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Using a Ship's Propeller for Hull Condition Monitoring

ABSTRACT

As a ship's hull condition degrades due to marine fouling, more power and fuel are needed to maintain service speeds. A by-product of the increased fuel consumption is increased Green House Gas emissions. Rising fuel costs, hull maintenance expenses, and mounting environmental regulations make hull condition monitoring a crucial tool for prudent ship operators to eliminate energy waste due to hull fouling, reduce carbon emissions, and eliminate the carriage of invasive species between ports.

Methods for using a ship's propeller as a power absorption dynamometer employ the propeller as a measuring instrument to estimate either speed or power. The calibration is typically performed for clean hull conditions, allowing the resulting propeller model to be used to track ship performance degradation due to hull fouling against a standard "clean-hull" baseline.

The propeller power absorption technique is presented, along with the salient results of using it to monitor two Navy sisterships over a year-long time period. This information may be useful for Navy decision makers responsible for hull/propeller maintenance and hull paint selection.

INTRODUCTION

Most ship owners and operators realize that hull fouling causes drag-related speed loss and increased fuel consumption when more power is required to maintain ship service speeds. Hull fouling is also a topic of growing environmental concern and international regulation as it relates to green house gas emissions and the carriage of aquatic invasive species on fouled hulls.
No ship operator can afford to waste energy. Ship performance losses due to hull and propeller fouling can be substantial but have historically been difficult to quantify, since changing ship and environmental conditions introduce a large degree of variability in performance data that makes separation of hull and propeller effects a difficult task. For example, beyond the hull and propeller condition, ship performance measurements will change with draft, trim, rudder activity, wind, waves, currents, water depth, etc. This paper describes a method of separating out these effects and using a ship's propeller as a tool for early detection of hull fouling.

Economic Penalties of Hull Fouling

Most recently, (Schultz et al. 2011) performed a comprehensive estimation of the economic impact of hull fouling on the US Navy's Arleigh Burke-class destroyers (DDG 51). Estimated hull fouling-related costs were based on a range of factors, including extra fuel consumption, hull coatings, coating application and removal, and hull cleaning expenses. As input to this work, predictions of full-scale ship resistance and powering were made for antifouling coating systems across a range of roughness and fouling conditions (Schultz 2007). These estimates were based on scale-model tank testing resistance measurements and similarity law analysis. Based on this, the overall costs associated with hull fouling for the Navy's present coating, cleaning, and historical fouling levels were estimated to be approximately $56M per year and $1B over 15 years for the entire DDG 51 class (56 ships). It is clear that hull fouling is a major expense for the entire Navy fleet. Depending on fouling severity, fleet-wide hull fouling-related costs could fall in the $180M - $540M per year range (Schultz et al. 2011).

The Navy has recognized the importance of hull condition monitoring in their energy conservation guidelines to the fleet (NAVSEA

2010). It is stated therein that fuel consumption increases caused by hull and/or propeller fouling are often the largest single cause of excess fuel consumption. It is also recommended that hull and propeller cleaning be condition-based, but rather than directly measuring performance losses, as described in this paper, the Navy regularly schedules hull inspections by divers. These visual inspections provide useful information on hull condition, but do not offer quantified performance loss data that can be further employed for optimal hull and propeller maintenance strategies.

The Naval Ships Technical Manual CHAPTER 081 (NAVSEA 2006) provides that latest official guidance on waterborne underwater hull cleaning criteria to maintain a vessel's optimum performance.

Modern Hull Coating Technologies

Marine bio-fouling increases the frictional drag of a ship's hull, thereby requiring more power and fuel to maintain operational speeds. Marine growth can be retarded through the use of anti-fouling paint and until about a decade ago, the majority of ship hull coatings were tributyl-tin (TBT) self-polishing co-polymers. Through a steady release of the TBT toxin, ships could be kept free of fouling for up to 5 years. Unfortunately, due to TBT's negative environmental side effects, the International Maritime Organization (IMO) imposed a ban on TBT paint, leading paint manufacturers to develop non-toxic alternative paint systems. Amongst these paint alternatives are low-copper and copper-free ablative antifouling (AF), foul release (FR) coatings, and surface treated coatings (STC).

ABLATIVE ANTIFOULING

Ablative/self-polishing AF paints have typically contained biocides mixed into co-polymer paint. The surface layer of paint is gradually dissolved *("ablated")* by the seawater, revealing fresh biocides that were buried beneath. For this reason, several coats of paint can be built up to provide effective protection for many years. Since they contain biocides, normal ablative types offer excellent anti-fouling performance. Surface roughness after the self-polishing process is designed to be less than when originally applied. Most manufacturers of ablative AFs have several types, designed for different ablation rates, depending on fast, medium, or slow speed service.

(Yebra and Catala 2011) discuss the advantages of new formulations of silylated acrylate (SA) coatings being offered by most major paint companies. This self-polishing, biocide paint is reportedly effective for up to 90 months, with dynamic exposure test results to date showing that it is half as rough as a comparable copper acrylate. But as these authors point out, there is a lack of reliable studies linking AF performance to fuel consumption and a scarcity of accurate performance monitoring systems that can be used to quantify the economic benefits of competing coating systems.

FOUL RELEASE

Foul release or "low surface energy" coatings act to prevent hull fouling by providing a low-friction surface onto which marine organisms have difficulty attaching. If vessels are stationary for short periods of time, fouling may occur, however; there will be a weak bonding between the fouling organisms and the coating surface. The organisms may be subsequently removed by either the hydrodynamic forces on the hull when the vessel transits at a sufficiently high speed or by underwater cleaning. The lifetime of foul release coatings may be limited as they are mechanically soft and easily damaged. Underwater cleaning must be done with soft brushes which may not remove all fouling organisms, for example after longer in-port periods. In addition, mechanical damage to the hull may result in local unprotected areas that will eventually require touch-ups in dry-dock.

SURFACE TREATED COATINGS

Surface treated coatings consist of large glass-platelets suspended in a reinforced vinyl ester resin. The hull coating is conditioned by divers

following ship launch using mechanical brushes. Additional cleanings are performed on an as needed basis and, due to its non-toxic properties, without adversely affecting the marine environment. Since the hull surface is hard and can withstand many cleanings, long-term service life is possible (e.g. 20 years), and the coating becomes smoother after each cleaning.

A comprehensive summary of antifouling coating technology as of 2004 is provided in (Yebra, Kiil, and Dam-Johansen 2004). Although there are several non-toxic paint systems currently available, the apparent marine industry consensus is that there is no paint technology yet available that is comparable in performance to TBT-based underwater hull coatings. This has resulted in a significant amount of R & D to find better solutions. Definitive results can only come from operational ship performance monitoring, as opposed to laboratory testing. The economic choice between alternative paint systems is not a straightforward decision in today's climate, as each paint manufacturer claims similar fuel savings can be obtained by using their products. Clearly, an accurate hull monitoring capability that measures actual performance differences to prove or disprove marketing claims, rather than relying on paint company-sponsored studies, could be put to good use in support of ship operators' purchasing decisions.

Naval vs. Commercial Ship Operations

As noted in (Schultz et al. 2011), naval vessels represent a unique challenge to paint manufacturers because of the extent of their time spent pierside, compared to commercial ships. This is a particularly important operational characteristic when considering paint containing no antifouling properties, such as FR or STC. As discussed in this paper, viable solutions for fast-moving commercial vessels may not work well for naval vessels. The U.S. Navy continues to investigate antifouling coatings offering effective fouling control for ships operating in all geographic areas, with the goal of reducing hull cleaning and dry-docking frequency.

