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Shipboard Applications of Non-Intrusive Load Monitoring

ABSTRACT

Field studies conducted on board two different ships and in the laboratory have demonstrated that the non-intrusive load monitor (NILM) [1, 2, 3, 4] can effectively evaluate the state of many mechanical systems through analysis of electrical power data. Data collected from the sewage system of the *USCGC Seneca (WMEC-906)* identified metrics that can be applied, for example, to cycling systems (high pressure air, hydraulic systems, etc.) to differentiate between periods of heavy usage and fault conditions. Trend analysis of pump operating frequency also provided indicators of overall system health and integrity. Other important shipboard systems are also examined in this paper.

INTRODUCTION

In today's modern Navy, there is a growing trend of "electrification" that is causing major changes on both the generation and load sides of a vessel's electrical network. On the supply side, the Navy is currently exploring the use of integrated power systems. Vessels using this scheme are equipped with generators that drive the propulsion machinery, a change that allows generators to operate with improved efficiency. On the demand side, there has been a marked increase in the number and variety of electrical loads. Advances in computing and power electronics have made it possible to replace many mechanical, hydraulic, and pneumatic systems with more efficient and reliable electrical or hybrid electrical systems. All of these changes create a pressure for monitoring tools that can reliably provide real-time information regarding the behavior of individual loads and the quality of the power delivered to them [1, 2, 3, 6, 7, 14].

In order to address the clear and present need for a reliable electrical monitoring system on modern naval vessels, we have investigated the shipboard use of the non-intrusive load monitor (NILM). The NILM is a device that determines the operating schedule of all of the major loads on an electrical service using only measurements of the input voltage and aggregate current [1,2]. This paper presents a discussion of the non-intrusive concept and how it can be used to obtain a wealth of information from a modest suite of sensors. Experimental observations have been made on real systems onboard an operating vessel. These measurements, while not made by a fully non-intrusive monitor, demonstrate the potential of the NILM for naval vessels. The NILM has already been demonstrated effective in residential, commercial [2,4,11], and automotive environments [15], and could reliably provide useful load information in a shipboard environment.

SHIPBOARD MONITORING

Consider first how the NILM can be used to cost-effectively address the unique problems of shipboard monitoring in the context of previous and current monitoring systems.

Background

With the transition from the use of sail power to steam propulsion, it became necessary for a marine vessel to have watchstanders whose duty was to monitor the performance parameters of the steam plant. As the number of mechanical loads grew with time, so too did the need for reliable, automated monitoring. Today, engineering plants are often equipped with high quality logging systems that collect measurements made by numerous transducers. They may also record information entered manually by the crew. For instance, the *Seneca* is equipped with a system that records changes in main engine revolutions on a per minute basis.

Although this type of system alleviates some watchstander burden, it does not provide any analysis or control functions. An ability to trend such information automatically would reduce demands on the crew. It might also reduce the possibility that a negative trend might be missed through operator error.

Modern monitoring systems also suffer from the problem that, in order to obtain a wealth of useful information, they require a complex and expensive sensor network. While mass production is continually reducing the cost of many sensors, it is also true that the cost of sensor installation and maintenance is likely to remain high. Also, the reliability of a monitoring system will decrease as the number of sensors, and thus the number of possible points of failure, increases. This point is particularly crucial in combat vessels, where the inadvertent failure of individual sensors could potentially hinder damage assessment, reconstruction, or fight-through efforts.

Dual-Use to Improve Reliability

As the previous section suggests, two critical requirements of an ideal shipboard monitoring tool are that it should automate the analysis of sensor data and that it should minimize the need for a large array of sensors. The NILM performs both of these tasks. It makes "dual-use" of the power system, which continues to serve its primary function of delivering power to loads, but which also becomes an information network for monitoring the behavior of these loads based on power demand. The NILM requires only a set of voltage and aggregate current measurements made at a single or a limited number of points in the power system. It operates with a comparatively small sensor network. This benefit comes at the cost of requiring sophisticated signal processing to disaggregate useful information about individual loads. The NILM therefore offers a trade-off between hardware installation, data processing and collation complexity, and the risk of failing to identify an important pathological or diagnostic condition. At a minimum, the NILM offers a valuable opportunity to add redundancy inexpensively in an overall suite of shipboard monitoring tools. It is also conceivable that data from the NILM could serve as an automated data stream for current or anticipated monitoring systems on-board ship like ICAS [7].

The NILM analyzes the aggregate current signal with a Pentium class PC and signal processing and parameter estimation algorithms that can determine the operating state of individual loads [4, 17]. The hardware required for the NILM is relatively low-cost compared to a custom sensor network. The COTS NILM computer can easily be programmed to analyze data automatically and to send the ship's engineering crew regular status reports.

The NILM is capable of tracking the operating schedule of significant electrical loads on the power distribution system. It can also use measurements of the current flowing into the stator terminals of an induction motor to track and trend all of the key motor resistances, inductances, and mechanical shaft parameters [13, 5]. This can potentially preclude the need for complicated sensor arrays that measure motor flux in order to study motor behavior. The NILM can be used to diagnose faults that commonly occur in electromechanical systems like HVAC plants [16]. The NILM's ability to examine harmonic current information can be used to create performance metrics for variable speed drives and to study the electrical interference caused by power converters [11].

