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Effects of Hull and Propeller Cleaning on Propulsion Efficiency of an Offshore Patrol Vessel

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Abstract

The effects of hull and propeller cleaning on propulsion efficiency are evaluated for an offshore patrol vessel belonging to the Canadian Coast Guard. Dedicated sea trials were conducted between cleanings to evaluate propulsion efficiency using standard speed and power trial procedures. These results are compared with efficiency analysis performed on continuous operational data. A hull recoat was applied in fall of 2018, and the condition of biofouling and coatings observed at dry dock is discussed.

1. Background

The Canadian Coast Guard Ship (CCGS) Cygnus is an offshore patrol ship that operates out of St. John's, NL. It is the first CCG vessel to be instrumented with a vessel performance monitoring system, developed by OpDAQ. The system measures shaft torque, shaft speed, shaft power, and vessel fuel consumption. The National Research Council (NRC) of Canada has a separate Data Acquisition System (DAS) onboard the CCGS Cygnus since Fall 2015. The NRC DAS stores data from a number of vessel systems such as the navigation system and propulsion system. The NRC has also been obtaining OpDAQ data from the CCGS Cygnus since 2016. The data from the NRC DAS and OpDAQ system is used for the current project to quantify changes in vessel performance as a result of hull and propeller cleaning.

This report summarizes the propulsion efficiency analysis of the CCGS Cygnus operational data prior to and subsequent to cleaning the hull and propeller. This data is used to quantify any changes in vessel performance, specifically the power versus speed relationship. In addition, the vessel fuel consumption at a given power level will be quantified prior to and post cleaning events.

Three dedicated sea trials were conducted to support this project. Each set of trials is a dedicated Speed and Power trial and was planned and conducted in accordance with International Towing Tank Conference (ITTC) guidelines. The first set of trials is a baseline trial to quantify the performance before the hull or propeller are cleaned. The second set of trials is a post hull cleaning trial to quantify the performance subsequent to cleaning the vessel hull only. The third trial is conducted post propeller cleaning and is used to quantify any changes in speed and power performance as a result of cleaning the propeller.

The result of this project suggests how the power and speed relationship for the CCGS Cygnus changes after cleaning events within the scope of the trials. It also quantifies how the power and fuel consumption relationship changes as per the observed data. These changes are quantified using measured data from dedicated sea trials. This information could be used to support planning and optimization of vessel cleaning schedules.

2. CCGS Cygnus – Vessel Details

The CCGS Cygnus is an offshore fisheries patrol vessel that operates out of St. John's. It operates on a two week rotational schedule. This generally involves the vessel departing St. John's, transiting to the Grand Banks area which it patrols and then returning to St. John's for crew change. The day after crew change the vessel departs again for Grand Banks to continue patrolling. The vessel has two main medium speed, diesel engines. The ship particulars of the CCGS Cygnus are outlined in Table 1.

Table 1: CCGS Cygnus Main Particulars

Particular	Value
Length (m)	62.4
Breadth (m)	12.2
Draft (m)	4.0
Freeboard (m)	0.9
Cruising Speed (kts)	13.0
Maximum Speed (kts)	16.0
Number of engines	2
100% MCR (kW)	~3000
Number of propellers	1

3. Hull and Propeller Fouled Condition

Prior to cleaning the hull and propeller, a subsea survey was conducted to characterize the level of fouling present. A guideline from the *Royal Navy (2011)* was followed for this procedure. The hull fouling was characterized as a specific type and rated from 0 to 100 to indicate the level of severity. The hull cleaning was completed by divers when the vessel was docked in Conception Bay, NL on June 5, 2018. The diving company prepared a report to document the level of fouling on the hull. When assessing the level of fouling on the hull, the divers divided the vessel into 27 regions. At each of these regions photos were taken to document the fouling condition. The location of each region is shown in Fig.1, as taken from the diver's report. Note that this image is not to scale, nor is it a representation of the CCGS Cygnus. It is used only to indicate general location and quantity of underwater areas that were surveyed.

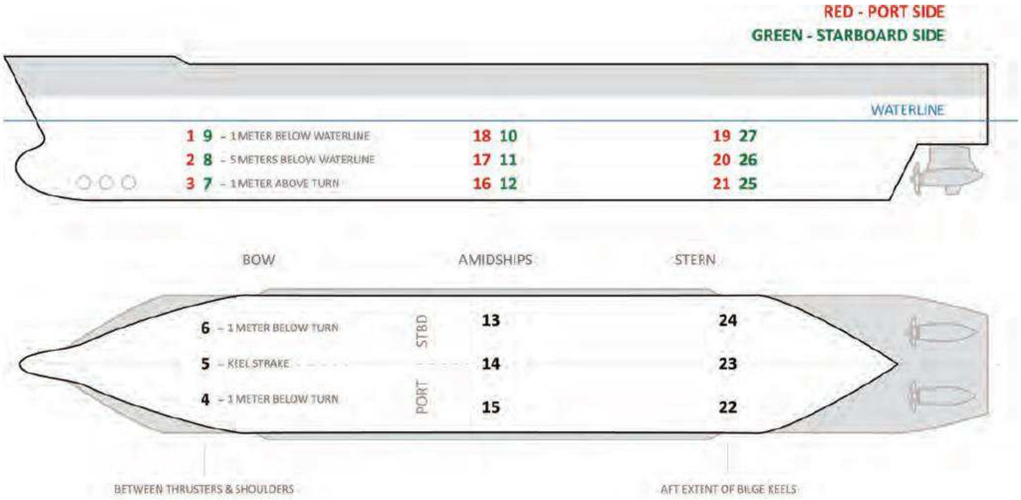


Fig.1: Hull fouling characterization locations (from diver's report)