Environmental Regulatory Pressure

Ship hull fouling can impact the environment in several ways:

1) extra power and fuel consumption are needed to maintain ship service speeds, thereby increasing green house gas emissions,
2) periodic hull cleaning for fuel economy can pollute marine environments with toxic paint residuals, and
3) aquatic invasive species resident on a ship's fouled hull may be transported from port to port, damaging ecosystems and creating hazards for livelihoods, human health, and local economies.

The IMO, among others, will continue to impose both direct and indirect regulatory pressure on ship operators to keep their hulls clean. Ongoing global regulatory issues are covered in some detail in (Hydrex 2010, 2011).

Purpose of Paper

Ship performance monitoring traditionally has been a complex subject, requiring a deep and diverse background in naval architecture, marine engineering, mathematics, statistics, and more recently, computer science. The subject has a long and rich history, spanning the better part of a century and leaving a wide trail of research literature. Surprisingly enough, ship performance analysis still seems today to be somewhat of a "black art", requiring highly specialized knowledge and skills.

The author spent nearly seven years researching the subject during the oil crisis of the 1970's (Logan 1980), and after pursuing other areas was surprised to learn that practical techniques for assessing the performance of a ship at sea have changed relatively little during the past 35 years. For example, using logbook data, recorded periodically by a ship's crew, not only creates an added work burden, but more importantly creates a dependency on crew diligence for data quality that, more often than not, prevents high accuracy results from being

obtained. This can mean the difference of saving a few percent in fuel or not. Another example is the reliance on various resistance models (e.g. wind and wave effects), developed decades ago using model testing, to predict performance losses for an altogether different full-scale ship!

The constraints on ship performance analysis techniques that were practical and useful 35 years ago were generally related to data quality. With modern sensor and computer technologies, as well as the extensive automation systems installed on today's vessels, these constraints no longer apply. High speed data acquisition, low-cost computers, and advanced database technology are now at the practitioner's disposal to eliminate past barriers to achieving the high accuracy ship performance models needed to measure even small effects to save fuel.

This paper highlights an innovative technique of using a ship's propeller, coupled with modern data acquisition and database methods, to accurately track power increase due to hull fouling. *It is amusing to note that this "innovation" was developed in 1926!* Contrast is made to more recent and complex resistance-based modeling. The propeller power absorption technique is demonstrated through the analysis of two naval sisterships being used to evaluate alternative hull coatings in an ongoing study for the U.S. Navy Military Sealift Command.

SHIP PERFORMANCE MONITORING

Factors Effecting Ship Performance

There are many ship and environmental factors which can influence the speed/power performance of a ship. These include:

Ship factors: Draft, trim, steering/rudder activity, operating transients (e.g. speeding up or slowing down), hull condition, propeller condition

Environmental factors: Currents, wind, waves, water density and temperature, water depth, air humidity and temperature, barometric pressure

The effects of these factors are complex and have been studied for decades by the international maritime research community. Historically, mathematical models have been derived to estimate the effects of each variable. Once developed, the models are then used to correct speed and/or power performance to some "standard baseline" set of conditions (e.g. calm weather, specific draft/trim condition, etc.). Model development is an expensive, time-consuming effort, usually performed through ship model testing in a towing tank facility. Model development and validation through full-scale ship trials requires a large data set covering a multitude of ship and environmental conditions, which may take many years to accumulate.

Traditional Approach

The technical literature abounds with references describing ship resistance modeling approaches to ship performance analysis. Detailed theoretical foundations can be found in (Todd 1967) and (Carlton 2008), as well as numerous technical papers from various conferences and symposia in the interim years. Depending on the focus of various authors, there appears to be significant variation in the components of ship resistance included in the total ship resistance equation.

RESISTANCE MODELING

The estimation of ship resistance is crucial in determining required engine power and the selection of the correct propeller to move a ship at its design speed. Ship powering prediction is a well-developed field and resistance modeling plays a central role.

The power required to overcome total resistance is defined as:

$$P = cR_T V \quad (1)$$

Where: $P = power,$
$R_T = total\ resistance,$
$c = constant, and$
$V = speed\ through\ water.$

Total resistance is comprised of a number of components related to various sources of resistance that have complex interactions with each other.

The following components are commonly considered to comprise total calm-water resistance, R_T (Todd 1967):

1) frictional resistance
2) wave-making resistance
3) eddy resistance
4) air resistance

Additional resistance will come into play when a ship experiences heavy weather and considerable research has been performed to quantify these effects. (Carlton 2008) references some of these techniques, but in general, most practical methods for estimating weather-related resistance rely on model testing, either for deriving regression equations or empirical correction factors.

RECENT WORK

One of the most recently published works describing the practice of ship performance monitoring can be found in (Aas-Hansen 2011). Although newly published, the book describes the decades-old, traditional approach of attempting to quantify the effects of hull and propeller fouling by first removing or correcting for all other factors that affect ship resistance. These factors include those previously mentioned (i.e. wind, waves, etc.).

The book describes detailed mathematical models founded on known principals of naval architecture and previous experimental work by several researchers, but lacks information regarding the expected accuracy of ship performance predictions based on these techniques.

In a recent study of the economic impact of hull fouling for the US Navy (Schultz et al. 2011), resistance models were used for predictions of full-scale ship resistance based on scale-model tank test measurements and similarity law analysis (Schultz 2007).

PROBLEMS WITH TRADITIONAL APPROACH

Because not all researchers include all components of resistance in their work, the power prediction results are inconsistent. Typically, a separate model is developed for each resistance component and component interaction effects are largely ignored.

Resistance models developed by many researchers remain unvalidated against actual ships. The correlation allowance is essentially a correction factor applied to align power estimates from model tests with results from ship trials (Bose and Molloy 2009). Correlation allowances are sometimes considered as proprietary information by model basins; as such, technical details of their derivation remain obscure. Correlation allowances vary with the extrapolation method used and are somewhat dependent on the tank facility at which testing is performed.

Model-ship extrapolation relies heavily on the work of Froude from more than 100 years ago. Froude's *Law of Comparison* was established experimentally and is not a rigorous physical law.

(Bose and Molloy 2009) provide an examination of the accuracy of frictional resistance coefficient values. They stated that historically these values have been found from experimental results and that there is no absolutely accurate way to separate the frictional resistance from the total resistance measured during a ship model test. It is therefore important to know the level of uncertainty in the powering prediction process from these sources. Uncertainty in the extrapolation process stems not only from the results of the model tests, but also in the assumptions made in formulating the method, the analysis methods employed to estimate

parameters in the analysis, and in selection of variables.

(Pedersen and Larsen 2009) note the difficulties of traditional ship performance analysis techniques requiring the estimation of a number of unknown friction-related coefficients, often from limited model test or empirical full-scale trials data. As an alternative to resistance modeling, their research outlines a method of using artificial neural networks to predict propulsive power from the same theoretical variables influencing ship resistance, such as ship speed, relative wind speed and direction, air temperature, and sea water temperature. Using actual ship datasets segmented by draft and trim conditions, they report propulsion power prediction accuracy of greater than 2.7%, compared to range of 18-28% using traditional resistance techniques (Pedersen and Larsen 2009).

