwidth signals that maybe configured for up to seven channels of vibration and one tachometer channel for a variety of 7FA applications. These signals are the signal-conditioned outputs from the Bently-Nevada system, thus eliminating the need for another signal conditioning system. A tachometer channel is also of critical importance. A “raw” tachometer signal, such as a TTL square wave is required for the most accurate results. The tachometer signal does not need to be a TTL signal as the hardware and software can be configured to read multiple types of tachometer signals. All of the signals could be sampled up to 102.4 kHz, the maximum sampling rate for the card, but will only be sampled at 5000 Hz to limit storage and processing requirements. Sampling will be continuous with analysis performed on a seconds worth of data.

Software Specification

Software development will occur in National Instruments™ LabVIEW™ environment. LabVIEW™ is a data acquisition, data analysis, and graphical user interface development tool. Currently LabVIEW™ has over 450 built-in data analysis tools and techniques. This extensive library of tools greatly reduces software development time by eliminating “reinventing the wheel.” Included are tools the allow LabVIEW™ to communicate with Windows® applications like Excel and Access as well as other applications (such as PI Historian) through TCP/IP sockets. Development of the software will focus on the integration of the various preexisting techniques and tools.

In addition to reducing development costs, LabVIEW™ also reduces installation costs. A standalone executable can be generated directly from LabVIEW™. Then the standalone executable can be installed and used on multiple other machines without requiring additional LabVIEW™ licenses from National Instruments™.

Software Architecture & Modes

The Vibration Diagnostic Module will have two components and operate in two modes.

Software Components
The software will be developed with two components: an Analysis component and a Display component. This allows flexibility in the placement of diagnostic system.

Analysis Component
The Analysis component, will calculate the diagnostic features and system health assessment. These features derived from the raw, high bandwidth proximity probe data will be intelligently combined through a diagnostic reasoner to arrive at a robust, accurate, and timely health state assessment. The features, as well as the health assessment, will then be stored on the PI Historian for future analysis/trending.

This component will reside and operate on the embedded PXI controller. It will be responsible for acquiring the data, analyzing the data, extracting the features, making the health assessment, and posting the results to the PI Historian. Even though most of the tools already exist, the Analysis component development is a major integration task.

Trends of features versus time plots will be available on system's host computer as well as order, orbit and waterfall plots.

Display Component
The Display component will plot the data posted to the PI Historian by the Analysis component. Features will be plotted with respect to time. These features are the single value results from the various diagnostics, such as the RMS or peak-to-peak value. Each graph will include pre-set alarm band levels for each sensor. This will provide a visual aid for the operator in the control room, indicating engine and sensor performance. Due to the limited bandwidth, only the feature, order, and health assessment plots will be available in the control room located Display component. The orbit and waterfall plots will only be available on the Analysis component's host computer due to the large number of PI "points" that would be required to display these plots. The actual software the display component is developed in/ for can be any number of products including LabVIEW and Microsoft Excel.

Operational Modes
The Vibration diagnostic module will make a distinction, based on shaft speed, between operational modes of the monitored unit. The software will have two operational modes: Startup/Shutdown and Steady State. Startup events will be detected by monitoring the tachometer signal for a shaft speed above 120 RPM. Shutdown events will be detected in a similar manner, when the shaft speed drops below a specified speed such as 3500 RPM. Steady state operation will be detected again by monitoring the shaft speed, but for a shaft speed equal to 3600 RPM plus and minus a tolerance (such as 3%).

The analysis of the signals and calculation of the results will be the same for each mode, except the waterfall and tracked order plots will only be calculated during startup/shutdown events. That is the entire suite of features and results presented herein will be calculated during each of the modes. The main distinction between modes is the availability of plots on the diagnostic system's host computer.

Startup/Shutdown Mode
During startup/shutdown events, when the shaft speed is between 120 and 3600 RPM, the software will operate in Startup/Shutdown mode. The entire suite of features and results will be calculated and posted to PI Historian by the Analysis component while the current postings in PI are extracted and displayed by the Display component. Since they are most useful during transients, waterfall, order, and orbit pots will be displayed during this mode. Again these plots will only be available on the diagnostic system's host computer and not via PI Historian.

Also while in this mode the waterfall information is saved to the host computer's hard drive. Only the most recent two startup/shutdown events' waterfall data is saved. An operator could compare successive startup/shutdown events by renaming the saved data or by plotting it.

An additional feature will be calculated during this mode. A baseline startup event's features and results will be saved to the host computer's hard drive. Then during subsequent startups, a comparison will be made between the current results and the historical baseline results.
Posting to PI Historian will occur once a second during Startup/Shutdown mode. All features and results will thereby be archived as often as the other monitored parameters.