An underwater video was also taken to support characterization of hull fouling. By evaluating the vessel in situ, through photographs and using the underwater videos, the divers characterized the level of fouling at each of the 27 locations across the hull. The divers used the *Royal Navy (2011)* and US *Naval Ships Technical Manual (2006)* to define fouling type and rating values so that results would be consistent with Navy practices. A summary of the hull fouling characterization is provided in Table 2. All fouling on the CCGS Cygnus hull was noted to be soft. The dominant organisms in the soft fouling type are slime and grass. The fouling rating included FR 20 and FR 30. This type of fouling involves advanced slime and grass filaments up to 76 mm long. The percentage of fouling coverage in each area ranged from 40-100%. It was noted that fouling was located from waterline down to turn of the bilge with heavier growth present near the waterline.

Table 2: Hull fouling characterization – type, rating and percent coverage

Location	Fouling Type	Fouling Rating	Percentage Coverage (%)
1	Soft	30	80
2	Soft	20	50
3	Soft	20	75
4	Soft	20	100
5	Soft	20	80
6	Soft	20	90
7	Soft	20	100
8	Soft	20	50
9	Soft	30	50
9	Soft	20	50
10	Soft	30	70
11	Soft	20	50
12	Soft	20	40
13	Soft	20	80
14	Soft	20	80
15	Soft	20	90
16	Soft	20	90
17	Soft	30	65
18	Soft	30	80
19	Soft	20	90
20	Soft	20	60
21	Soft	20	90
22	Soft	20	100
23	Soft	20	90
24	Soft	20	100
25	Soft	20	95
26	Soft	20	50
27	Soft	20	80

The hull and propeller of the CCGS Cygnus had not been cleaned in two years prior to this project. The level of fouling present was a result of 2 years of operation. The CCGS Cygnus operates year round on a two week rotation with a two day layover. Vessels with an off-season or with long layover periods would likely have more fouling in similar operational and environmental conditions.

Fig.2: Typical propeller pressure face pre (left) and post (right) cleaning

The propeller was also assessed by divers to quantify the level of fouling present on July 18, 2018. All propeller blade faces were covered in a light to moderate slime which was heavier at the root and tapered towards the tips. Under the slime the propeller blades were covered with a heavy calcium buildup. The level of propeller fouling was measured using a ship propeller roughness gage which characterizes the propeller roughness per the Rubert Comparator scale. The propeller fouling was rated as Rubert scale E. Once polished, the propeller was rated at a Rubert scale A/B. Post polishing trials were conducted at this polished state. Fig.2 illustrates the pre-cleaning and post-cleaning condition of a typical propeller pressure face of the CCGS Cygnus propeller. This report includes a number of images of pre and post cleaned propeller surfaces.

4. Sea Trials

Three separate sets of sea trials were completed. The first was conducted prior to cleaning the hull or propeller and provides data to use as a baseline. The second set of sea trials were completed after the hull was cleaned and the third set of sea trials were completed after the propeller was cleaned.

All trials followed the same procedure and occurred at the same location. The trials followed ITTC 2014 guidelines for the completion of speed and power trials. These guidelines outline boundary conditions as a cutoff point for the completion of such trials. These boundary conditions relate to location, water depth and environmental conditions and vary based on the vessel size. The specific trials boundary conditions for the CCGS Cygnus, are summarized in Table 3.

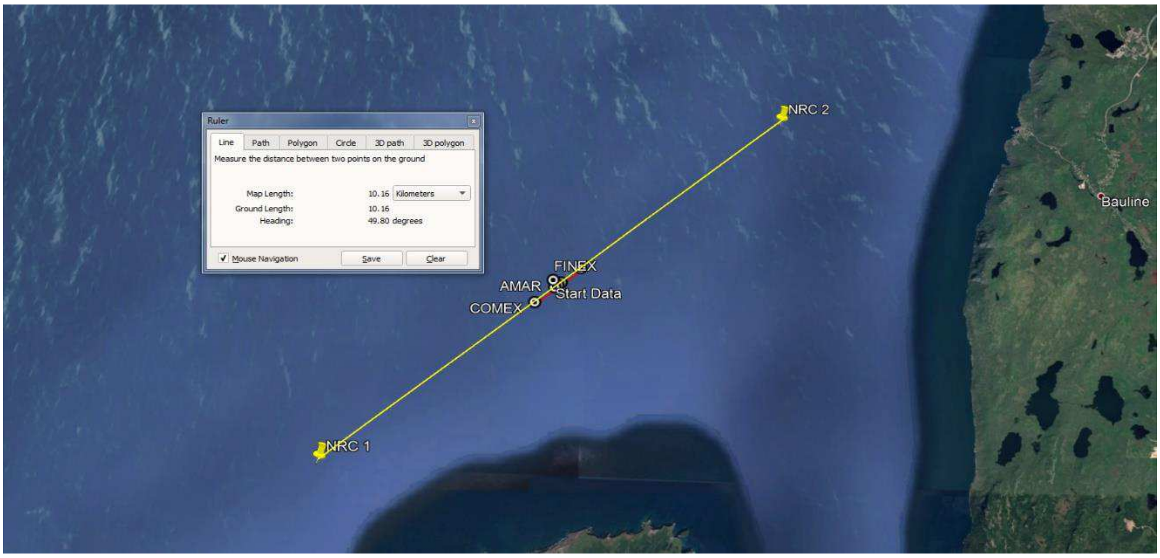
Table 3: Sea Trials Boundary Conditions

Parameter	Parameter Detail or Value
Location	Selected location should have minimal vessel traffic and should be sheltered to avoid wind / wave where possible.
Water Depth	Minimum water depth of 52.2 m. Data corrections required for water depths less than 71.8 m.
Wind	Wind shall not be higher than Beaufort 5. Beaufort 5 relates to mean wind velocity between 17-21 knots.
Sea State	The maximum wave height when derived from visual observation should be 1.2 m.
Current	Areas with known large current variations in time or space should be avoided. Small currents will be corrected for by completing tests in two directions, one upwind and the other downwind.