PROPELLER MODELS

Calibration of Propeller as Speed/Power Measuring Device

Methods for using a ship's propeller as a speed or power measuring device were established at least eighty years ago. A propeller calibration procedure using actual ship data results in a quantitative model specifically chosen to represent clean hull and calm weather conditions. Once this calibration has been performed, the resulting propeller model can be used to track speed and/or power changes over time by continually comparing the current ship's performance to the baseline "clean hull" performance. Significant differences from the baseline will be indicative of hull and/or propeller degradation. The analytical methods are primarily based on the power diagram work of Telfer (Telfer 1926, 1964).

TELFER'S METHOD

(Telfer 1926, 1964) developed a simple yet effective method for calibrating a ship's propeller as a power absorption dynamometer over a range of slip conditions. He defined a torque constant, Q_c, and developed a slip function to allow it to be used to monitor for hull fouling. The torque constant was defined as:

$$Q_c = \frac{100Q}{\rho n^2 D^{3.5} H^{1.5}} \quad (2)$$

where:

$Q = propeller\ torque$
$\rho = seawater\ density$
$n = propeller\ rpm$
$D = propeller\ diameter$
$H = propeller\ pitch$

He then defined a simple linear relationship between Q_c and apparent slip, S_a, as follows:

$$Q_c = a + b\,S_a \quad (3)$$

The calibration procedure essentially involves determining the slope and intercept of equation (3) from ship trials, presumably during acceptance trials or following hull and propeller conditioning in drydock.

As with any similar type of linear curve fit, the wider the variation of the independent variable in the test data set, the more accurately the model can be fitted. Because slip may not vary substantially during a sea trial, Telfer developed the following expression for the torque constant at the 100% slip condition (denoted as the constant C):

$$C = \left(8 + \frac{Z^2}{8}\right)\sqrt{\alpha}\sqrt[4]{\frac{H}{D}} \quad (4)$$

where:

$Z = no.\,of\ propeller\ blades$
$\alpha = disc\ area\ ratio$

$\frac{H}{D} = face\ pitch\ ratio$

The average values of the torque constant and slip, $\overline{S_a}$, $\overline{Q_c}$, were determined from sea trials, providing a second data point with which to calculate the unknown coefficients in equation (3).

Using the known data points, (1, C) and ($\overline{S_a}$, $\overline{Q_c}$), and simple algebraic equations for straight lines, the slope, b, can be determined as follows:

$$b = \frac{(C-\overline{Q_c})}{(1-\overline{S_a})} \quad (5)$$

The intercept can then be determined:

$$a = C - b \quad (6)$$

This completes the calibration for the "clean-hull" condition. Equation (3) can now be used to monitor hull/propeller condition. There are various ways in which this can be accomplished. (Telfer 1964) chose to monitor the changes in the slope, b, of the model, noting that b will increase with hull fouling. A different method will be presented in the following.

Telfer's work has not been highly publicized over the years, although it has been the basis of ship performance monitoring by several researchers, including (Townsin, Moss et al. 1975), (Bustard 1978), (Townsin, Byrne et al. 1980), (Logan et al. 1980), and (Townsin and Svensen 1980).

MODIFIED APPROACH

The approach taken in this work more closely follows that of (Bustard 1978), although the same principals as described by Telfer apply. Instead of developing the Q_c-S_a relationship as Telfer does, Bustard develops an equivalent linear relationship between SHP/n^3 and V_a/n, where V_a is the inflow velocity to the propeller. In order to do so, a suitable value for Taylor wake fraction, w, must be estimated from performance data, since:

$$V_a = V(1-w) \quad (7)$$

The relationship between SHP/n^3 and V_a/n derives from the well-known equations for the propeller torque and advance ratio coefficients:

$$K_q = \frac{SHP}{\rho n^3 D^5} \quad (8)$$

$$J = \frac{V(1-w)}{nD} \quad (9)$$

where:

SHP = shaft horsepower
V = ship speed through water
Kq = torque coefficient
ρ = density of seawater
n = rotational speed
D = propeller diameter
J = advance ratio
w = Taylor wake fraction

The propeller open water characteristics define a linear relationship between K_q and *J* within the normal working range of the propeller. Similar to Telfer, this is essentially a torque-slip function and once known, can be used to estimate shaft power from rpm and speed or, alternately, to estimate speed from rpm and shaft power (Logan et al.1980). Figure 1 illustrates typical propeller open water characteristic curves. The typical operating range of {*J, K_q*} values is relatively small and their relationship is linear within this range.

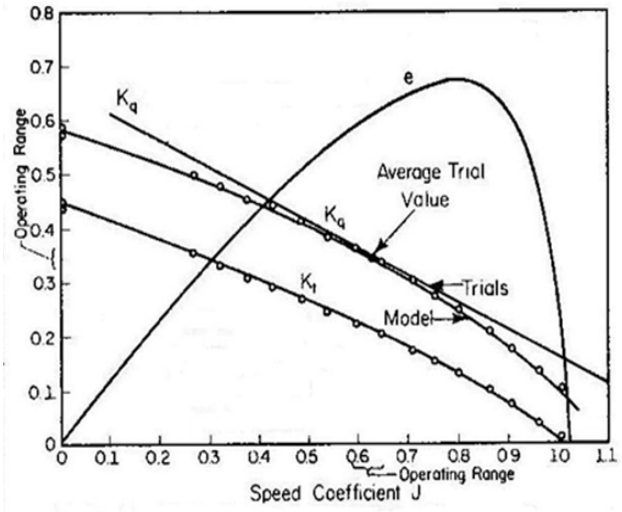

Figure 1 - Typical Propeller Open Water Characteristics Relating K_q and *J*

Since K_q and *J* are linearly related within the normal working range of the propeller, by combining the constant terms relating to seawater density, propeller diameter, and wake

fraction, the preceding equations (8) and (9) indicate that the power ratio defined by SHP/n^3 will be linearly related to the speed ratio defined as V/n.

The intent is to define a propeller power absorption model for a standard set of baseline conditions, which will include clean-hull, calm weather, fixed draft and trim, and constant conditions for all other slip factors. In this case, wake fraction in equation (9) may be assumed constant.

The essence of Telfer's original work is that shaft torque and rpm are related to propeller slip, which embodies speed through the water.

Factors that affect propeller slip include:

- Draft
- Trim
- Propeller pitch (for ships with controllable pitch propellers (CPP)
- Current
- Weather-induced ship motions
- Rudder-induced ship motions
- Operating transients (rapid power and speed changes)
- Hull and propeller fouling

As noted in (Bustard 1978), "the propeller does not sense wind, waves, fouling, or any other resistance. It does sense a reduction in the rate of inflow". All factors above that influence slip also impact the inflow water velocity to the propeller. The ship performance problem is one of separating out these individual contributors to slip (inflow) variation.

Regarding draft and trim, it is easy enough to calibrate the propeller based on the most common loading conditions and then use the technique only for those (baseline) conditions to assess hull condition. For a tanker, two separate calibrations can be performed (e.g. loaded and ballast conditions). For other vessels, it is easy enough to determine the most frequent loading conditions from past voyage data and then calibrate to those conditions. Note that the technique easily lends itself to determining the relative power absorption at different draft and trim conditions as historical data is archived covering the full range of variation of each parameter. This lends itself readily to trim optimization applications. A similar approach can also be taken to quantify performance losses due to heavy weather.