Steady State Mode
During steady state operation, when shaft speed is at or near 3600 RPM, the software will operate in the Steady State operational mode. Like the transient mode, the entire suite of features and results will be calculated and posted to the PI Historian by the Analysis component. Also like the other mode the Steady State mode will post data to the PI Historian every second. PI Historian can then decimate and archive the results according to its schedule.

Unlike in the Startup/Shutdown operational mode, the Analysis component will not display the waterfall plots on the host computer in Steady State mode. Also instead of only saving the waterfall information to the host hard drive, the Analysis component will save the latest minute of raw data during while operating in this mode. This recent buffer of high bandwidth data will be useful in troubleshooting any emergency shutdowns that may occur.

Data Storage
To facilitate analysis of diagnostic events, the software will automatically archive a predetermined amount of raw data for each significant detected event. If a diagnostic feature value exceeds a preset limit, the software will automatically save raw data from before and after the over limit event. For instance, after an over limit of RMS the software will save the preceding ten minutes and the following five minutes of raw data. In addition the software will automatically archive a snapshot of data periodically during operation. For example the software could be configured to save five minutes of data every hour during operation of the monitored unit. By only saving data while the monitored unit is running disk space is conserved. The above mentioned intervals of time are software configurable, but the amount of data generated could potentially be significant.

Although the host computer of the vibration diagnostic module has up to a 60 gigabyte hard drive, storage space can quickly be filled. Archiving all nine channels (eight proximity probes and tachometer) of raw data for many minutes will require significant disk space. Figure 6 shows the method used to calculate the required disk space.

Table 1 shows the calculations for the proposed archiving scheme. This table can be used to estimate the disk space required for the storage of the raw data in binary format. It can be seen that storage space is quickly filled.

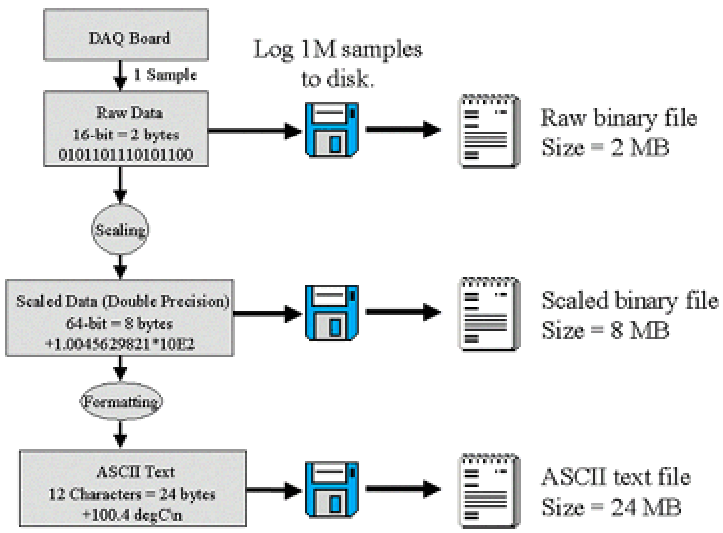

Figure 6 – Example Disk Space Requirement (From: www.ni.com)

Table 1 -- Required Disk Space for Archiving Scheme

Fs	Hertz	5000
Number Channels	#	9
Sampling Period	min	15
Sampling Times	# per day	24
Bytes per point	bytes	4

3.89E+09

Total 3.888 Gigabytes per day

Minimum (will be some overhead)

Definitions:

Fs: sampling rate
Number Channels: number of channels acquired
Sampling Period: lengfh of time data will be collected
Sampling Times: number of times a day data will be collected
Bytes per point: data format size

DAQ Resolution	Min Bytes
12 bit	2
16 bit	2
24 bit	4

Remote Access
A possible solution to the disk space issue is provided by the host computer's built in network card. Remote access to the host computer can allow the archived data to be removed and permanently backed up on another machine. An operator can remotely connect to the module's host machine and copy the data from its hard drive to a more permanent storage computer.

In addition to allowing data storage, the remote access ability will allow remote monitoring of the host computer. Any plots and interfaces viewable on the host computer, where the Analysis component resides, will be viewable via the remote connection.

User Interface

The user interface for the Analysis component of the Vibration Diagnostic module is an intuitive and easy to use graphical user interface (GUI). The GUI allows the user to configure the data acquisition system, plot the raw data from all of the proximity probes, configure the analysis, and view the diagnostic features versus time. Like the diagnostic components, the GUI is built entirely with built-in LabVIEW components.

Sections of the GUI are organized into separate pages. Navigation between the sections is done by a tabular dialog that is found in many applications and is easy to use. The user can switch between sections by selecting the appropriate tab. Figure 7 shows the first page of the GUI. On this page a simple schematic shows the data acquisition setup. It diagrams the interaction between the National Instruments PXI-4472 (the vibration acquisition card) and the MIO board (in this application the PXI-6221 tachometer acquisition board). While nothing is configurable on this page, it is still useful to see how the hardware components interact.