Prevalent weather conditions and vessel traffic intensity were considered when selecting a trials location. The location was selected to be within Conception Bay to reduce the likelihood of heavy sea states when compared to a location along the normal Cygnus operational route. The location was set to north of Bell Island since there was relatively little vessel traffic at this location than other areas of the Bay.

During each trial three or four different power settings were tested. The power settings tested included 50%, 65%, 80%, and 100% of the main engines Maximum Continuous Rating (MCR). All tests were completed in two directions: upwind and downwind. A double run at 65% MCR was conducted once during each set of trials. The double runs completed at 50%, 80% and 100% MCR were conducted twice, as per the ITTC 2014 guideline. The baseline trials included only three power settings (65%, 80%, and 100%) as the original plan did not specify runs at 50% power setting. After analysis of the baseline trial data, it was decided to include runs at 50% power in the subsequent trials to provide additional context for the higher power data points. It was attempted to perform all trials at a consistent displacement and as such there were no significant changes in cargo or machinery between trials.

Fig.3 shows the location of the sea trials. The direction of all trials was along the yellow line, between the points NRC 1 and NRC 2. This track has a total length of ~10 km to provide space for the high-speed runs. Each test required 10 minutes of constant rpm, pitch, and speed settings. As such, some tests were shorter in distance than others. All tests were centered near the subsea acoustic probe (Autonomous Multichannel Acoustic Recorder – AMAR) point in Fig.3. The AMAR point is located at 47°41.757’ latitude and -52°56.509’ longitude. The direction of the yellow line relates to in and out of the Bay, which corresponds with the prevailing wind direction. Once a test was completed in one direction, the vessel would turn around and complete the same test in the opposite direction.



Measure the distance between two points on the ground

Map Length: 10. 16 Kilometers

Ground Length: 10. 16

Heading: 49.80 degrees

Fig.3: Trials location and direction in Conception Bay, NL

Each trial run involved a period to get up to speed and attain constant settings, a 10 minute constant setting period, and then a Williamson turn to return vessel to opposite direction for subsequent testing. The trial trajectory was similar to that shown in Fig.4.

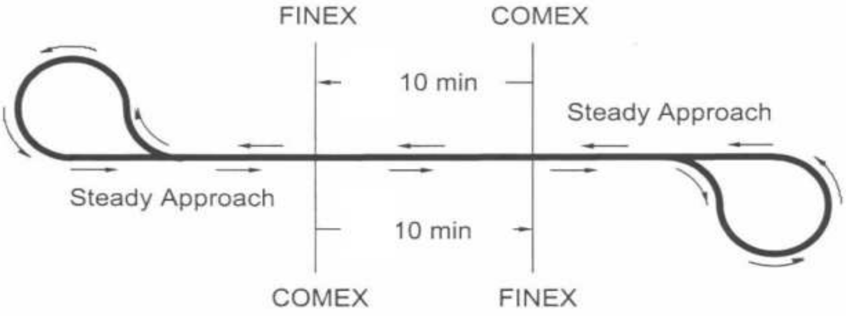


Fig.4: Trial trajectory illustrating the approach for each reciprocal run

4.1 Baseline Trials

Baseline (pre-cleaning) trials were completed on May 23, 2018. The wind and sea conditions during the morning were higher than the boundary conditions for these tests and as such all tests were completed in the afternoon when conditions calmed. The conditions during baseline trials are summarized in Table 4. There were 11 runs completed in total. Two of these were runs at a MCR setting of 65% (upwind and downwind), four at MCR of 80% (two upwind and two downwind) and four at a 100% MCR (two upwind and two downwind). There was a repeat test of the first run which was 65% MCR in the upwind direction. The repeat was conducted because the wave and wind conditions were higher during the first test of the day than they were during the remainder of the tests.

Table 4: Baseline Trial Conditions

Condition	Value
Testing timeframe	13:30 – 16:15
Vessel forward draft (m)	3.35
Vessel aft draft (m)	4.83
Range in true wind speed (kts)	16 - 22
Range in wave heights (m)	0.5 – 1.0
Range in swell height (m)	0 – 0.5
Water temperature (ºC)	4.0

During the baseline trials the wave and swell heights were estimated by the vessel Captain. These values were not measured during baseline trials as the wave buoy was not deployed due to morning weather conditions. The water temperature was also estimated for the baseline trial, using historic water temperature values from the area. In addition, the estimated water temperature was compared to water temperature measurements taken from a wave buoy that was located in Holyrood Harbor, which is not too far from the trials site.

4.2 Post Hull Cleaning Trials

The post hull cleaning trials were completed on July 18, 2018. The weather conditions during post hull cleaning trials are summarized in Table 5. There were 14 runs completed in total. Four of these were runs at 50% MCR (two upwind and two downwind), two at a 65% MCR (one upwind and one downwind), four at 80% MCR (two upwind and two downwind) and four at a throttle setting of 100% MCR (two upwind and two downwind).