For the purposes of hull condition monitoring, the effects of current, weather-induced ship motions, rudder-induced ship motions, and transients can be eliminated through advanced data filtering to exclude data containing these effects from the analysis. Baseline conditions are established to allow filtering of all data not meeting the baseline criteria. For example, a comparison of GPS-derived speed over ground to speed log-derived speed through water will indicate the magnitude of current and a threshold "tolerance" can be established. Heavy seas are usually accompanied by strong winds, so wind speed provides a commonly available measurement by which to filter out a "calm-weather" data set to allow more accurate calibration. For ships with fixed-pitched propellers, slip variation due to heavy weather may actually help with the calibration, as it will provide data with a wider range of slip variation from which to estimate the coefficients in equation (3) (Telfer 1964).

Hull and propeller fouling are the long-term effects of interest. Presumably, the data used for calibration represents "clean-hull" conditions immediately following drydock. So hull fouling effects are not present at the time the calibration is performed (although roughness due to the quality of paint application will have an influence). After such data filtering, all that remains left to consider from the slip contributors listed above is propeller pitch, as pertaining to CPP ships.

After filtering performance data to meet the established baselines discussed above, the main source of slip variation remaining in data for CPP ships will be propeller pitch. In this case, the torque-slip relationship of eq. (3) may be revised without losing meaning as follows:

$$\frac{SHP}{n^3} = c_1 + c_2\, H \qquad (10)$$

In this work, the term $\frac{SHP}{n^3}$ will be referred to as the *Power Ratio*.

Furthermore, since the Power Ratio is equivalent to the propeller torque coefficient, K_q, from eq. (8), and it is linearly related to the advance ratio, J, a *Speed Ratio* similar to (Bustard 1978) can also be defined:

$$\frac{V}{n} = c_3 + c_4 H \qquad (11)$$

For the CPP type ship, equations (10) and (11) relate propeller shaft power, revolutions, and ship speed through the water to the only remaining source of slip after data filtering to baseline conditions, that being propeller pitch. In this work, it was found that the reciprocals of the speed and power ratios yielded slightly more accurate estimates than the forms of equations (10) and (11) and were used without changing the validity of the foregoing description.

High-Accuracy Performance Analysis

As simple as it may appear, the technique was used to consistently predict ship power with less than 0.5% error, even from manually collected ship logbook data (Telfer 1926). Telfer further indicated that similar levels of accuracy were obtained for several ships under his study.

(Bustard 1978) also reported good accuracy using his slightly modified technique in the analysis of the tanker *Esso Edinburgh* data, showing an average absolute error of 1.0% across the first six voyages of a seven-month drydocking cycle. The technique readily showed the onset of fouling during the sixth and seventh voyages, after which drydocking was shown to restore performance. Accuracy was determined by comparing model-based SHP to that measured via torquemeter.

Similar accuracy levels were found in this work and will be discussed further. As a preview, the average speed and shaft horsepower errors found here for one test ship were -.10% and -.13%, respectively, over a baseline data set of 3325 records. The average absolute errors (i.e. absolute value function removed negative values) were 1.8% for speed and 0.9% for shaft horsepower over the same 3325 record dataset.

Ship performance monitoring methods typically have difficulty eliminating data scatter due to varying ship and environmental conditions, hampering the ability to detect small performance losses early in the hull fouling evolution. Higher accuracy allows detection and quantification of hull-related losses at the earliest possible time, allowing improved maintenance planning and more fuel savings to be achieved. As pointed out in (Schultz et al. 2011), even small percentage losses can result in large fuel penalties.

Separation of Hull and Propeller Effects

The separation of hull fouling from propeller fouling is generally not possible without both shaft torquemeter and shaft thrustmeter measurements. Torquemeters are in common use, but thrustmeters are rarely installed.

In an attempt to develop a method by which hull and propeller effects could be separated without relying on a thrustmeter, (Wan, Nishikawa, and Uchida 2002) developed an experimental method by which the relationship between the torque coefficient, K_Q, and the thrust coefficient, K_T, was determined experimentally through model testing with varying degrees of propeller roughness.

By knowing how the K_Q-K_T relationship changes with fouling (i.e. surface roughness), K_Q was calculated from onboard torque measurements (Uchida and Nishikawa 2005). K_T was then estimated from the K_Q-K_T relationship without relying on thrust measurements. Uchida found that increased fouling will generally cause K_Q to increase and K_T (and propeller efficiency) to decrease.

For a given propeller installed on a ship, practical considerations will prevent experimental determination of surface roughness effects as outlined in (Wan, Nishikawa, and

Uchida 2002). Hence, for the work described in this paper, as well as in most other reported ship performance analysis techniques, only the combined effects of hull and propeller fouling can be determined. Fortunately, it is the combined effect on fuel economy that most ship operators are concerned with, hence the rare use of thrustmeters on ships. Most prudent ship operators have adopted a time-based propeller maintenance approach relying on regular diver inspections and cleanings.

The remainder of this paper describes the application of the techniques just described in an ongoing study to evaluate the relative effectiveness of alternative hull coatings on two Navy sisterships operated by the Military Sealift Command (MSC).

HULL PAINT STUDY

In 2009, MSC initiated a comparative study of the cost benefits of foul release paint over the biocide ablative paint traditionally used on MSC vessels.

Two identically designed, 667 foot fleet oilers, the USNS Kanawha (T-AO 196) and the USNS Big Horn (T-AO 198), were selected as the test ships based on their drydocking schedules.

The Kanawha was coated with a biocide-free, fluoropolymer foul-release coating during her Summer 2009 drydocking. The Big Horn was painted with a tin-free, self-polishing, biocide anti-fouling coating during Fall 2009. Both ships are outfitted with dual CPPs, but of slightly different designs, which influences their respective baseline speed/power performances.

Automated data acquisition systems were installed on both ships to monitor hull performance throughout the study period. Data was regularly transmitted ashore for analysis. The Kanawha's propeller models were calibrated from a 3326 record data set collected during the September-November 2009 time period immediately following drydock.

Big Horn's propeller models were calibrated from a much smaller dataset (392 records) collected during December 2009 through February 2010 time period immediately following her drydock. The smaller dataset is attributed to the limited number of days Big Horn operated at sea during this time period.

Data Management

ONBOARD DATA ACQUISITION

Automated data acquisition systems were installed on both test ships during their last drydocking periods in the fall/winter of 2009. No additional effort on the part of the ship crews was required for collecting the data needed for this study. This was accomplished by leveraging two existing shipboard systems, the DEXTER Ship Health Monitoring System (MACSEA 2011) and MSC's Shipboard Automated Maintenance Management (SAMM) system, both of which were already installed on the test ships. The DEXTER system acquires real-time machinery and navigational performance data, while SAMM records periodic manual entries of typical logbook data, such as drafts, sea state, etc. SAMM also manages periodic data replication to a shore side data center.

DATA ELEMENTS

Table 1 lists the salient data items for this study. All data are timestamped and archived once per minute.