FIELD TESTS

The NILM has demonstrated capability for monitoring important electrical loads in commercial and industrial facilities on land [3, 11, 18]. It has also been tested successfully in land-based transportation systems [15]. We have recently begun field tests to extend the capabilities of the NILM to naval vessels.

We have installed basic monitoring systems on three different naval vessels: *USCGC Seneca* (Boston, MA), the Woods-Hole *Oceanus*, and the ONR YP (Annapolis, MD). The majority of NILM data presented in this paper was collected on the *Seneca*. With the generous help and assistance from *Seneca's* engineering officer, LT Mike Obar, and his staff, monitoring systems were in-

stalled to gather information on the following shipboard engineering systems[1]:

- Cycling (Sewage) System
- Auxiliary Seawater (ASW) System
- HVAC System
- Steering System
- Controllable Pitch Propeller
- Roll Stabilization Fin
- Anchor Windlass

The results presented in this section are taken primarily from the sewage, ASW, and steering gear systems onboard *Seneca*. These particular systems are of immediate importance to the crew of the *Seneca*.

Cycling Systems

Cycling systems require periodic mechanical "charging" by an electromagnetic actuator like a motor. Examples include high-pressure air, some pneumatic actuators, and vacuum-assisted drains and disposals. These systems may be mission critical or mission enabling, and may have elusive pathological behavior. A casual inspection of such a system may fail to reveal the differences between periods of high use versus a leak or other pathological condition. We have conducted field experiments to see if the NILM can reliably determine the difference between high usage or crew demand and actual leaks.

The sewage system onboard the Seneca, for example, consists of toilets, urinals and drains that discharge into a vacuum collection tank. Vacuum is maintained in the tank by the operation of two alternately cycling pumps. When the system vacuum reaches the low vacuum set point (14 in. Hg), one of the pumps begins to operate in order to restore vacuum. When this occurs, the on-line pump will not secure until the high vacuum set point (18 in. Hg) is achieved once again. If for some reason the system vacuum is allowed to reach the low-low set point (12 in. Hg), then both

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[1] The NILM is typically installed to monitor the aggregate signature of a large collection of loads. In these early field tests, we have used separate monitors for relatively small collections of (typically 3 or 4) loads. As we develop increased confidence and experience with naval loads, we expect to dramatically expand the number of loads that an individual NILM will monitor.
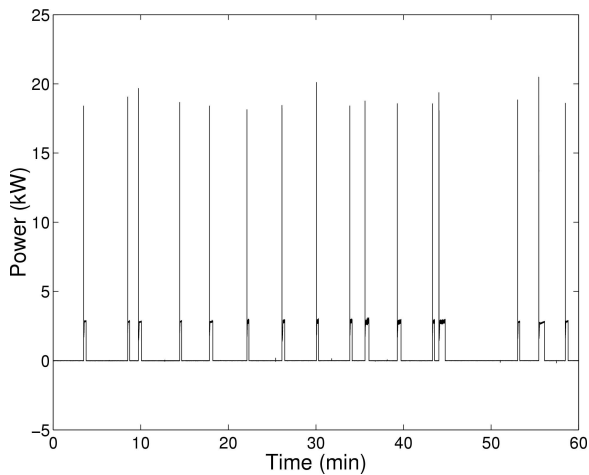
pumps are energized and operated until the high vacuum set point is restored. Figure 1 shows a picture of the system's two vacuum pumps with the vacuum collection tank shown in the background.

FIGURE 1: *USCGC Seneca* **sewage system**

In order to study the statistical behavior of the cycling of the vacuum pumps, the NILM was configured to collect continuous "snapshots" of the real power delivered to the pumps. A typical data set of real power versus time collected over a one-hour period is shown in Figure 2. Note that the data plotted in this figure indicates sixteen distinct periods of pump operation. Each spike on the graph indicates the start of a sewage vacuum pump. Notice that the NILM samples sufficiently quickly to detect the motor in-rush. This is seen in more detail in Figure 3, which shows a detailed view of the power drawn during the start-up, operation, and shut-down of one of the vacuum pumps.

The ability to trend operating data collected by the NILM can be extremely useful in predicting equipment failures. One example that we have analyzed off-line occurred onboard *Seneca* during the fall of 2003. A four-week data snapshot (October 24, 2003 – November 22, 2003) of the sewage system was captured while the ship was underway on patrol. During this time period, the NILM continuously monitored the sewage system. Figure 4 shows a histogram plot of the time between pump runs during this cruise.
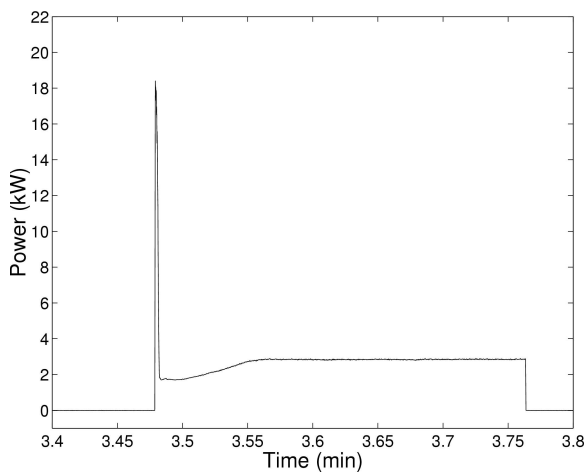
FIGURE 2: Vacuum pump transients