Also in Figure 7, the additional tabs corresponding to the additional sections can be seen. Details for these tab pages follow.

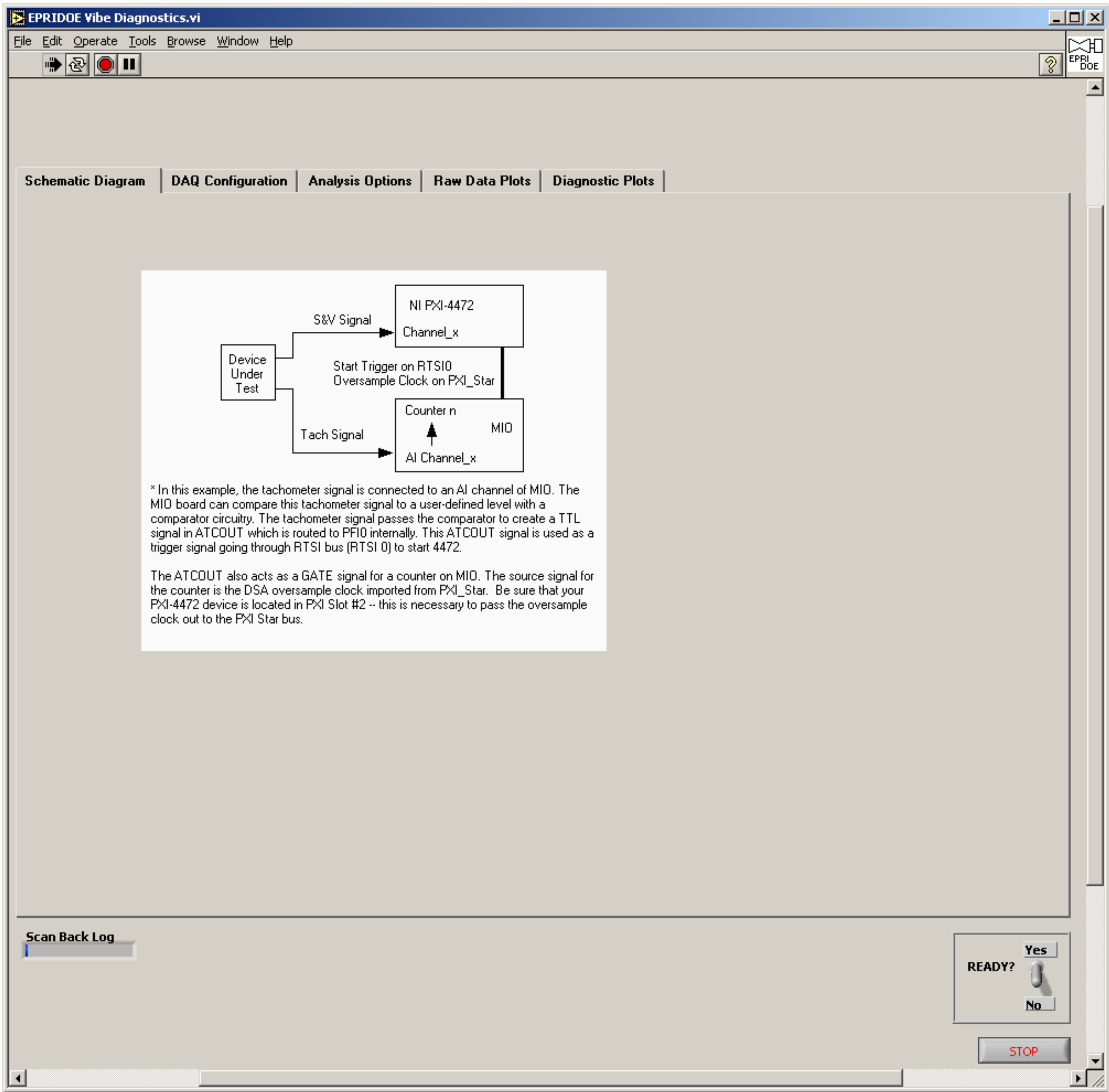

Figure 7 – GUI Schematic of DAQ Setup Page

Data Acquisition Configuration

Figure 8 shows the DAQ configuration page. The setup and configuration of the data acquisition system for the Vibration Diagnostic Module is performed on this page. The input channels are defined on this page. Channel names, types, ranges, sensor sensitivities, and labels are defined by the user on this page. In addition the sampling rate and duration are defined on this page. Although these configurations can be changed by the user, it is not necessary as the default configuration will be correct for the target application. Also, there will be an option to load and save the configuration to facilitate various applications.

