I. CONCEPT DESCRIPTION

a. Concept Title - Condition Monitoring of Military Aircraft Electric Fuel Pumps by Electrical Signature Analysis

b. Concept OPR

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c. Background

ESA is based on the knowledge that time-dependent load and speed variations occurring throughout an electro-mechanical system will induce variations in the motor's and/or generator's electrical response. These variations are observed as a change in current (for a motor) or a change in voltage (for a generator). ORNL researchers have pioneered the development and application of signal conditioning techniques for extracting these electrical perturbations and relating them to their source and have thus opened a new field for diagnostic innovations.

d. Laboratory Research

ESA has matured over the last 12 years as a result of continued R&D at the Oak Ridge National Laboratory (ORNL). During this time, several new signal conditioning and signature analysis methods have been developed that capitalize on the intrinsic abilities of conventional electric motors and generators to act as *transducers* (see Table 1).

Table 1 ORNL ESA-Related Patents

Patent No.	Title
4,965,513	Motor current signature analysis method for diagnosing motor operated devices
5,461,329	Method and apparatus for generating motor current spectra to enhance motor system fault detection
5,483,833	Method and Apparatus for Monitoring Rotating Aircraft Components
5,483,841	Method and apparatus for monitoring motor operated valve motor output torque and power at valve seating
5,512,843	Monitoring method and apparatus using high-frequency carrier
5,519,337	Motor monitoring method and apparatus using high frequency current components
5,523,701	Method and apparatus for monitoring machine performance
5,578,937	Instrument for analysis of electric motors based on slip-poles component
5,612,601	Method for assessing motor insulation on operating motors
5,661,386	Method for assessing in-service motor efficiency and in-service motor/load efficiency
5,767,780	Detector for flow abnormalities in gaseous diffusion plant compressors

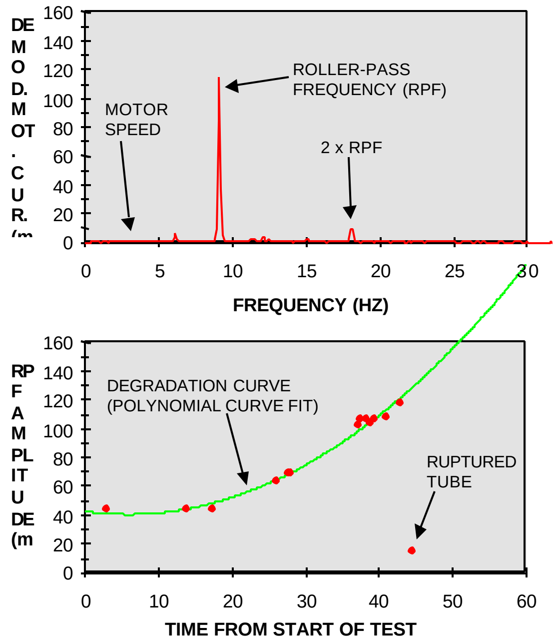
ESA techniques have been successfully demonstrated by ORNL in a wide variety of applications as shown in Table 2.

Table 2. Partial List of Equipment That Has Been Tested With ESA By ORNL

Material pulverizers	Chilled-water systems

Army ammunition delivery system
NASA propellant control valve
Navy fire and seawater pumps
Consumer hand tools and home appliances
Electric vehicle motors & alternators

Motor-operated valves
Fans and blowers
Nylon spinning machines
Water pumps
Helicopter rotor and gearbox



Aircraft integrated drive generator
Air conditioning systems

Multi-axis machine tool
Gear boxes

Figure 2. Motor current spectrum (top) and feature trend plot (bottom) of a peristaltic pump.

Diagnostic information provided by ESA is comparable to that provided by conventional vibration analysis in that both time waveforms and frequency spectra are produced. In its simplest form, ESA can be viewed as a “non-accelerometer-based” vibration tool. A primary benefit of ESA is that an extensive range of diagnostic information can be obtained from a single sensor that is much less position-sensitive than a standard accelerometer. For example, in a typical industrial application, ESA can be performed several hundred feet or more from the monitored device because access to the equipment surface is not required, as it is in other equipment diagnostic methods. ESA only requires access to electrical lines supplying input power (e.g., to a motor) or carrying output power (e.g., from a generator).

ESA signatures can also be used as an aid in predicting the remaining life of monitored equipment. When the functionality of a device ceases as a result of the failure of a subcomponent (e.g., a bearing failure preventing a pump from running), the condition and remaining life of the subcomponent is monitored since it ultimately determines the remaining life of the entire device. As an example, Figure 2 shows that the motor current spectrum of a peristaltic pump contains a discrete frequency peak at the “roller-pass frequency” (RPF) which is the rate at which the tubing, containing the fluid being pumped, is being compressed.

The amplitude of the RPF peak shown in the top plot of Figure 2 reflects the energy needed by the motor to compress the tubing containing the fluid being pumped. The bottom plot of Figure 2 shows a time trend plot of the RPF amplitude that is observed to increase over time. The RPF motor current component increases in response to the tubing losing its resiliency as it is repeatedly compressed. Eventually, the tubing becomes so stiff that it cracks, resulting in fluid leakage and pump failure. Once the relationship between the RPF and the tubing condition was established, the RPF may now be monitored, referenced to the degradation curve for this failure mode, and used to predict the remaining life of the tubing and peristaltic pump.