Table 5: Post Hull Cleaning Trial Conditions

Condition	Value
Testing timeframe	10:30 – 14:00
Vessel forward draft (m)	3.05
Vessel aft draft (m)	4.66
Range in true wind speed (kts)	14 - 25
Range in wave heights (m)	0.2 – 0.4
Range in swell height (m)	0 – 0.25
Water temperature (°C)	10.2

During the post hull cleaning trials the wave and swell heights were estimated by the vessel Captain. These values were also measured by a wave buoy during these trials. Estimated values were compared with those measured. Values estimated were consistently higher than those measured, by approximately 50%. Measured values are summarized in the trials log as well as in Table 5.

4.3 Post Propeller Cleaning Trials

The post propeller cleaning trials were completed on August 1, 2018. The weather conditions during post propeller cleaning trials are summarized in Table 6. There were 14 runs completed in total. Four of these were runs at 50% MCR (two upwind and two downwind), two at 65% MCR (one upwind and one downwind), four at 80% MCR (two upwind and two downwind) and four at 100% MCR (two upwind and two downwind).

Table 6: Post Propeller Cleaning Trial Conditions

Condition	Value
Testing timeframe	11:45 – 15:05
Vessel forward draft (m)	3.02
Vessel aft draft (m)	4.72
Range in true wind speed (kts)	4.5 – 10.2
Range in wave heights (m)	0.3 – 0.6
Range in swell height (m)	0
Water temperature (°C)	14.9

During the post propeller cleaning trials the wave and swell heights were measured by a wave buoy deployed for the test.

5. Measured Speed and Power Data

The measured shaft power versus speed through water for each test during each trial are plotted on the same axes in Fig.5. All collected data points follow a similar relationship that can be fit with an exponential curve. There is less variation in the post propeller trials data when compared to the other trials results for a given engine setting. This is expected due to the calm wind and sea conditions during the post propeller polishing trials which were lighter than those for the other two trials.

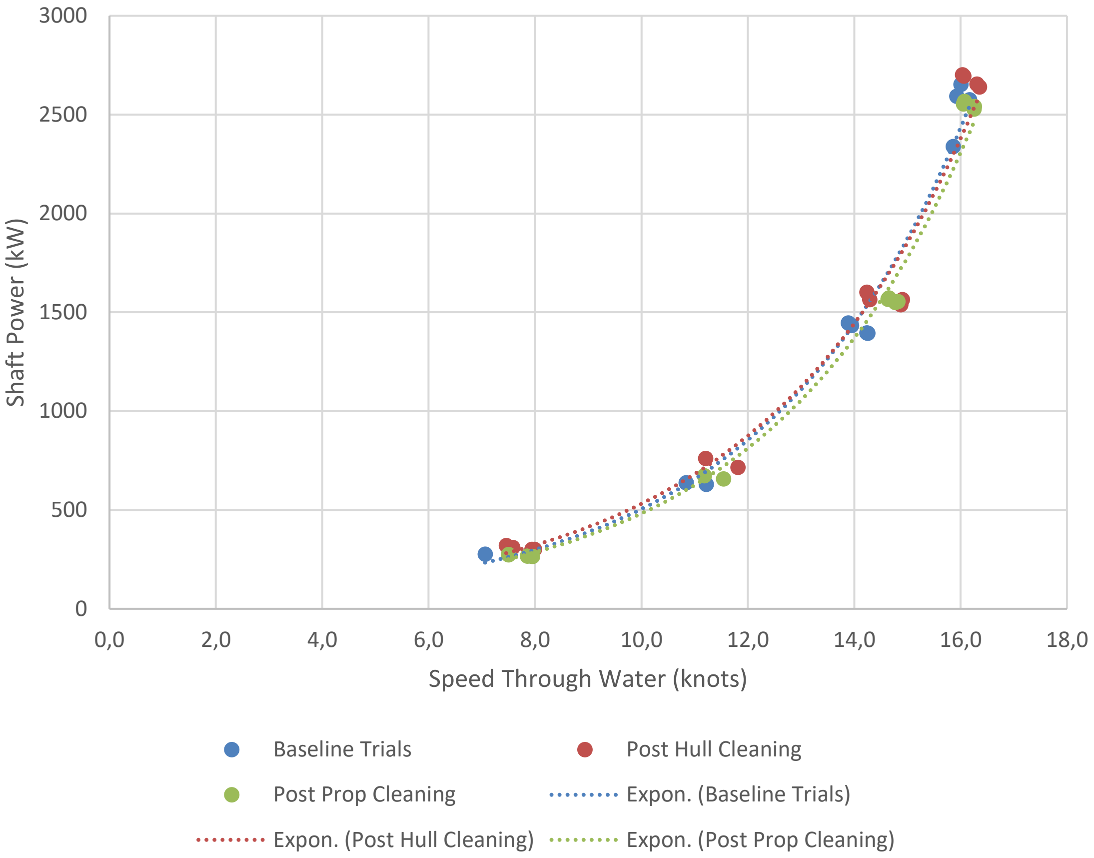


Fig.5: Uncorrected power versus speed data from each test run during each trial. An exponential curve fit is shown to illustrate the trends between trials. The uncorrected data does not show a significant difference between trials in the speed curve.

The measured data was analyzed first using the mean of means method to provide further insight towards data trends between trials. The mean of means method involves taking the mean of consecutive double runs at a given engine setting and then taking the mean of those means to represent the speed and power values at that engine setting. The intent of this method is to eliminate the unidirectional effects of wind and current under the assumption that these effects will average to zero. The mean of means for all trials completed at a given engine setting, within each sea trial, were calculated. The results of shaft power and vessel speed through water for each sea trial were plotted (Fig.6). Trend lines were fitted through the data for each sea trial.