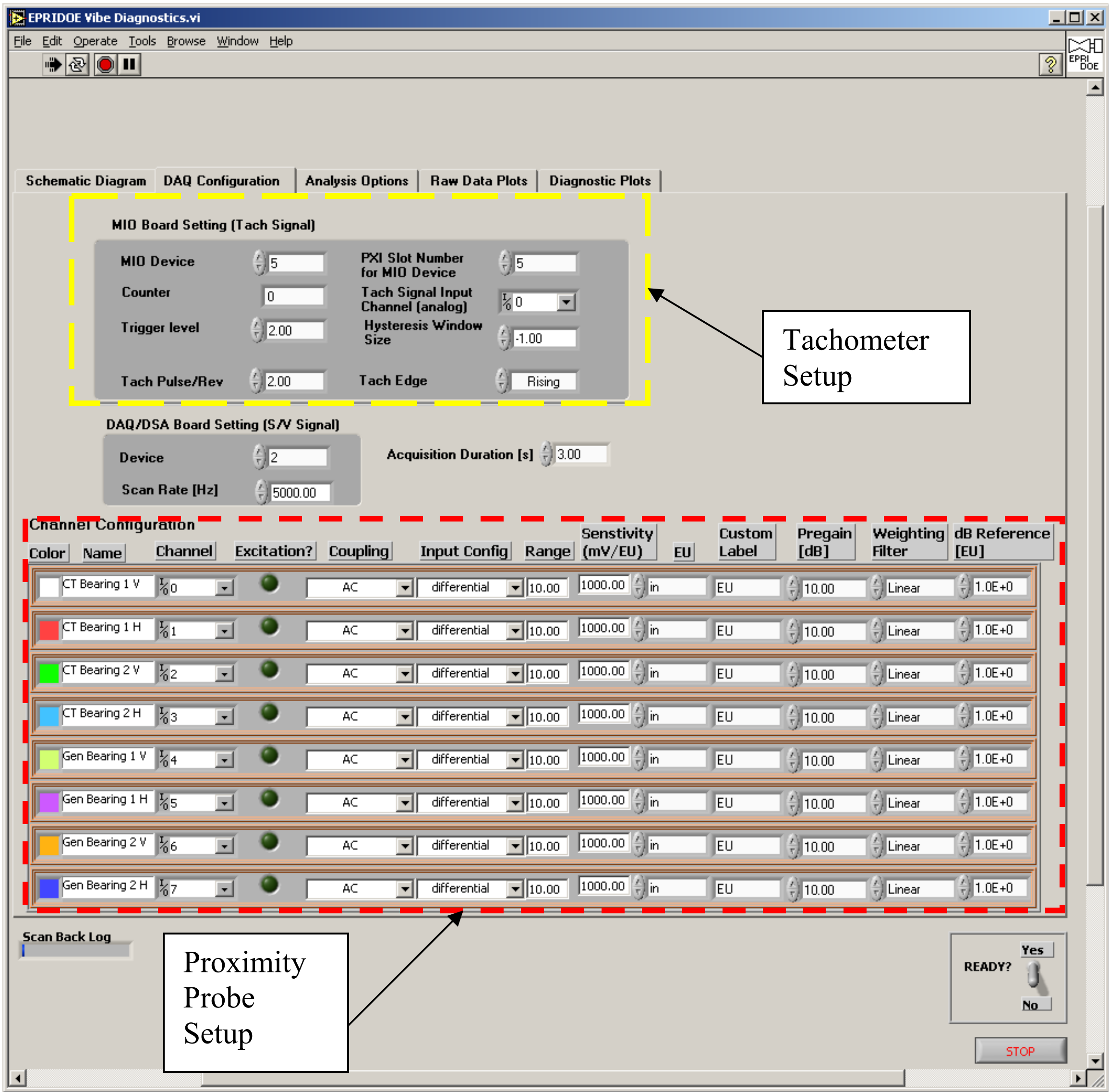

Figure 8 – GUI DAQ Configuration Page

Analysis Specification

The vibration diagnostic module (in particular the Analysis component) will use many signal processing techniques to extract useful diagnostic features from the monitored signals. Some of these features are extracted from directly from the raw time domain signal and others are extracted after further analysis. Traditionally there are two domains:

time and frequency. Time domain features are extracted directly from the time-based signal. Frequency domain features require a frequency analysis such as a Fast Fourier Transform (FFT) to be performed before the features calculation.

As mentioned above, the analysis will be conducted every second on one second blocks of data. Since the sampling rate is 5000 Hz the amount of data analyzed every second will be 5000 points per channel with 9 channels (including the tachometer) for a total of 45000 analysis points per second. This amount of data is easily analyzed in the one second time because of the computational power of the embedded computer and efficient programming.

"Slow roll compensation" will be performed to correct the proximity probe signals shaft imperfections (such as scratches, nicks, and concentricity issues). The effects of the imperfections are measured at low speeds (slow roll), saved, and subtracted from subsequent measurements at higher speeds. As with all of the presented features, LabVIEW™ has a built in function for slow roll compensation.