Table 1 – Salient Ship Performance Data

Description	Source	Units
Ship Speed Over Ground	GPS	KTS
Ship Heading - True	GPS	Degrees
Ship Heading - Magnetic	GPS	Degrees
Ship Speed Through Water	Speed Log	KTS
Wind Angle	Anemometer	Degrees
Wind Speed	Anemometer	(K/M/N)
SHP (Port/Stbd)	Torque meter	SHP
Shaft Torque (P/S)	Torque meter	FT-LBS
Shaft RPM (P/S)	MCS	RPM
Propeller Pitch (P/S)	MCS	Degrees
Engine BHP (P/S)	MCS	BHP
Engine RPM (P/S)	MCS	RPM
Throttle (P/S)	MCS	%
Engine Fuel Consumed (P/S)	MCS	Gal/HR
Forward Draft	SAMM	Feet
Aft Draft	SAMM	Feet
Sea State	SAMM	Beaufort #
Sea Direction	SAMM	Degrees

STANDARD BASELINE CONDITIONS

As previously discussed, there are many ship and environmental factors which influence the speed/power performance of a ship. These include:

Ship factors: Draft, trim, steering/rudder activity, operating transients (e.g. speeding up or slowing down), hull condition, propeller condition

Environmental factors: Currents, wind, waves, water density and temperature, water depth, air humidity and temperature, barometric pressure

Within the context of this study, it was desirable to eliminate the effects of all major factors except the combined hull/propeller effects. With performance data being recorded once per minute, the abundance of data allows the use of database filtering to remove records that do not meet standard baseline conditions defined in table 2.

Table 2 – Baseline Conditions for Ship Performance Analysis

Parameter	Baseline Condition
Mean Draft	[32, 35] feet
Trim	[1, 3] feet
Speed through water	≥ 10 knots
$Speed_{diff}$ = Water - Ground Speed	± 3%
Sea State	≤ 3 (Beaufort)
Wind Speed	≤ 15 knots
STW Rate of Change	≤ .25 knots/minute
Mean Shaft RPM* Rate of Change	≤ .5 rpm
Total SHP (both shafts)	[5000, 11,000] SHP
Port/Stbd Pitch Difference	≤ .3 feet
Port/Stdb RPM Difference	≤ .5 rpm

Draft and Trim

Baseline draft and trim conditions were established on the basis of values at which the ship normally operates the majority of the time.

Speed Through The Water

Only data records for which speed through the water was 10 knots or greater were considered for analysis. This speed also happens to be the lower limit at which fouling release is designed to occur for this type of hull coating.

Eliminating Ocean Current Effects

The effects of ocean currents, weather, and to some extent, rudder activity, can be eliminated by analyzing only data in which speed over the ground (SOG) and speed through the water (STW) closely match. The presumption is that without significant influence of these perturbations, SOG and STW will be roughly the same, as the ship traverses a relatively straight course. The following speed difference metric was used as a data filter:

$$Speed_{Diff} = \frac{(STW - SOG)}{STW} \quad (12)$$

Any data exceeding 3% agreement between STW and SOG was filtered out from the analysis.

Eliminating Wind and Wave Effects

Wind resistance and heavy weather/wave effects have a significant impact on ship performance. Within the data items listed in table 1, there are several parameters available to filter out heavy weather data:

Sea state – This is a manual entry in SAMM logbook, entered as a Beaufort Number, as subjectively determined by the crew. Only data records for which sea state was Beaufort 3 or less were considered for analysis.

Wind speed – Only data records for which wind speed was 15 knots or less were considered for analysis.

Transient Operating Conditions

The propeller models discussed previously are designed for use in steady state operations. Hence, the models should not be used during sudden changes in ship speed or RPM during course changes or maneuvering situations when slip variation occurs. With data being recorded once per minute, consecutive records were assessed to determine the Rate of Change (ROC) for both speed through the water (STW) and mean propeller RPM. Only data records with STW ROC of .25 knots or less were considered for analysis. Only data records with mean shaft

RPM ROC of .5 revolutions or less were considered for analysis.

Shaft Horsepower

The torque meters installed on each propeller shaft provide an indication of shaft horsepower (SHP). Total SHP was calculated as the sum of the port and starboard SHP readings. In order to eliminate extreme power conditions which influence accuracy, only data records for which total power was in the [5000, 11,000] range were considered for analysis.

Synchronized Propeller Operation

The propeller models assume equal contribution of the port and starboard propellers and basically treat the combined effect of the two as a single propeller. The ship generally operates with equal pitch and revolutions for the two propellers, however; this is not always the case. Since the effects of unequal settings are unknown, a data filter was established to ensure equal pitch and RPM readings on the two shafts. Only data records for which the difference in pitch settings between the port and starboard shafts was .3 feet or less were considered for analysis. In addition, the difference in RPM readings between the port and starboard shafts was required to be within .5 revolutions.

Propeller Calibration Models

The Kanawha's propeller models were calibrated from a 3326 record data set collected during the September-November 2009 time period immediately following drydock. Due to limited ship operations, this time period was necessary to establish an adequate range of pitch variation in the filtered data set used for the calibration.

As previously noted, the reciprocals of the speed and power ratios (i.e. n/V and n^3/P) provided slightly higher accuracy, so they were used as the basis for model development. Figure 2 shows a plot of the power ratio versus pitch for the Kanawha baseline dataset, filtered to the standard conditions listed in table 2, along with its linear regression model. The power ratio is highly correlated with pitch, with the linear model accounting for over 97% of the variance in the data. Figure 3 shows a plot of the speed ratio versus pitch for the Kanawha baseline dataset, filtered to the standard conditions listed in table 2. The linear regression model is a good fit, accounting for approximately 95% of the variance in the data

Similar high correlation was also found for the propeller models developed for the Big Horn.

Key Performance Indicators (KPIs)

The calibrated propeller relationships are used to estimate clean-hull speed through the water and shaft horsepower over time. By comparing these estimates to actual measured ship values, the KPIs of speed loss and power increase can be monitored, providing a clear signal of hull fouling. Power increases attributable to fouling can be readily converted into fuel and emission increases and tracked as well.

INCREASED POWER ABSORPTION

The power ratio, P_{ratio}, is linearly dependent on propeller pitch under the established baseline conditions. The derived model, representative of clean hull, baseline conditions, can be used to estimate SHP from measured RPM and pitch as follows:

$$P' = \frac{n^3}{P_{ratio}} \tag{12}$$

where:

$P_{ratio} = c_1 + c_2 * H$ (model)
n = mean shaft RPM
c_1, c_2 = model coefficients

A deviation metric is tracked over time to monitor power increase:

$$\Delta Power(t) = SHP(t) - P'(t) \tag{13}$$

As the hull/propeller condition degrades, $\Delta Power(t)$ will increase.