FIGURE 3: Real power drawn during the start-up and steady state operation of one of the sewage system vacuum pumps
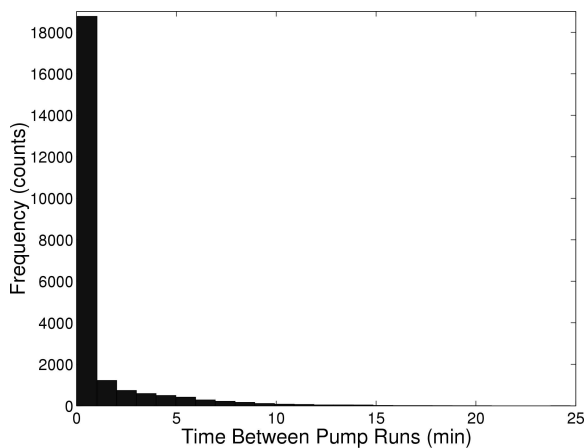

FIGURE 4: Fall 2003 *Seneca* cruise profile of time between sewage system pump runs

Figure 4 highlights a potential problem in *Seneca's* sewage system. The high frequency

(>18,000) and short duration (< 1 min) of pump runs could be an indication of system overload and/or system leak. Unfortunately, the shear magnitude of pump runs (indicated by a short time between pump runs) overwhelms and obscures the data that corresponds to a longer duration between pump runs.

Using an algorithm that detects statistical changes in the time between pump runs, it was discovered that there was a sharp increase in the time between pump runs on November 8th. Because the NILM captures the data in hour-long snapshots, it was even possible to note the hour of this change (1200). Based on this observation, it was decided to split the data set into two parts to be analyzed separately, with the hope that this might unmask any trends hidden by the shear number of runs. Histograms of the time between pump runs for each of the two week periods before and after 1200 on November 8th are shown in Figures 5 and 6, respectively.
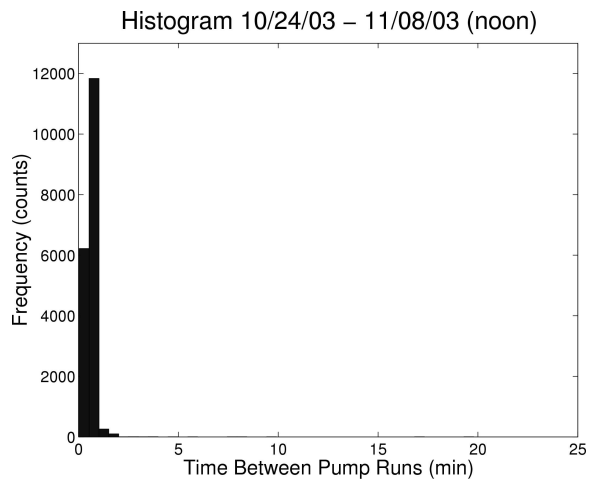

FIGURE 5: *Seneca* time between sewage vacuum pump runs (10/24-11/8)

The data indicates that before noon on November 8th, the average time between pump runs was less than one minute; after noon on November 8th, that number significantly increased. Although there were still some very short time durations between pump runs, the general trend observed in Figure 6 is that the amount of time elapsed between pump runs increased (therefore, the number of pump runs per hour decreased). From this data, it was proposed that some modification or change in sewage system operation occurred on or about November 8th. After checking with the Engineer

Officer of *Seneca*, he relayed that new check valves for the sewage system were ordered on November 6th and installed on either the 7th or the 8th [8]. The faulty check valves created the observed variation in the pump runs.
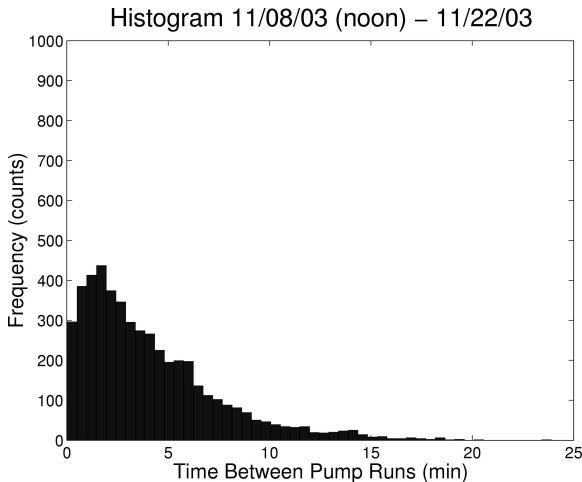

FIGURE 6: *Seneca* **time between sewage vacuum pump runs (11/8-11/22)**

This example illustrates the potential value of continuous monitoring with the NILM. The NILM platform is capable of analyzing operating data like the vacuum pump operation on a continuous, real-time basis. This data could be analyzed in many ways. In this case, a statistical analysis of pump runs can be conducted, updated, and compared to baseline data for a healthy system on an almost continuous basis. Deviations from nominal conditions can be quickly flagged as potential pathological conditions to a watchstander. In the case of the sewage system during normal underway operation, the average number of hourly runs should be between 10 and 12. An increasing number of hourly runs can indicate that the system should be inspected for failed components and/or leaks.