Time Domain Features
Time domain features are typically statistically based. They are derived from the raw time waveform of each acquired channel. Although there are many time domain features used in diagnostics, experience has shown the following features to be the most robust indicators of system health. In addition all of the presented features are available in LabVIEW™ as built in tools.

Maximum Amplitude
The maximum absolute vibration amplitude measured during the specified time interval can indicate the onset of unbalance, rubs, and bearing faults.

RMS
The root mean square (RMS) value of a vibration signal is a time analysis feature that is the measure of the power content in the vibration signature. It can also be very effective in detecting a major out-of-balance in a rotating system.

Crest Factor
Crest factor is defined as the ratio of the peak level of the input signal to the RMS level, and is useful in detecting transient events such as partial rubs and loose mechanical connections.

Kurtosis
Kurtosis is the fourth statistical moment of the time domain vibration signal. A kurtosis value greater than three indicates that the frequency of large spikes is greater than would be expected for normally distributed noise.

Peak-to-Peak
The peak-to-peak value of a signal is a measure from the signal's minimum to maximum value.

Shaft Orbits
Although not a feature itself an orbit plot can be analyzed for features indicative of faults. The time domain signal is used to generate an often circular type representing the relative displacement of the shaft during a revolution. The shape of the orbit can be analyzed for indications of misalignment, unbalance, and other faults.

Baseline Comparison
As mentioned above, a baseline startup event will be permanently saved to the host computer's hard drive. Then comparisons between the historic results and all subsequent results can be made. By comparing the current startup to the historical baseline, the software can detect and diagnose many fault types.

Frequency Domain Features
Frequency domain features are useful in not only identifying a fault but also identifying the type of fault. The magnitude of the monitored signal at specific frequencies (1xRPM, 2xRPM, 3xRPM) can be used to determine resonances of the structure, unbalance, misalignment and many other mechanical faults.

Fast Fourier Transform (FFT)
The basis of frequency domain features is the FFT, a frequency analysis technique. During the FFT calculation a window is applied to the data. Then the magnitudes of the specific frequencies of interest can be extracted from the FFT by a "peak-picking" algorithm. These peaks represent the magnitudes of the signal of interest. Frequencies (and signals) of interest may include shaft speed and its harmonics, bearing frequencies, and aerodynamic characteristic frequencies (i.e. nozzle pass).

In addition to the peaks at frequencies of interest, the sidebands of the peak can be used in diagnostics. Sidebands are peaks in the FFT magnitude that are near a larger peak. The existence and magnitude of sidebands can be used to diagnose and characterize faults.

The one-second sampling period will allow one hertz resolution on the FFT-based diagnostics. This will be sufficient for diagnosing most faults.

Waterfall
A waterfall is a three-dimensional plot useful in vibration diagnostics. A waterfall illustrates the changes of the vibration spectrum with respect to time or shaft speed. As it is computationally intensive, only the latest 60 seconds of waterfall data are displayed by the Analysis component the during Startup/Shutdown operational mode.

Engine Order Tracking
Engine orders are the shaft speed and its harmonics. The signal magnitudes at these frequencies are extremely useful in diagnosing faults. By comparing and tracking the relative magnitude of the first three orders (i.e. 1, 2, and 3 times shaft speed) the software will be able to detect many fault types.

However, extracting the engine orders can be difficult. The vibration signal needs to be sampled at constant angular positions during a revolution. Typically sampling is performed at constant times not positions. If the shaft is accelerating the sampling will not be at constant angular positions. Many methods can be used to resample the time-sampled signal into a position-sampled signal. Again LabVIEW™ has built in functions to perform the necessary resampling.

Bode Plots
Bode plots are used to illustrate the relationship of the magnitude, phase and frequency response of a system on a logarithmic scale. The plots will be available on the host computer through the Analysis component. Lower bandwidth diagnostic features based on the Bode plot will be passed to PI Historian.

Nyquist Plots
Similar to the Bode plot, the Nyquist plot relates the magnitude and phase of a signal shown on the complex plane. Again the plot will be available only on the host machine and the derived diagnostic features will be posted to PI Historian.

Health Assessment
While any one of the above features can be used individually to diagnose a problem, health assessments based on as single feature may not detect a fault under all conditions and may lead to unacceptable false alarms. To provide a robust health assessment it is necessary to intelligently fuse all of the above results in to a single robust and accurate prediction on the system health. The Analysis component will use a Bayesian-type data fusion to combine the individual results in to one scalar system health indicator. This is the health assessment indicator that the operator will be able to see in the control room.