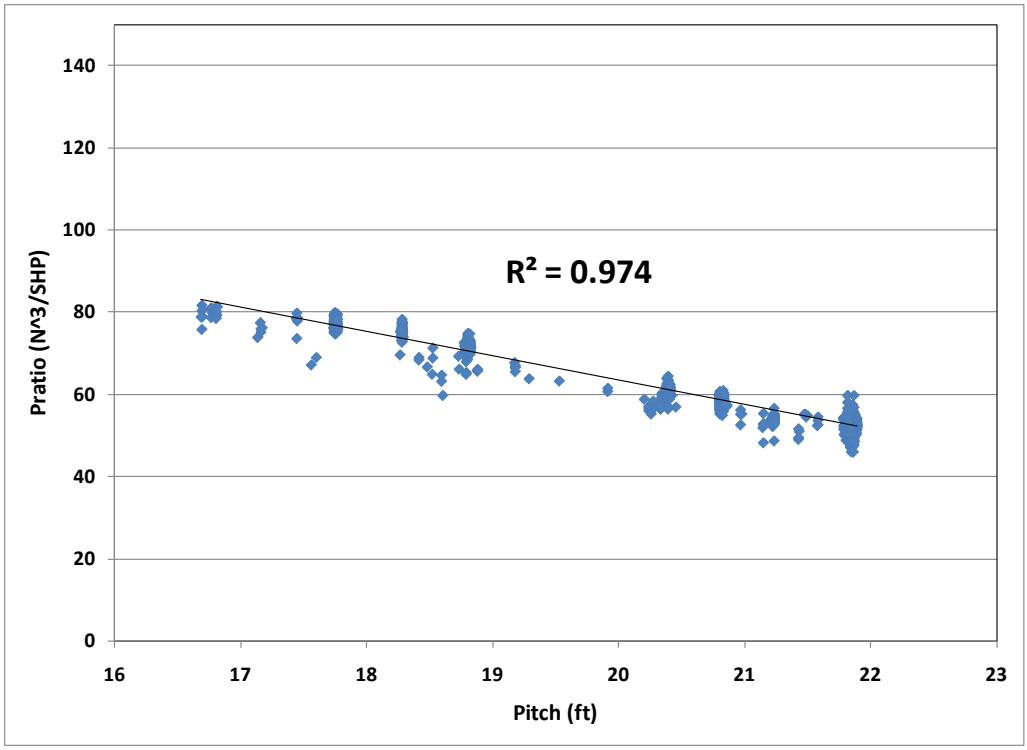

Figure 2 – Pratio Propeller Calibration Model (Kanawha)

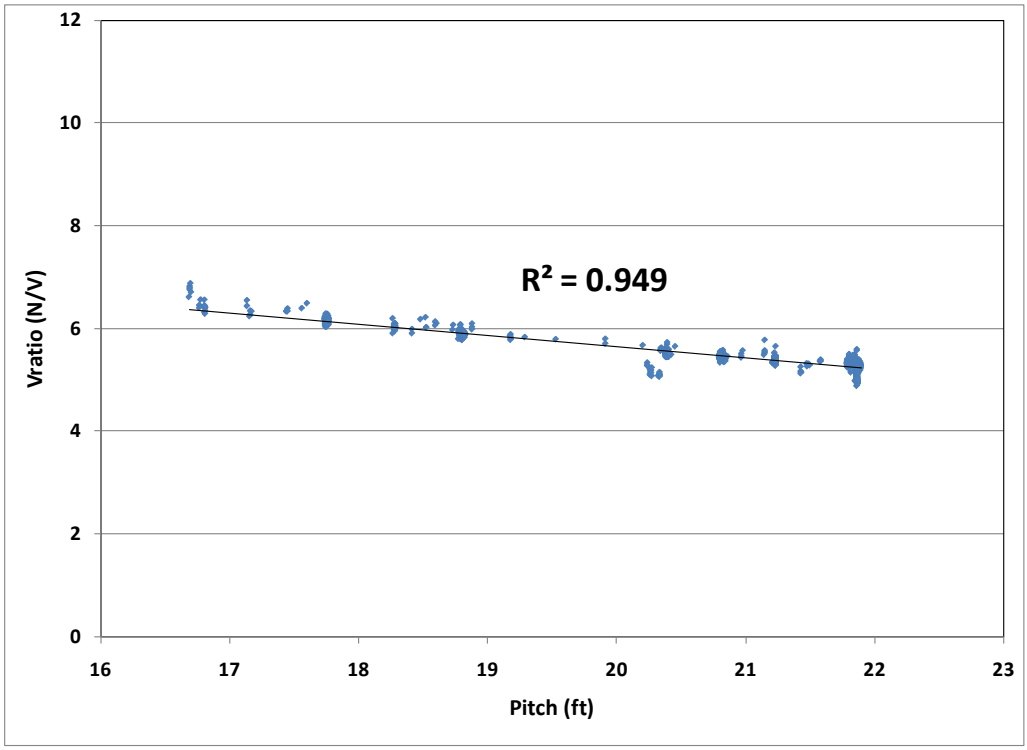

Figure 3 – Vratio Propeller Calibration Model (Kanawha)

SPEED LOSS

The speed ratio, V_{ratio}, is linearly dependent on propeller pitch under the established baseline conditions. The derived model, representative of clean hull, baseline conditions, can be used to estimate speed from measured RPM and pitch as follows:

$$V' = \frac{n}{V_{ratio}} \quad (14)$$

where:

$V_{ratio} = c_3 + c_4 * H$ (model)
n = mean shaft RPM
c_3, c_4 = model coefficients

A deviation metric can be calculated and tracked over time to monitor speed loss:

$$Speed\ Loss(t) = V'(t) - STW(t) \quad (15)$$

As the hull/propeller condition degrades, speed loss will increase.

Figure 4 compares the measured SHP against the model estimates across the baseline data set. The average SHP error across the entire data set was -6.14 SHP, indicating high model accuracy.

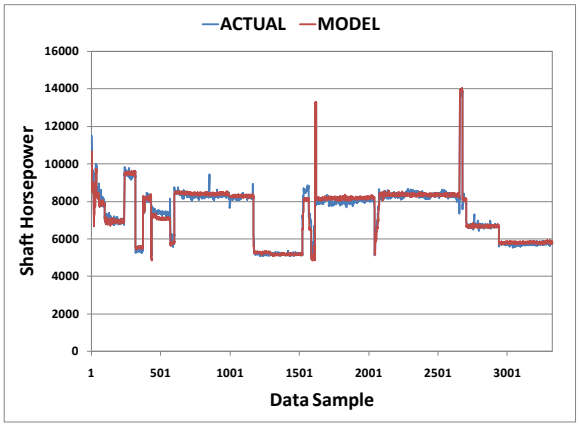

Figure 4 – Kanawha SHP – Measured Vs. Model

Figure 5 compares the measured speed through the water against the model estimates across the baseline data set. The average speed error across the data set was -.02 knots, again indicating high model accuracy.

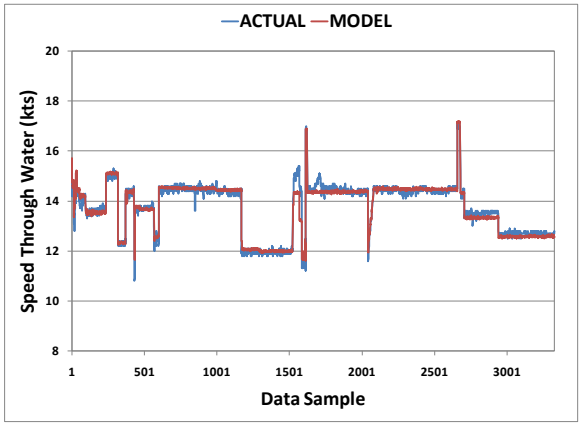

Figure 5 - Kanawha Speed – Measured Vs. Model

Similar accuracy levels were obtained for the Big Horn models.