Cycling systems like the sewage system are influenced not only by physical conditions in the system but also by human behavior. For condition-based monitoring to succeed with a minimum number of false alarms, the NILM must be capable of distinguishing a genuine leak from increased system usage. We have been developing metrics that permit the NILM to differentiate between a system leak and heavy crew usage.

In order to correlate the cycling of the vacuum pumps with a fault (leak) in the sewage system, vacuum leaks of various sizes were inserted into the sewage system onboard *Seneca*. The vacuum leaks were controlled (and quantified) by a flow meter attached to the vacuum collection tank gauge line. The throttle valve on the flow meter was adjusted to achieve the desired flow rate. At least 16 hours of underway data was collected for each of 6 different leak rates.

In addition to leak data, two weeks of "no leak" sewage data was also captured. This data not only provided a "no leak" baseline, but it also helped to determine *Seneca's* underway usage patterns. Interesting patterns include the following:

- Flushing is generally constant in a 24-hour period.
- The time of day (e.g. meal time, watch rotations, etc.) doesn't impact flushing/cycling patterns.
- The day of week has no appreciable effect of flushing patterns when the ship is underway.

A problem with performing controlled tests on a cycling system is control of the human element. It is possible to insert vacuum leaks of various sizes into the sewage system and to trend the resulting system cycles. It is more difficult to control usage by the ship's crew. Because of this, we decided to build a statistical model for the sewage system using a MATLAB simulation. For purposes of validation, the results of this simulation were compared to measured data.

Simulation

In order to determine the effects of vacuum leaks and crew usage on system run times, a MATLAB computer simulation was created. The purpose of the simulation was not to fit a computer model to the data, but to permit a thorough exploration of system behavior that might not have been exposed during the underway observations. The simulation assumes that:
- Every flush removes the same amount of vacuum from the sewage system.
- Flushes occur with an exponentially distributed arrival time (Poisson Distribution).

- Leak rate is constant regardless of system pressure (vacuum).

The simulation was run for various leak rates. Figure 7 presents a histogram of the amount of time between pump runs as generated by the simulator. This plot can be used as a baseline histogram to which all other simulated data can be compared.
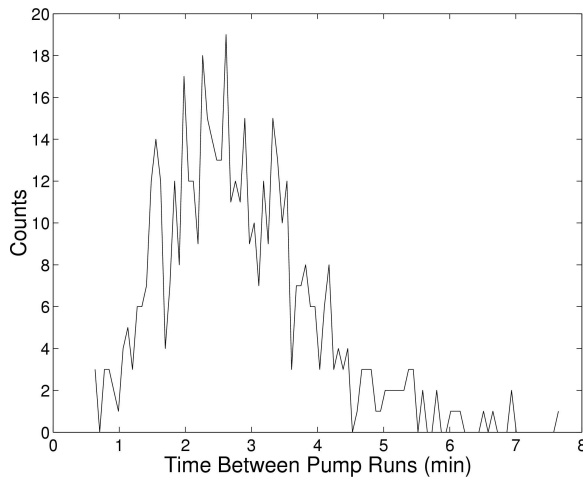

FIGURE 7: Histogram generated from a MATLAB simulation with no leak (24 hours)

Figure 8 shows a similar histogram for a simulated case in which there is a small leak. The dramatic spike in Figure 8 indicates the departure from nominal operating conditions caused by the leak. Thus, this figure suggests that a leak can be detected by the presence of a spike in the trended histogram data.

As shown in Figure 9, which presents a histogram resulting from a simulation with a larger leak rate, increasing leak rates cause the observed spike to shift farther to the left (i.e. an decrease in the time between pump runs) and to increase in amplitude.

The simulated results presented in Figures 7, 8, and 9 suggest that it is possible to observe leaks in the system when the magnitude of the leak is relatively large in relation to the amount of vacuum the system loses with each flush.

Field Tests

Actual sewage system data collected on *Seneca* displays trends consistent with those observed in the simulated data. Figure 10 illustrates seven dif-

ferent histograms collected in the presence of different, known leaks in the sewage system. The small peak in the first "no leak" histogram in Figure 10 is probably due to a baseline loss in the vacuum system. As the rate of the leak increases, its associated peak is generally observed to grow in amplitude and to move to the left on the graph, indicating more frequent operation of the pumps. Our preliminary analysis indicates that the size and location of the peak can indicate both the presence and the extent of a system leak.
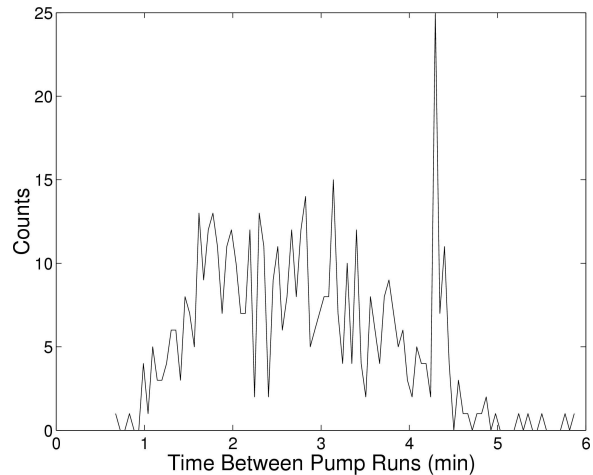