Analysis Options/Configuration

Figure 9 shows the setup page for the diagnostic analysis; note currently this page is incomplete. On this page the user could modify some of the analysis options, such as speed and features limits. Again the default values will be appropriate for the target application. As with the DAQ set up, the analysis setup will be able to be saved and loaded from a file to facilitate various applications.

Shown in Figure 9, are the shaft speed thresholds to allow the software to detect startup/shutdown events and steady state conditions.

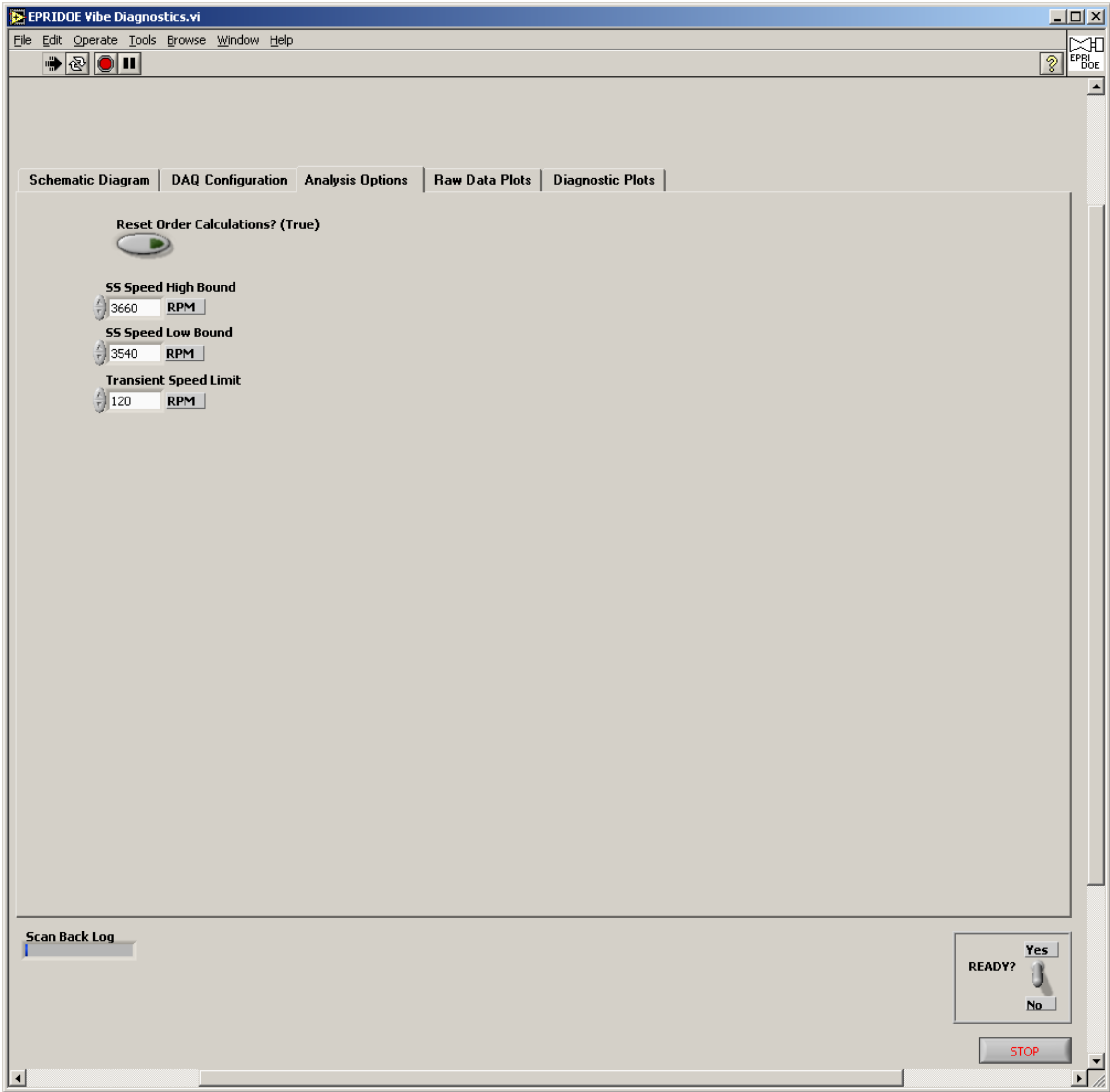

Figure 9 – GUI Analysis Options Page

Raw Data

Figure 10 shows the Raw Data Plot page of the GUI. On this page a small amount of the most recent vibration and tachometer signal will be displayed. A limited amount, about 5 seconds, will be displayed to reduce the computer usage. However this amount should allow the user to quickly check for on circuits, disconnected sensors, and other signal quality type issues. The proximity probe plot will simultaneous display all eight channels in the colors specified on the DAQ setup page. In addition the legend for the plot will display the channel names defined on that page.