The differences in the relationships between power and speed for the three sea trials is clearer here. The trend line relationships between trials change across the speed range. The post-hull cleaning trials trend line requires approximately 4% less power to attain speeds between 12.5 and 16 knots. In this same speed range, the post-propeller cleaning trials trend line indicates that approximately 5% less power is required to attain a given speed when compared to the post hull cleaning trials. These results indicate that a total of approximately 9% less power is required to attain a given speed (in speed range between 12.5-16 knots) as a result of cleaning both the hull and propeller. For speeds less than approximately 12 knots, more power is required to attain a given speed for the post hull cleaning trials when compared to the baseline trials. This result is unexpected and may be influenced by the higher level of uncertainty involved in the lower engine setting trials.

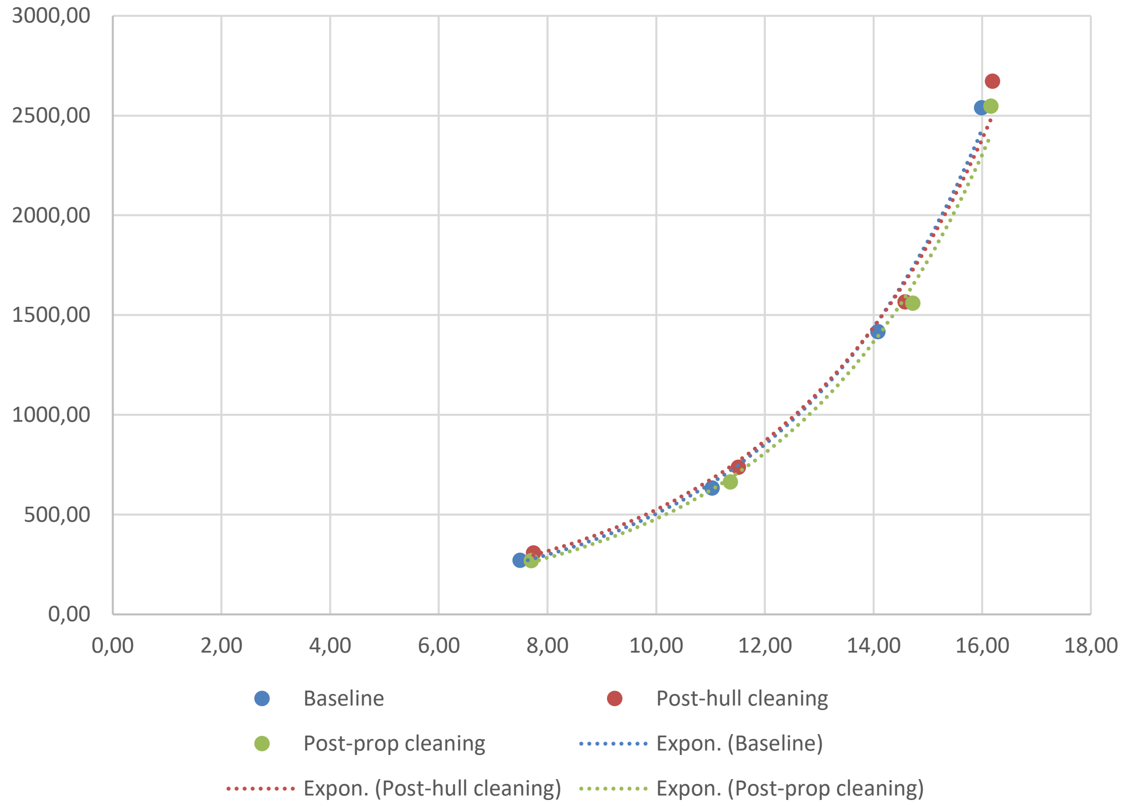


Fig.6: Means of means for each trial. Each data point is the mean of 2-4 runs at that speed in reciprocal runs.

It is also noteworthy to discuss the fact that these results are presented in terms of power versus speed rather than overall resistance versus speed. Overall resistance is more difficult to characterize since it takes into account the propulsion as well as associated efficiencies (hull efficiency, propulsive efficiency, and relative rotative efficiency). The power can be roughly calculated by dividing the resistance multiplied by the vessel speed, by the overall system efficiency. The overall propulsion system efficiency is a combination of multiple complex factors. For example, the propulsive efficiency would increase as a result of cleaning the propeller. Another example is that the hull efficiency, which describes how the water flows around the hull and into the propeller, can affect the propeller efficiency as a result of cleaning the hull. It is therefore possible that the resistance versus speed relationship for each set of trials would not exhibit the same performance gains across the speed range compared to simply comparing power versus speed.

6. Speed and Power Analysis and Results

The speed and power data measured during field trials was analyzed to remove variations due to environmental differences between trials. This was completed following ITTC guidelines for the analysis of full-scale speed and power trials, *ITTC (2005)*. This analysis method was complimented using insight from ISO 15016 when additional guidance was needed. The ITTC guideline requires the conversion of measured power data to vessel resistance in order to apply certain correction factors to account for environmental effects and correct data to a common, calm state. The ITTC guideline describes a method to determine the resistance of each trial run by using the measured torque along with information from associated propeller curves. A major element of uncertainty in this analysis is that the open water propeller curves for the Cygnus propeller are not available to support data analysis. As such, a standard B-Series propeller curve was assumed to be representative of the Cygnus propeller.