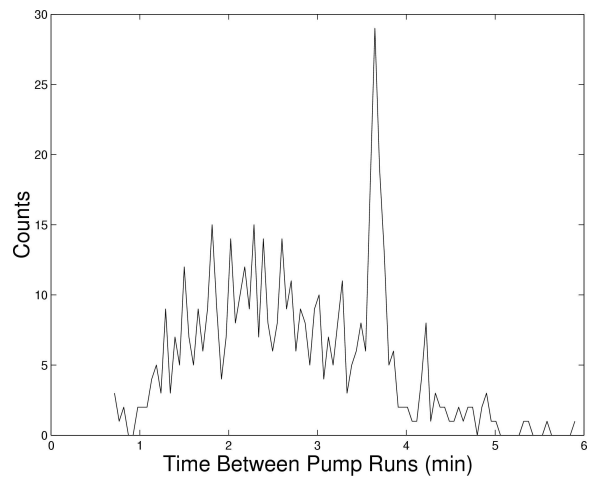**FIGURE 8: Histogram generated from a MATLAB simulation with small leak (24 hours)**

FIGURE 9: Histogram generated from a MATLAB simulation with large leak (24 hours)

These peaks are distinct from the base data in each histogram. This base data appears in both the simulation and in the empirical data to be associated with crew usage. A leak indicator can be developed from this type of histogram, which serves as a metric that indicates the possible presence and extent of a leak.
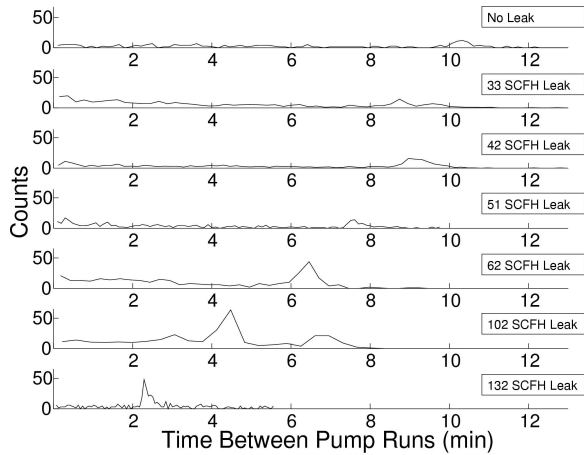
FIGURE 10: *Seneca* **leak data**

Auxiliary Seawater System

Seawater systems are of utmost importance because they cool critical loads. On the *Seneca* we have used the NILM to determine several important operating parameters of the ASW system. In particular, we have used the NILM to determine each of the following: the amount of flow that was sent to heat loads, clogging in the inlet strainers, sudden rapid failure of the coupling between the motor and the pump head, and flow blockage that might occur in any of the heat loads. The last item was of particular importance because *Seneca* crewmembers had made reference to marine growth (predominantly mussels) growing in the end bells of the tube-and-shell heat exchangers in the generators and HVAC units.

The auxiliary seawater (ASW) system onboard *Seneca* provides cooling for all heat loads onboard the cutter with the exception of those associated with main diesel engine cooling. Heat loads that are cooled by this system include the HVAC units, refrigerators, freezers, diesel engine air coolers, and diesel engine lube oil coolers. Suction to the two ASW pumps is taken through two supply lines from the sea chest. Changing the flow rate is accomplished by throttling two butterfly valves at the outlets of the two pumps. In order to balance this system, a pump is started with the overboard throttle valve completely open and the heat load throttle valve shut; the heat load throttling valve is then opened while the overboard discharge valve is partially closed. The overboard discharge valve is throttled until the pressure of

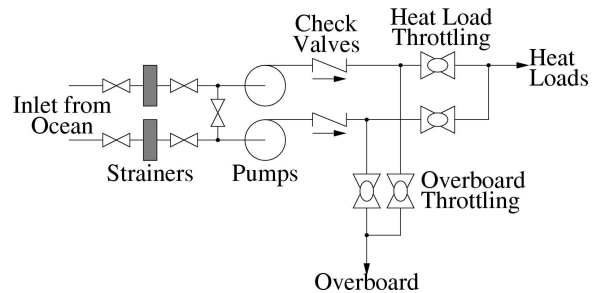the system is measured at 35 psig. Figure 11 shows a line diagram of the system.

FIGURE 11: *Seneca* **ASW cooling system**

Although many useful metrics were derived from the study of the ASW system [10], this paper will focus on the effects of pump power versus flow rate and fluctuations in the real power demanded due to flow obstructions.

Flow Detection

One of the first goals of monitoring the ASW system of the *Seneca* was to investigate if steady state power values could be used as an indicator of flow through the system. To this end, the ASW system was run with the overboard discharge valve throttled to various valve positions while collecting power data. An HVAC unit and two diesel generators were connected to the system as heat loads, and the overboard discharge valve was throttled in order to control the flow to them. In other words, as the overboard discharge valve was closed, there was less water flowing overboard and more water flowing to the heat loads.

The overboard discharge valve is a butterfly valve that has discrete settings from notches cut in the operating handle. A valve of this type is shown in Figure 12.

For each setting of the overboard throttling valve, the pump discharge pressure, heat load pressure (pressure downstream of the heat load throttling valve) and pump power were collected. Only the pump electrical power would normally be available from strict electrical monitoring. In these experiments, we collected all of this information to see if we could establish a reliable correlation between pump electrical demand and cooling flow.