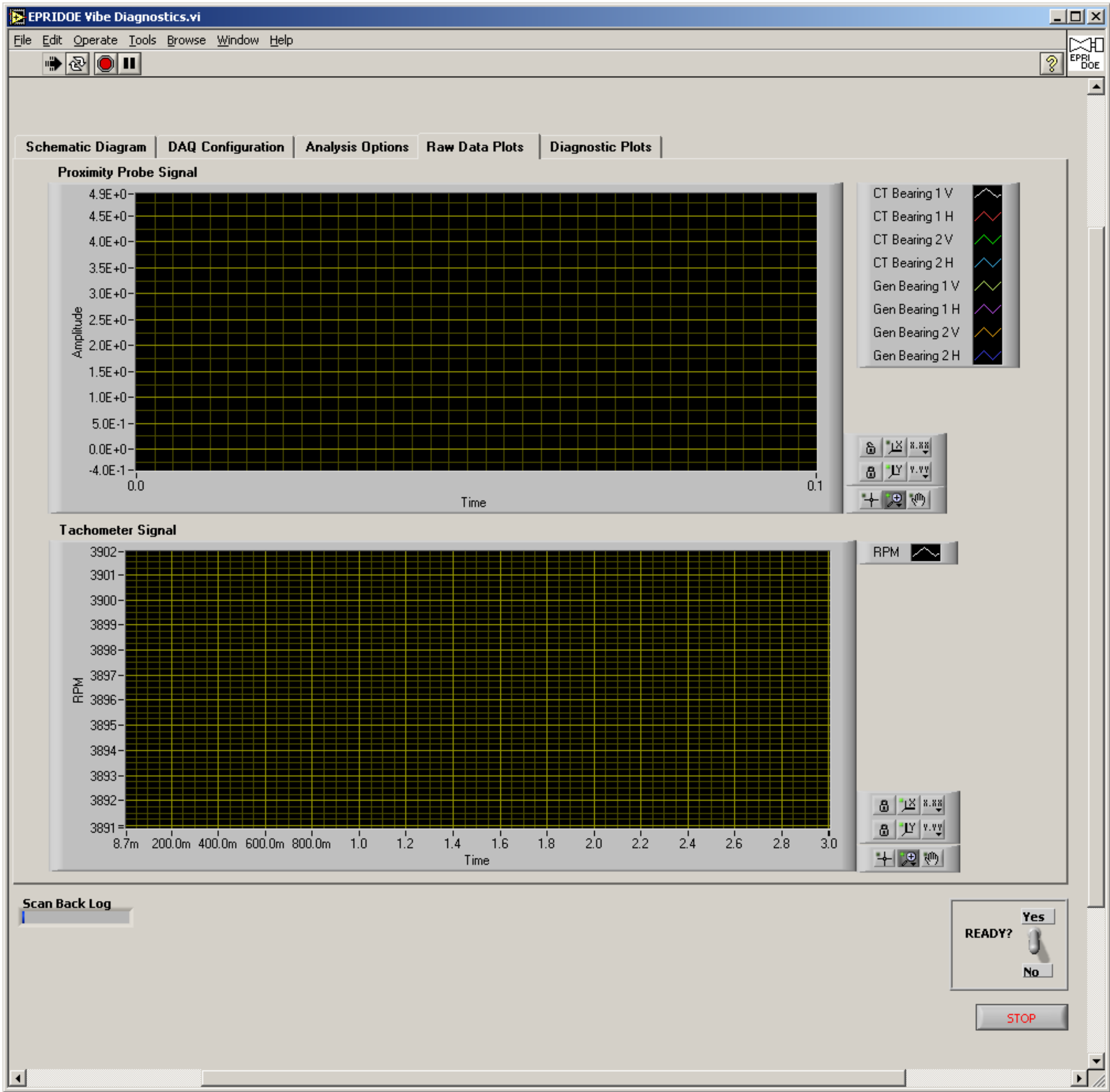

Figure 10 – GUI Raw Data Plots Page

Diagnostic Feature Plots

Figure 11 shows the Diagnostic Feature Plot page of the GUI. On this page the user can see the extracted time domain and frequency domain features for one user defined sensor. To limit computer usage only the diagnostic features for one sensor can be displayed at a time. The user can select from any of the defined sensors and plot any of the time or frequency domain features. A list box for the time domain features lists all of the available features. Similarly the list box for the frequency domain features lists all of the available features, which are dependent on the operational mode of the monitored unit. As previously described some of the frequency and time domain plots will be disabled during steady state operation, due to their limited utility during constant speed operation.