The ITTC guideline provides methods to calculate resistance corrections for: wind, waves, deviation in water temperature and density, water current, shallow water, and displacement variation. Resistance corrections were calculated for each trial run within each specific sea trial. For all cases, the resistance correction to account for water current was not calculated since the vessel speed through water was measured directly. Also, the shallow water correction was not calculated for any trials since the trials were conducted in deep water. The resistance correction to account for variations in vessel displacement were provided only for displacements that varied less than 2%. Based on the forward and aft draft measurements taken at the beginning of each trial, the displacement varied by approximately 8%, exceeding the range of the correction method. As such, there were no corrections added to account for displacement variation and the change in displacement is a source of variability within the results. Note that the forward and aft were estimated by the vessel crew based on draft marks prior to each trial and were not measured directly. Therefore, the variation in displacement could differ than the percentage value calculated using the estimated trim values.

The resistance corrections calculated for each trial were subtracted from the trial resistance that was calculated to reduce the resistance to a calm water baseline which could be used for direct comparison between trials. The corrected vessel resistance was used to calculate the corrected power. The ITTC analysis method required estimation of a number of coefficients specific to the vessel used in trials as well as the estimation of a number of environmental parameters that were not directly measured. Estimation of these parameters leads to a level of uncertainty in the results. A summary of the estimated parameters is provided below.

- Wake fraction, thrust deduction fraction and propeller relative rotative efficiency. These coefficients can be found from model test results for a particular vessel. Model test data for the CCGS Cygnus was not available for this data analysis. As such, the commercial software NavCad was used to model each trial and output the associated coefficients. The measured and predicted shaft power values compared well (within 10%) and thus the coefficients output from NavCad were deemed as reasonable.
- Thrust coefficient and advance coefficient. The ITTC analysis guideline states that the propeller open water thrust and advance coefficients, both required to calculate resistance, are to be retrieved from propeller open water curves. The CCGS Cygnus propeller open water curves were not available for this analysis. As such, standard B-Series open water propeller curves were used to represent the Cygnus propeller. The standard B-Series open water propeller curves were updated to match the pitch (as approximated by NavCad) of each trial run. Each unique set of curves was then used to retrieve the required data associated with the corresponding run. Unfortunately, the actual pitch relating to each test was not known and had to be approximated based on the pitch percentage which was noted from a gage on the bridge of the vessel and using NavCad. This added to the uncertainty involved in using the standard B-Series curve. In addition, the Cygnus propeller is controllable pitch and the standard B-Series propeller is not. The ratio of hub diameter to propeller blade length is larger for a controllable pitch propeller than for a fixed pitch propeller.
- Wetted surface area. The wetted surface area of the CCGS Cygnus was estimated with NavCad using input of the vessel main particulars and selection of representative vessel type.
- Transverse projected area above waterline. The transverse projected area above waterline of the CCGS Cygnus was estimated using measurements from the general arrangement drawing of the vessel and known draft.
- Wind resistance correction. The correction for wind resistance was estimated using recommended equations for the calculation of wind resistance.
- Wave height during baseline trials. The wave height was not measured during baseline trials. It was estimated using the measured wind speed and the fetch limited JONSWAP wave spectrum. The value of fetch used for the trials was 30 km. These estimates were compared to measured wave height data from a nearby (Holyrood) wave buoy and the results matched well (within 10%).
- Water temperature during baseline trials. The water temperature was not measured directly during baseline trials and was estimated based on historic water temperature data during the

same time of year. The estimated value was compared to measured data from a nearby (Holyrood) wave buoy and the results were similar.

- Water density for all trials. It was assumed that 3.5% salinity was representative of the water density during trials.
- Kinematic viscosity for all trials. The water kinematic viscosity was not directly measured and was estimated using the water temperature and ITTC Salt Water Property tables.

Preliminary results of the analysis showed that the wind resistance correction the most significant factor in comparison to the other corrections, for all sea trials. In addition, for the baseline trials and the post hull cleaning trials, where wind speeds were towards the upper wind speed limits of the trials, the wind resistance correction was very large in comparison to the bare hull resistance, particularly at the lower speeds.

The measured speed and power data was analyzed three separate times to correct for environmental conditions, each using the ITTC 2005 method or a slight variation to the method. The first analysis approach was conducted strictly to the ITTC guideline. The second and third analysis approaches were conducted using the ITTC 2005 guideline with a different estimation of wind resistance correction. The second attempt involved a wind resistance correction estimation using the Fujiwara method. This method was one of the wind resistance predictors recommended in NavCad, a commercially available vessel performance evaluation software. The third attempt involved a wind resistance correction estimation of half the predicted value using the Fujiwara method. Three separate analysis were completed to illustrate the variation in result that occurs due to different estimations of wind resistance correction.

6.1 Results – Baseline Trials

The results of the three analysis methods for all trials data is summarized in Fig.7. The measured trials data have higher power per speed than the corrected data for all test cases except the 11 knot speed. It is expected that the measured power would be higher since the power is being corrected to a calm condition and less power would be required to attain a given speed in calm seas. The measured data is very close to the corrected values at 11 knots which suggests that the wind and wave conditions during these tests were relatively mild. There is not much difference between the corrected results using the ITTC wind correction and the NavCad (Fujiwara) wind correction, for all tests. The corrected data using half the Fujiwara wind correction, lies in between the measured data and the other corrected data.