Detection of Hull Fouling

The KPIs of power increase and speed loss were used to continually monitor the performance of the hull coatings throughout the study. As shown in both figures 6 and 7, the onset of Kanawha hull fouling was readily apparent in September 2010 after the ship sat at birth throughout most of the summer. When the ship did operate, its speed rarely exceeded the 10 knot threshold at which its new foul release paint is effective at releasing bio-fouling. At around 384 days out of drydock (Sept '10), an additional 2700 SHP were needed to maintain service speeds, as compared to clean-hull powering conditions. Kanawha's power performance for October and November 2010 also showed levels significantly higher than clean-hull conditions, although not as high as September 2010, suggesting that some biofouling may have sloughed off.

Figure 6 also shows Big Horn's power performance tracking the baseline levels, indicating that her hull remained clean after one year with the ablative antifouling coating. Figure 7 shows similar performance patterns for the speed loss KPI as for the ΔPower KPI for both ships.

An underwater hull inspection performed by divers in early November 2010 verified the presence of hull fouling evident in Kanawha's

performance data. An underwater hull cleaning was performed in late January 2001 that restored Kanawha performance back to baseline conditions as shown in figures 6 and 7.

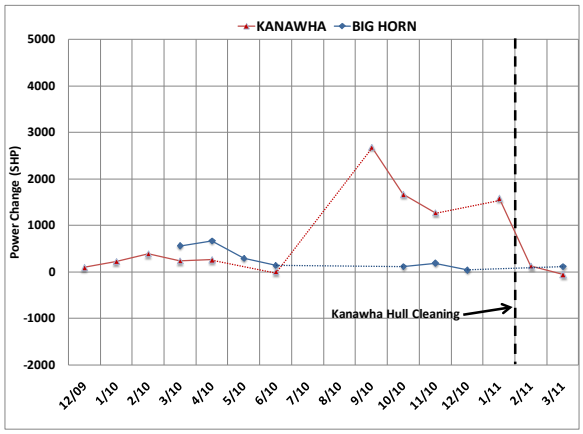

Figure 6 - ΔPower versus Time

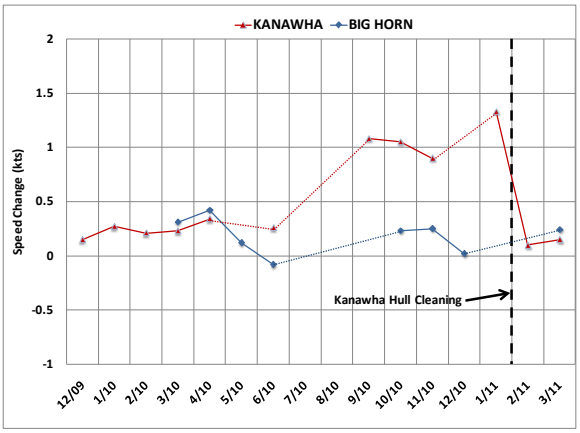

Figure 7 - Speed Loss versus Time

Figure 8 compares Kanawha's Speed-Power performance before and after hull fouling took place. From December 2009 through June 2010, her performance remains constant, following a well-defined speed-power curve. Subsequent to the fouling that occurred during the summer of 2010, a marked upward curve shift occurred, as evident by the August-September 2010 data.

Figure 6 showed that Kanawha incurred a power penalty due to hull fouling during the September 2010 through early January 2011 time period.

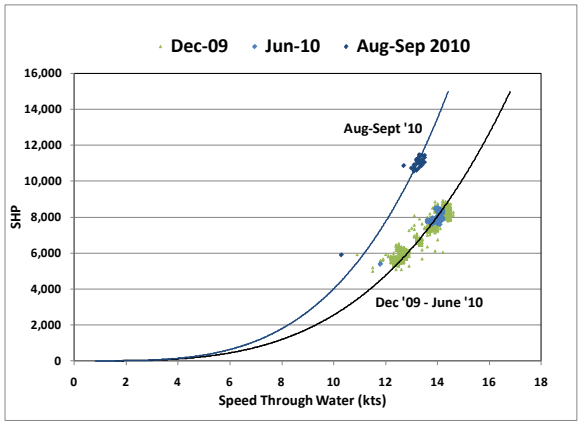

Figure 8 - Kanawha Speed-Power Performance

As a fleet oiler, the Kanawha is required to maintain fixed speeds during underway fuel replenishment operations. The data shows that in order to make up for the approximate one knot speed loss due to hull fouling during September 2010 operations, the ship had to generate 2700 additional shaft horsepower (see figures 6 and 7). As a percentage of normal operating power levels (i.e. clean-hull), 2700 SHP was about 35% more power than what would be needed if the ship had a clean hull, as the September 2010 data in figure 9 indicates.

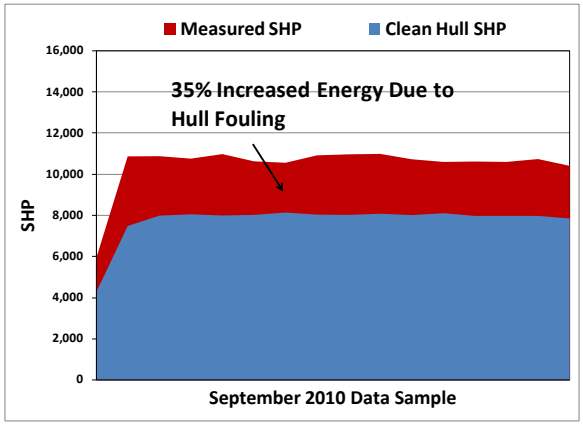

Figure 9 - Kanawha Power Penalty – Sept '10

Figure 10 expresses the average monthly increased power as a percentage of clean-hull power from the onset of hull fouling in September 2010 until just before the underwater cleaning was performed in January 2011.

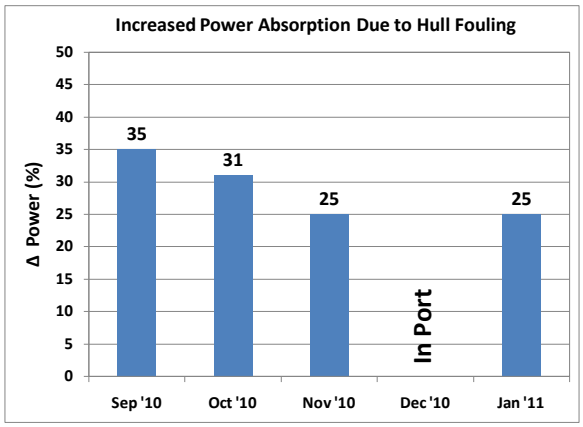

Figure 10 – Historical Kanawha Power Penalty

Figure 10 indicates that a significant amount of additional energy was consumed as a result of hull fouling. When converted into equivalent fuel cost, the savings available from a proactive hull and propeller maintenance strategy are substantial, particularly when considering a large fleet. In addition, since burning a gallon of diesel fuel generates about 22 pounds of CO_2 emissions (EPA 2011), potential fuel savings directly translate into quantifiable emissions reductions.

By using high accuracy propeller power absorption models, hull and propeller fouling can be detected early in the fouling evolution. Added energy costs can be quantified such that prudent maintenance decisions can limit excess fuel consumption within the constraints of deployment requirements.

SUMMARY & CONCLUSIONS

The Cost of Hull and Propeller Fouling

Ship operators realize that hull fouling causes speed loss and increased fuel consumption. There is also growing environmental concern and international regulation relating to green house gas emissions and the carriage of aquatic invasive species on fouled ship hulls.