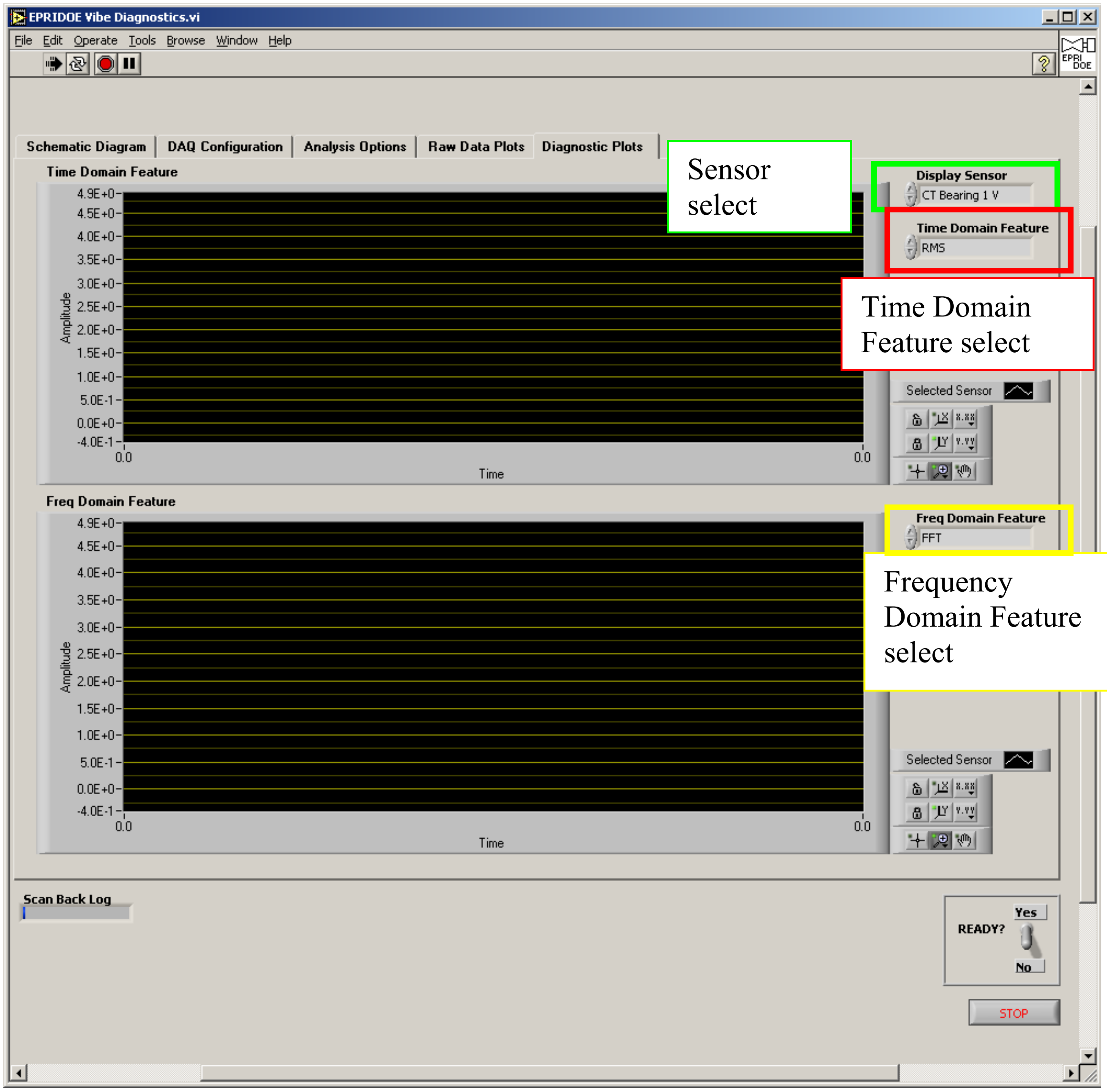

Figure 11 – GUI Diagnostic Plots Page

Hardware Costs

By using COTS hardware, the cost of fielding a new data acquisition system is reduced. COTS hardware is traditionally much less expensive than custom-built hardware. The hardware costs of the proposed system are summarized in Table 2. These are the hardware costs as per the National Instruments online ordering website on August 27, 2004. Expected lead time is ten days. The price could be reduced if an off-the-shelf desktop computer was used in place of the PXI chassis. However a standard desktop computer may not be rugged enough for use in this application. In addition the PXI chassis is smaller in size than most desktop computers.

Table 2 -- PXI Hardware Costs

Component	Cost	Lead Time (days)
PXI-1031	995.00	5-10
PXI-6221	575.00	5-10
6221 Cabling	200.00	1-3
PXI-8184	1,995.00	5-10
PXI-4472	3,995.00	5-10
TOTAL	**$7760.00**	**5-10**

Future Work

Over the next report period, results from the beta testing of RLM and SUDM should be available to enhance the features of both these modules. Final drafts of the topical reports based on the module development will be completed as the module approaches "commercial" status.

Future activity will also focus on completing the vibration fault diagnostic module.