FIGURE 12: ASW throttling valve

We calibrated our measurements by establishing system pressure gauge readings with no hydrodynamic flow. That is, we zeroed the pressure readouts before beginning our experiments. The "no flow" values were 3.0, 1.5 and 6.0 psig for pump one discharge pressure, pump two discharge pressure, and heat load pressure, respectively. These offsets were subtracted from the readings taken from the gauges in order to remove hydrostatic pressures from the readings and to account for error in the gauge zeros. Table 1 summarizes the data recorded for ASW pump one.

Using the pump information contained in [9], the system pressures were converted into flow rates. Among the pump curves plotted in [9] was the total discharge pressure of the pumps versus flow rate. Points on this curve were fit to a third-order polynomial in MATLAB to arrive at an equation relating total discharge head to volumetric flow rate (gpm).

TABLE 1: Pressure and power data for throttling of overboard valve

Notches Throttled	Pump Outlet Pressure	Heat Load Pressure	Pump Power (kW)
1	32	7.75	28.43
2	32.5	8	28.21
3	32.5	8.2	28.18
4	33	9.5	28.01
5	34	12.5	27.87
6	35.5	17.5	27.17
7	41.5	30.5	26.68

The value of flow rate was calculated for each value of discharge head collected onboard *Seneca*. These calculated values represent the total flow rate discharged from the pump, as opposed to the amount of flow going to each heat load. The pump power and flow rate appear below in Table 2.

TABLE 2: Power and flow data for throttling of overboard valve

Notches Throttled	Pump Power (kW)	Total Flow Rate (gpm)
1	28.43	1167
2	28.21	1157
3	28.18	1157
4	28.01	1147
5	27.87	1127
6	27.17	1096
7	26.68	946

The experimental data summarized in Table 2 indicates that measurements of the power consumed by the pump motor can certainly be used to monitor gross changes in the ASW system flow volume. For the substantial flow changes created by the action of the ASW throttling valve, it is possible to use electrical system measurements as either a direct or backup indicator of flow. Based on this observation, we also examined the ASW system to see if more subtle restrictions, such as blockages in branch pipes in the heat load distribution system, could be detected by electrical monitoring.

Power Fluctuations Due to Flow Blockage

An unexpected underway overheat of *Seneca*'s number one ship service diesel generator (SSDG) provided a unique opportunity to observe the effects of obstructions in the fluid system. While underway on routine patrol, *Seneca* was required to secure the number one SSDG due to overheating. Marine growth in the end bells of the SSDG lubricating oil cooler restricted water flow to the cooler. The lack of cooling water caused a temperature rise in the SSDG. Marine growth obstruction is a problem that commonly plagues ships that transit from cold to warm water. In most cases, mussels grow in the end bells of the heat exchangers while the ship is in cold water. They then detach themselves in warm waters, causing a reduction of flow through the heat exchangers.

These flow restrictions involve a relatively small, but absolutely critical, section of the ASW heat load pipes. Even a crippling complete blockage in a small branch pipe may not make a noticeable change in the average power consumed by the ASW pump. The NILM computes and examines the instantaneous aggregate real and reactive power demand of the monitored loads. To attempt to detect flow restrictions, we examined fluctuations in the real power drawn by the ASW pump. Our hope was that flow restrictions might cause noticeable pressure oscillations in the flow that could be detected in the pump electrical signature. In particular, we hoped that these oscillations might appear even if the steady power consumption of the ASW pump was substantially insensitive to a blockage.

Frequency domain analysis has shown that certain loads do not consume power at a steady, unchanging level, even during nominal operating conditions. In a fan, for example, aerodynamic fluctuations and wind can cause rapid fluctuations in the real power consumed by a fan motor [11]. In a fluid pumping system, it is possible that mechanical resonance in the piping system results in a modulation of the pump motor load current. Speculatively, such effects may manifest as higher frequency fluctuations in the real power consumption of the motor.

In the case of the ASW pump, we compared the frequency spectrum of the real power drawn immediately prior to the overheating episode to the frequency spectrum of the real power drawn immediately following the pump's return to operation after cleaning approximately two hours later (Figure 13). From this investigation we noticed that in both cases there was an approximately 10Hz variation in the amount of real power drawn by the pump. More importantly, we also noticed that the magnitude of this variation became significantly reduced once the generator became clogged. Since the ship's logs indicate that the only component in the ASW system whose temperature increased prior to the overheating incident was the number one SSDG, it seems likely that the change in the magnitude of the 10Hz variation was due to the blockage there.

We are working to model the *Seneca* ASW piping system to develop physics-based explanations for these phenomenological observations. If the

power fluctuations can be reliably associated with pathological conditions of interest, they may provide a unique means for detecting maintenance conditions. In particular, it may be possible to detect an impending flow restriction before it becomes crippling.
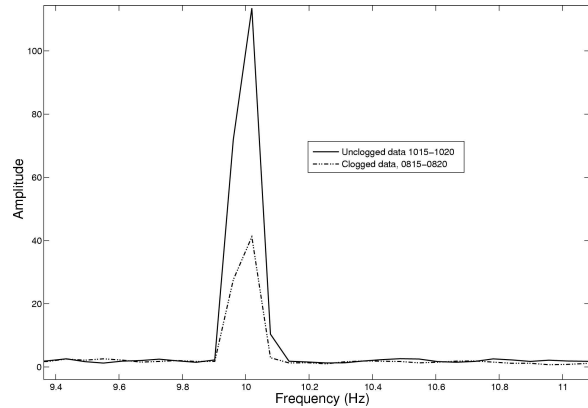

FIGURE 13: 10 Hz variation in the real power drawn by the ASW pump motor.