Ship performance losses due to hull and propeller fouling are difficult to quantify because changing ship and environmental conditions generate performance variations that makes separation of hull and propeller effects a difficult task.

The Navy has recognized the importance of hull condition monitoring in their energy conservation efforts and has stated hull and/or propeller fouling are the largest cause of excess fuel consumption. Depending on fouling severity, fleet-wide hull fouling-related costs have been estimated to be somewhere between $180M - $540M per year. Spending a fraction of this for improved monitoring solutions will certainly offer a rapid return on investment.

Hull Coating Solutions

Marine growth can be retarded through the use of effective anti-fouling paint, such as tributyl-tin (TBT) self-polishing co-polymers, however; due to TBT's negative environmental side effects, the International Maritime Organization (IMO) imposed a ban on TBT paint, leading paint manufacturers to develop non-toxic alternative paint systems. Amongst these paint alternatives are low-copper and copper-free ablative antifouling (AF), foul release (FR) coatings, and surface treated coatings (STC). Unfortunately, marine industry consensus is that there is no paint technology yet available that is comparable TBT's performance and a significant amount of industry R & D is underway to find better solutions. One thing appears certain; the IMO and other national and state organizations will continue to increase regulatory pressure on ship operators to keep their hulls clean.

Market Need for Independent and Transparent Hull Performance Monitoring

The choice between alternative hull coatings is not an easy one, considering that ship performance is difficult to measure and that the major paint companies all claim similar fuel savings by using their products. Clearly, an accurate hull monitoring capability that measures actual ship performance, rather than

relying on paint company-sponsored studies, could be put to good use in proving or disproving those marketing claims.

Naval vessels represent a unique challenge to paint manufacturers because of the extent of their time spent in port, compared to commercial ships. Viable coating solutions for fast-moving commercial vessels may not work well for naval vessels.

Modern Ship Performance Monitoring Alternatives

Ship performance monitoring traditionally has been a complex subject, requiring knowledge of naval architecture, marine engineering, mathematics, statistics, and more recently, computer science. The practice still seems to be somewhat of a "black art", requiring highly specialized knowledge and skills, as it has for decades. A need exists within the maritime and naval communities for a transparent and independent methodology for measuring actual ship performance over time, indexed to a "clean-hull" baseline.

In the past, the major constraints on ship performance analysis techniques were generally related to data quality. With the modern automation systems installed on today's vessels, these constraints no longer apply. High speed data acquisition, low-cost computers, and advanced database technology are now at the practitioner's disposal to eliminate past barriers to accurately measuring hull and propeller performance.

RESISTANCE MODELING

Ship powering prediction is a well-developed field and resistance modeling has played a central role. The estimation of ship resistance is crucial in determining required engine power and the selection of the correct propeller to move a ship at its design speed. Total resistance is comprised of a number of components related to various sources of resistance that have complex interactions with each other, including frictional resistance, wave-making resistance, eddy resistance, air resistance, and heavy weather effects. Depending on the focus of various researchers, there has been significant variation in the components of ship resistance included in the total ship resistance equation, making power prediction results inconsistent. In addition, a separate model is typically developed for each resistance component and component interaction effects are largely ignored. Resistance models developed by many researchers remain unvalidated against actual ships. The correlation allowance is essentially a correction factor applied to align model-based power estimates with results from ship trials. Beyond this, model development is an expensive, time-consuming effort, usually performed through ship model testing in a towing tank facility.

PROPELLER POWER ABSORPTION MODELS

Methods for using a ship's propeller as a speed or power measuring device were established at least eighty years ago, but were not highly publicized even though several ship performance researchers used them in the 1980 timeframe. The unique characteristics of these methods are their simplicity, high accuracy, and their use of actual ship performance data, instead of scale models. A propeller calibration procedure results in a quantitative model representing clean hull and calm weather conditions. The propeller model can be used to track speed and/or power changes over time by continually comparing the current ship's performance to the baseline "clean hull" performance using KPIs that are easily understood by both ship crews and their management counterparts.

From a theoretical standpoint, the propeller open water characteristics define a linear relationship between the torque coefficient, $K_{q,}$ and the advance ratio, J, within the normal working range of the propeller. This is essentially a torque-slip function and once known, can be used to estimate shaft power from rpm and speed or, alternately, to estimate speed from rpm and shaft power. The ship performance problem is one of separating out the individual contributors to slip or water inflow velocity. In

this regards, a propeller does not sense ship resistance caused by wind, waves, fouling, etc. It only senses a reduction in the rate of water inflow. All factors that influence slip also impact the inflow water velocity to the propeller and the majority of these can be filtered out of analysis datasets using modern database technology. The combined effects of hull and propeller fouling will be the only ones remaining after the filtering process is performed.

Propeller models as described herein can also be used to determine the relative power absorption at different draft and trim conditions such that optimal trim for any ship loading condition can be determined. A similar approach can also be taken to quantify performance losses due to heavy weather which has direct use in weather routing applications. The predictive accuracy achievable with this technique has been consistently reported by several researchers to be in the 0.5% to 1.0% range, significantly higher than that reported for resistance models. Higher accuracy allows detection and quantification of hull-related losses at the earliest possible time, allowing improved maintenance planning and more fuel savings to be achieved.

It should be noted that the separation of hull fouling from propeller fouling is generally not possible without both shaft torquemeter and shaft thrustmeter measurements. However, if thrust measurements are available, the propeller model has direct applicability for propeller fouling, as well.

Demonstration Through Navy Hull Paint Study

The propeller power absorption technique has recently been demonstrated during an MSC-initiated comparative study of foul release versus ablative antifouling paint performance. Two identically designed fleet oilers had their hulls painted during drydock and were outfitted with automatic data acquisition systems. Their performance has been monitored for the past 18 months. Power and speed predictions based on the calibrated propeller relationships of each ship were used to track speed loss and power increase based on actual ship performance measurements.

The onset of Kanawha fouling on her foul-release coated hull was readily apparent in September 2010 after the ship sat at birth throughout most of that summer. At that time, an additional 2700 SHP was needed to maintain service speeds, as compared to clean-hull powering conditions. Kanawha's power performance for ensuing months was also significantly higher than clean-hull conditions. An underwater hull inspection performed in early November 2010 verified the presence of hull fouling evident in Kanawha's performance data and MSC immediately planned an underwater hull cleaning, which was subsequently performed in late January 2011. Subsequent analysis clearly showed that Kanawha's performance was restored back to baseline conditions.

Big Horn's performance data indicated that her hull remained clean after over one year with the ablative antifouling coating.

Final Conclusions

Rising fuel costs, hull maintenance expenses, and mounting environmental regulations make hull condition monitoring a crucial tool for prudent ship operators to eliminate energy waste due to hull fouling, reduce carbon emissions, and eliminate the carriage of invasive species between ports.

Propeller models offer many advantages to Navy decision makers responsible for hull/propeller maintenance and hull paint selection:

- The techniques are well-established (albeit not well-publicized)
- They provide direct measurements of performance loss on actual ships in terms of easily understood KPIs
- They use sensor data that is available on most ships
- Propeller power absorption calibration, while based on propeller/propulsion theory,

is a simple and transparent process requiring only basic math skills

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