As another example, ESA was applied to an aircraft integrated drive generator (IDG). These units on certain aircraft experience complete failure, on average, at a rate of four per year. As many as ten have failed in one year. The primary failure mode is seizure and destruction of scavenge, drive pump, and axial gears on the generator's main shaft. Traditional re-certification tests do not detect incipient gear failure. A gear set costs $17,000; a gear unit costs $250,000. The method for predicting gear failures would obviously be highly desirable.

IDG units provide power to aircraft (117/208 volts at 400 Hz) for passenger reading lights and galley microwave ovens. To maintain their reliability, effective measures of the onset and levels of gear wear are needed. ORNL has demonstrated both on a test stand and on a jet that ESA techniques provide the signature attributes necessary to characterize good and worn gears. Preliminary test results show that even at extremely low generator loads, ESA provides excellent sensitivity to the gear-related problems.

Figure 3 shows that the magnitude of the scavenge pump gear-mesh peak in the conditioned generator voltage spectrum can be used to detect a bad gear set.

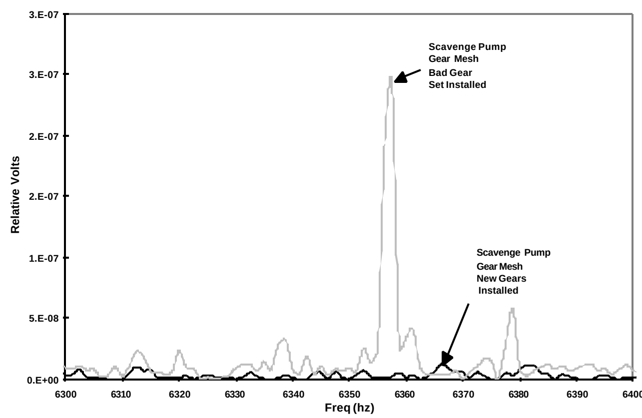


Figure 3. Degraded gear-mesh quality detected in an aircraft IDG (test stand data) using ESA.

e. Objective

The objective of this proposed effort is the development and commercialization of an easy-to-use automated system for quickly assessing the condition and remaining life of Air Force fuel pumps. The system will be based on a powerful new technology invented and patented by ORNL. This technology encompasses a broad range of electrical signal monitoring innovations that have been grouped under the general name of electrical signature analysis (ESA). ESA provides a breakthrough in the ability to detect and quantify mechanical defects and degradations in electro-mechanical equipment and unwanted changes in process conditions. ESA is truly non-intrusive and does not interfere with the operation of the equipment being monitored.

f. Approach

Oak Ridge National Laboratory proposes working as a team with the Tennessee Air National Guard (TANG) stationed at McGhee-Tyson Air Base, Maryville, Tennessee, the Oklahoma City Air Logistics Center (OC-ALC), the San Antonio Air Logistics Center (SA-ALC), and the Air Force Research Laboratory (AFRL). The goal will be to apply systems analysis and improved maintenance techniques, primarily predictive maintenance techniques, to reduce the loss of availability of the KC-135 due to unplanned repair or replacement of the fuel booster pump or override fuel pump.

Based upon discussions with TANG personnel, it was decided to define the scope of an improved maintenance approach effort as initially involving only the eight fuel booster pumps and the two override fuel pumps of the KC-135. The group of aircraft for initial study was selected to be the eleven KC-135 aircraft stationed at McGhee-Tyson Air National Guard Base.

The proposed predictive maintenance method(s) will be instituted on the eleven KC-135 aircraft located with TANG, with the permission of the OC-ALC Strategic Program Director for the KC-135. This fleet will be monitored periodically or continuously to determine the effectiveness of the method in providing forewarning of approaching pump failure.

If successful, the method(s) adopted for use on the TANG fleet will be formalized into a set of specifications/procedures, which can be adopted for use by the national fleet.

Since the majority of the failures, occurrences, and maintenance man-hours expended in the KC-135 series electric fuel pumps occur in the two override pumps, efforts to improve operability and reduce maintenance costs will begin with these two pumps. Also, since time trending reveals that the failure rate for these two pumps has been increasing for the past five years, a root cause analysis in conjunction with SA-ALC, which performs rebuilding operations for these pumps, will be conducted to determine the nature of this time-dependent degradation.

It is proposed that fuel pump electrical signals be acquired and analyzed with a computer data acquisition system that is capable of simulating the performance of a multitude of hardware instruments. In this manner, *virtual instruments* (VIs) will be designed that reliably detect and differentiate among the various fuel pump degradations. The VIs will be designed to provide clear indications of the degradation type and magnitude through simple visual indicators (e.g., bar graphs, gauges, and lights). Particular attention will be directed at minimizing false alarms by using multiple data evaluation algorithms to detect and differentiate between equipment degradations. A complete fuel pump monitor will be developed and will consist of commercial off-the-shelf (COTS) nonintrusive ESA sensors, signal conditioning electronics, and a COTS portable computer running an easy-to-use virtual instrument. An illustration as to what the VI main screen might look like is shown in Figure 4.