Steering System

Like seawater cooling systems, hydraulic systems are common across a wide range of ship types and classes. One critical hydraulic system found onboard ships is the steering system. The steering system provides the ship its maneuverability and therefore its status must be known at all times. Monitoring the steering system onboard the *Seneca* provided an opportunity to determine if the NILM could detect any degradation of system performance. Additionally, it was hoped that the NILM could provide a back-up indication of system parameter in the hope of developing a NILM-based autopilot or redundant control system.

Seneca Steering System

The steering system onboard the *Seneca* consists if two 30 hp pumps drawing hydraulic fluid from a common reservoir to a common pressure header. Rudder actuation is accomplished through two 4 in. hydraulic rams (one for each rudder stock). Parallel rudder motion is accomplished through the use of a large tie rod that connects the two rudder stocks Figure 14 shows one of the rudder hydraulic rams and the connecting tie rod.

Electrical Data From the Steering System

During our study of the steering system, real power data was collected while the rudder was "fishtailed" through several different heading angles. First, the rudder was moved from amidships (0 degrees) to left 5 degrees. After a brief pause, the rudder was returned to amidships. After another pause, the rudder was moved to right 5 degrees. This method of rudder movement was continued in 5-degree increments up to 25 degrees of rudder deflection. The power data collected during these tests is shown in Figure 16. Note that the motor run-time is longer when the rudder is ordered to higher angles.

FIGURE 14: Rudder stock and tie rod

The data in Figure 15 shows a variation in the amount of power drawn when the rudders are moving to the left or right. This is due to a difference in the cylinders. When this data was collected, it was noted that cylinder number one would vibrate when the ram was retracted into the cylinder, which is the action performed during the execution of a left turn. Correspondingly, the amount of real power drawn by the motor during a left deflection is lower than that drawn during a right deflection. That is, differences in the two hydraulic cylinders indicate different levels of wear, and create subtle signatures that distinguish right and left turns.

Following a cruise and *Seneca*'s return to port, a new round of testing was conducted with a newly serviced cylinder number one reinstalled in the system. The same "fishtailing" test was performed again. The power data for these tests appears in Figure 16.

The power data plotted in Figure 16 does not show as large a variation in the amount of power drawn when the rudders are moving right as opposed to left as can be observed in Figure 16.

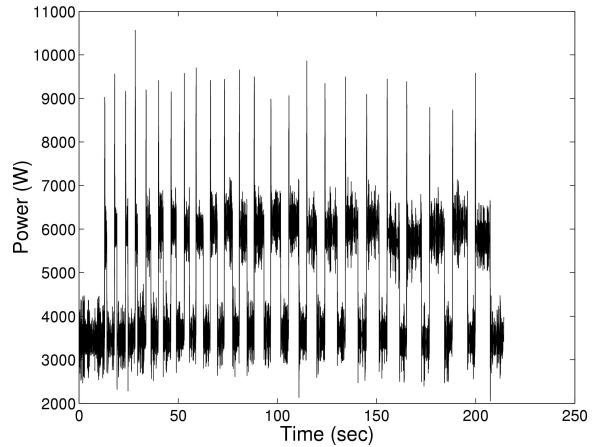There was clearly a maintenance condition present in the number one cylinder.

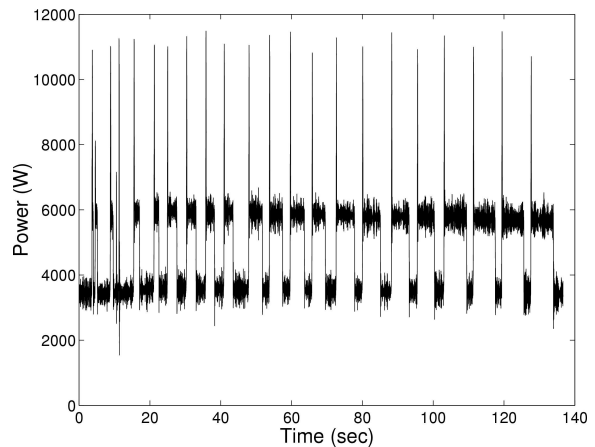**FIGURE 15: *Seneca* rudder transients, both rams, pump 1 running**

FIGURE 16: *Seneca* rudder transients, both rams, after repairs.

The same rudder "fishtailing" was also performed to determine if there is a difference in the amount of power drawn with only one ram functioning. That is, the electrical power was examined for an indication of a gross failure of one of the rams. The power data collected during these tests is shown in Figures 17 and 18.

Figures 17 and 18 show that when there is only one powered ram, there is a noticeable difference between the power drawn by the hydraulic pumps for left and right rudder movement. If ram one is powered, more power is drawn for a left turn, whereas more power is drawn for a right turn if ram two is powered. These experiments indicate that electrical power monitoring is certainly capable of detecting gross failures in the hydraulic sys-

tem, and appears to be capable of detecting subtle degradation in the performance of hydraulic system components as well.