The measured trials data have higher power per speed than the corrected data for all test cases except the 11 knot speed. It is expected that the measured power would be higher since the power is being corrected to a calm condition and less power would be required to attain a given speed in calm seas. The measured data is very close to the corrected values at 11 knots which suggests that the wind and wave conditions during these tests were relatively mild. There is not much difference between the corrected results using the ITTC wind correction and the NavCad (Fujiwara) wind correction, for all tests. The corrected data using half the Fujiwara wind correction, lies in between the measured data and the other corrected data.

6.2 Results – Post Hull Cleaning Trials

The data corrected using the ITTC wind correction and the NavCad wind correction are similar. The spread between the measured and corrected data increases with speed for the post hull cleaning trials.

6.3 Results – Post Propeller Cleaning Trials

The measured data is very close to the corrected data for the post propeller cleaning trials due to the mild environmental conditions during the trials. There does appear to be one outlier for the tests at speed between 11 and 12 knots for which the measured power is below the corrected power values.

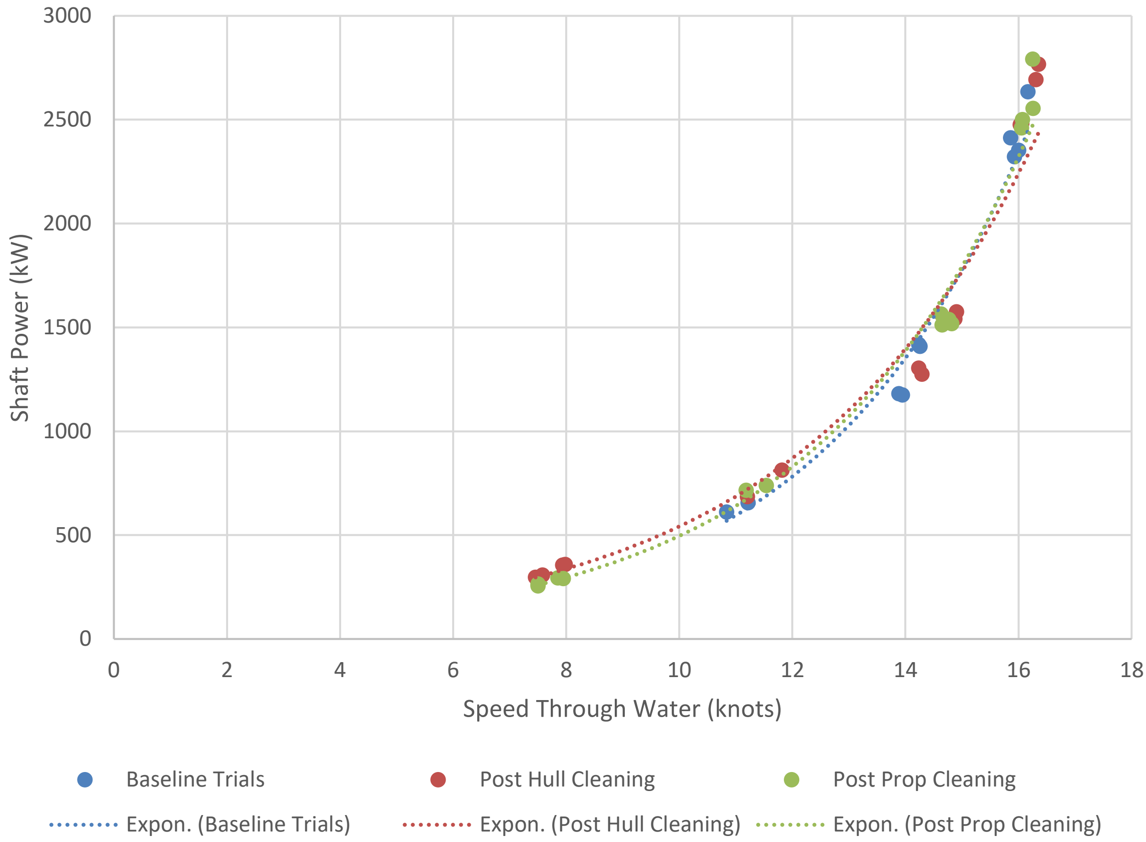


Fig.7: Corrected speed and power data for all trials. Due to the correction, environmental effect is reduced and the data points follow more closely the trend.

Table 7: Corrected speed and power data for all trials

Baseline		**Post Hull Cleaning**		**Post Propeller Cleaning**	
Speed (STW) (knots)	**Power (kW)**	**Speed (STW) (knots)**	**Power (kW)**	**Speed (STW) (knots)**	**Power (kW)**
		7.6	308	7.9	293
		7.9	356	7.5	264
7	276	7.5	298	7.9	291
8	265	8.0	359	7.5	256
10.8	611	11.2	685	11.5	739
11.2	657	11.8	813	11.2	716
13.9	1182	14.2	1305	14.8	1539
14.2	1418	14.9	1541	14.6	1512
13.9	1175	14.3	1275	14.8	1518
14.3	1409	14.9	1575	14.6	1565
16.0	2353	16.0	2477	16.3	2555
16.2	2635	16.3	2694	16.1	2501
15.9	2323	16.1	2481	16.3	2792
15.9	2413	16.4	2766	16.1	2460

6.2 Results – Post Hull Cleaning Trials

The data corrected using the ITTC wind correction and the NavCad wind correction are very similar.

The spread between the measured and corrected data increases with speed for the post hull cleaning trials.

6.3 Results – Post Propeller Cleaning Trials

The measured data is very close to the corrected data for the post propeller cleaning trials due to the mild environmental conditions during the trials. There does appear to be one outlier for the tests at speed between 11 and 12 knots for which the measured power is below the corrected power values.