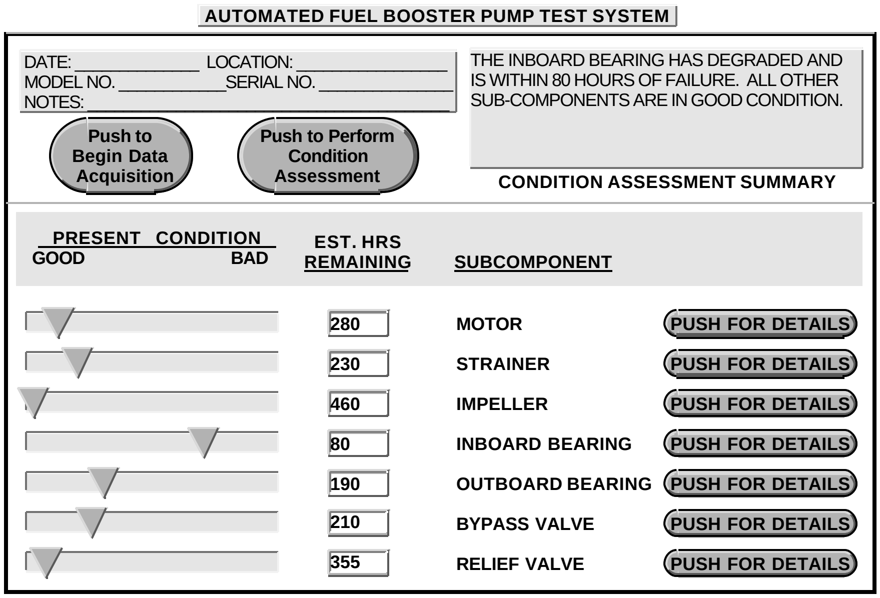


Figure 4 Example virtual instrument main screen.

g. Expected Results

During the five years preceding January 1999, 134 mission aborts due to electric fuel pump failures and 1,283 electric fuel pump failures in flight were recorded in the 506 KC-135 series aircraft tracked by the REMIS data system. There has been twice this number of in-flight fuel pump malfunctions and a total of 4,177 other in-flight fuel pump malfunctions during this same 5-year period. If the progress of these in-flight failures or malfunctions could be predicted or monitored in advance, their maintenance could be appropriately scheduled and their impact on operations minimized. During the past five years, approximately 81,068 man-hours of maintenance (which, at an estimated $50/hour is $4.1M over 5 years) have been performed on KC-135 electric fuel pumps. Of these, approximately 20,000 man-hours (or an estimated $1M over 5 years) have been in the form of tests in service with no defect. These in-service performance tests typically are “go-no go” performance tests, and, since the measurements are not recorded, only the outcome, the trend of the results cannot be followed as a predictor of future performance.

This program has the definite potential to reduce 50% of maintenance expenditures through predictive failure and appropriate maintenance/supply scheduling. Of the remaining 50%, 20% are inspections with no defect present. This number would be greatly diminished utilizing Electrical Signature Analysis (ESA). Of the remaining 30%, our goal would be not to eliminate maintenance expense. But, to eliminate operational impact of mission aborts and in-flight failures associated with unanticipated mechanical occurrences by health monitoring these systems so those repairs could be made during scheduled maintenance. Needless to say, this would also have a significant impact on budget forecast and DLR funds utilization. Utilizing the previously mentioned man hour expenditures and cost per man hour rates, the Air Force could experience a $32.8M savings over the remaining predicted service life (40 years) of the KC-135 fleet.

h. Initial Aircraft MDS on which EMD will be accomplished: KC-135

i. Is the technology applicable to other aircraft MDS=?: Yes

Any aircraft consisting of metallic or composite load bearing structures subject to crack-dominated failure modes can benefit from this technology.

j. Targeted level of implementation:

Depot level maintenance, with possible extension to field level maintenance.

k. Project start date: 1 Oct, 2000

l. Projected duration of EMD in years: Three years

m. Contract Vehicle:

The funding vehicle for this project is anticipated to require a MPIR between ORNL and either the TN-ANG, the OC-ALC, and/or the AAPO.

II. Funding Information

a. EMD Cost

FY	INITIAL FUNDING	ADJUSTMENT
FY01	$410,985	
FY02	$491,003	
FY03	$337,336	

III. Implementation and Sustainment

a. Where will the new capability be implemented after EMD?

The targeted implementation center will be the Oklahoma City Air Logistics Center, as the lead depot maintenance center for the KC-135 aircraft.

b. Who will provision for initial spares, follow-on spares, technical orders, training, manpower, and spare parts?

The C/KC-135 SPD will be responsible for operation and maintenance of the equipment. Provisioning will be accomplished via provisioning conferences pending receipt of source documentation

c. Who would prepare POM submission if EMD proves successful? C/KC-135 SPD

IV. Project Signatures and Approval Authority

Project OPR: ____

SPD Concurrence: ____