FUTURE WORK

The review of cycling systems, ASW, and steering gear on board the *Seneca* indicates that electrical system monitoring has enormous potential for detecting electromechanical pathologies on board ship. The real time monitoring capability of the NILM could drastically enhance the ability to detect equipment health and reliability issues. Further research is being conducted on all of these systems, especially with the goal of associating observed behavior with physical system models. While space limitations prevent a full review, other shipboard systems also appear to be good targets for electrical monitoring.
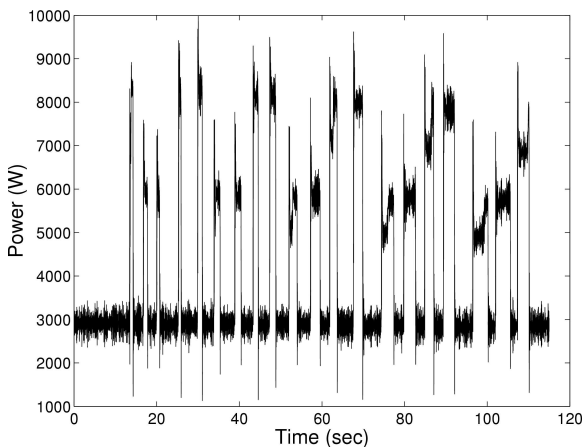

FIGURE 17: *Seneca* **rudder transients, ram 1 only**

Anti-Roll Stabilization Fins

For example, the *Seneca* has fins at the forward end of the hull on the port and starboard sides that are tasked with minimizing the effects of sea state on the roll motion of the ship. Actuation of the fins is hydraulic. Two 30 hp motors are used to drive the pumps that maintain pressure in the system. With the fins in automatic mode, pressure transducers that sense wave motion are used as the control input to position the fins. Actuation speed of the fins is variable and fin motion can be controlled manually.

It is possible that the power consumed by the hydraulic pumps that maintain pressure could be used as an indicator of fin position. It might even be possible to use this power as an indication of

sea-state. Real power data collected during both fast and slow speed motion with deflections of 10 degrees is shown in Figure 19. This data reveals differences that may be associated with the ship headway and sea state.
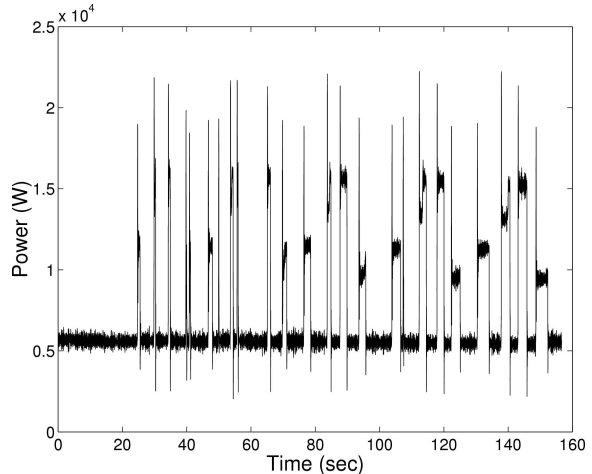

FIGURE 18: *Seneca* **rudder transients, ram 2 only**

Propeller Pitch Control

Another hydraulic system on *Seneca* is the system that maintains pressure for the propeller pitch control. The angle of attack of the propeller blades is adjusted by this system so that the main diesel engines can be operated at maximum efficiency. We are currently gathering electrical monitoring data from this system to understand what diagnostic indicators might be derived from power consumption signals. The NILM data might indicate shaft speed and also may be useful as a backup indication of propeller pitch angle.
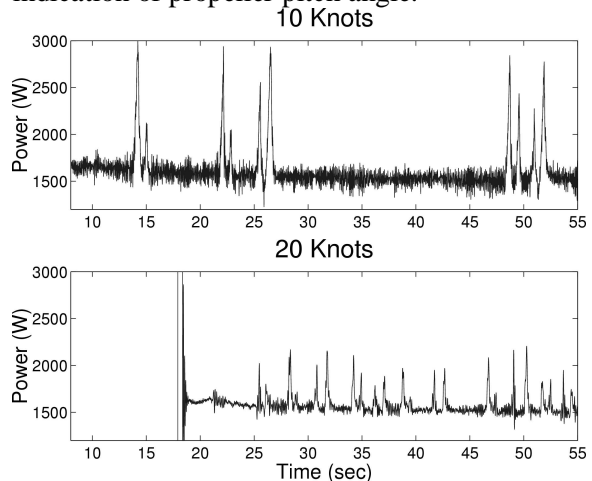

FIGURE 19: Real power consumption of Roll Stabilization Fins, 2 speeds.

CONCLUSION

Field experiments indicate that electrical monitoring could provide near real-time indication of the condition of many critical electromechanical systems on board naval vessels. The results presented here are for systems that are electro-mechanical in nature. The application of the NILM to more "purely" electrical systems such as radar or communications will be explored in the future.

The results presented show the suitability of the NILM for monitoring electromechanical loads on ships. It has also been shown that the NILM is capable of providing backup indications of system performance, trending equipment performance, and detecting different fault conditions. We expect that further development of hardware and software, along with continued research into the behavior of shipboard systems, will allow the NILM to augment existing monitoring systems and potentially serve as a stand-alone indicator of critical system performance.

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