6.4 Results – Comparison of Trials

The corrected power results for each sea trial were plotted against speed on the same plot to illustrate differences in performance. This was completed for each of the three wind correction approaches considered. For each analysis method, the results of each trial are relatively similar in terms of the power required at a given speed. Given this, it is difficult to quantify the gain in power associated with cleaning the hull and propeller, from this data. The regression lines for each trial are very similar for all analysis methods used. For each approach, the baseline trial regression line is higher than the post hull and post propeller cleaning regression lines, at speeds higher than approximately 13 knots. This indicates that there is a benefit of cleaning the hull and propeller in these speed ranges in terms of power required to attain a given speed. Below, approximately 13 knots, the regression line for baseline trials falls below the regression line for the other two trials. This change in regression line relationship between trials is consistent to the measured data results and may be due to higher uncertainty at the low speed tests.

The power savings above 13 knots were quantified using the regression line equations from the NavCad wind correction approach. Between 13.5 and 16 knots an average of ***5%*** less power is required to attain a given speed after cleaning the hull, when compared to the baseline power requirements. There is no additional power reduction identified within this speed range as a result of cleaning the propeller which was unexpected. In fact, the performance after cleaning the propeller, in terms of power versus speed, is worse in this speed range.

Note that there is variability within the tests conducted at a given throttle setting for a given trial in terms of speed through water and corrected power. The corrected power for a throttle setting for one trial often falls within the range of corrected power for the same throttle setting in a different trial. For example, at a throttle setting of 10 the speed through water varies between 15.9-16.2 knots for the baseline trials, 16.0-16.4 knots for the post hull clean trials and 16.1-16.3 knots for the post propeller cleaning trials. For this same throttle setting the corrected power (NavCad wind) ranges from 2272-2677 kW for the baseline trials, 2462-2823 kW for the post hull clean trials and 2438-2599 kW for the post propeller cleaning trials. The speed and power values from one trial, fall within the speed and power range for a different trial for this throttle setting. This is consistent for the other throttle settings considered and is true for the measured data as well as the corrected. This may be due to variability between trials (e.g. displacement variation, fouling present) and leads to less reliability in the power savings quantified using this data.

7. Operational Data Analysis

In addition to the sea trials conducted under somewhat controlled conditions, operational data was collected on an ongoing basis throughout the time period of the sea trials. From this data, the data was segmented based on speeds greater than 7 knots, and durations of at least 2 hours. Each segment meeting these criteria was averaged to provide a mean data point. These data points, color coded by period between cleaning events, are illustrated in Fig.8.

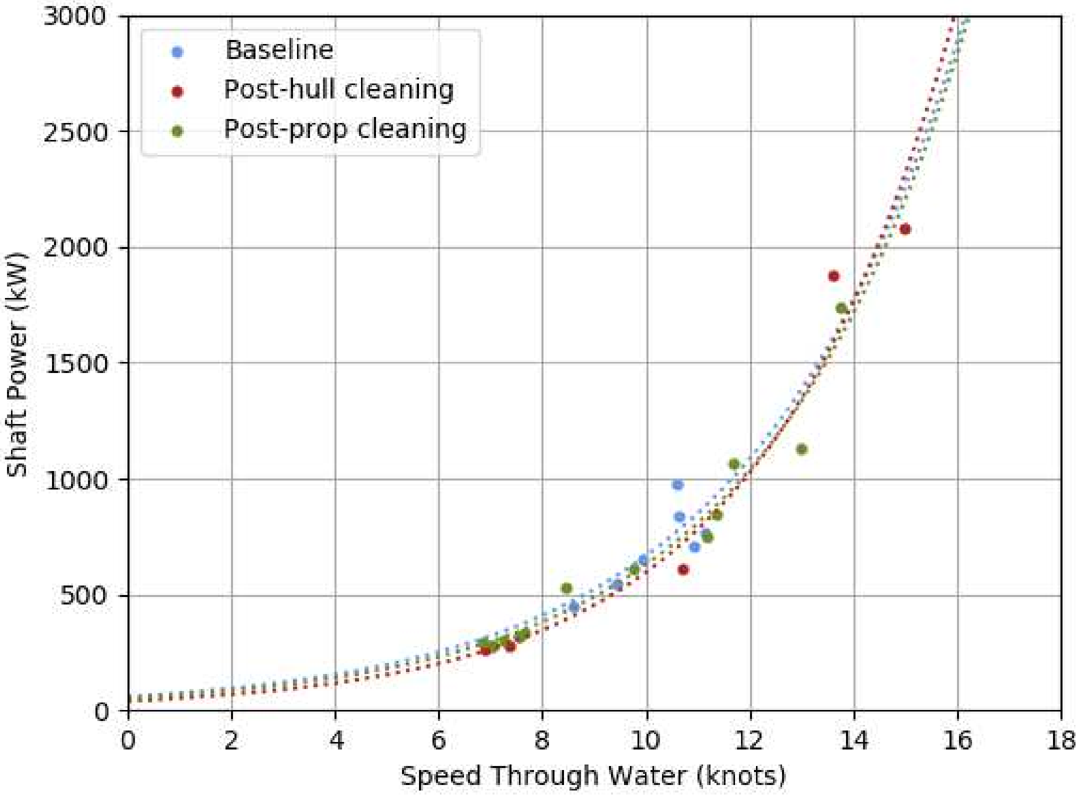


Fig.8: Mean data points extracted from operational data segments greater than 7 knots in speed and 2 hours in duration. Data points are color coded according to the period between cleaning events they correspond with.

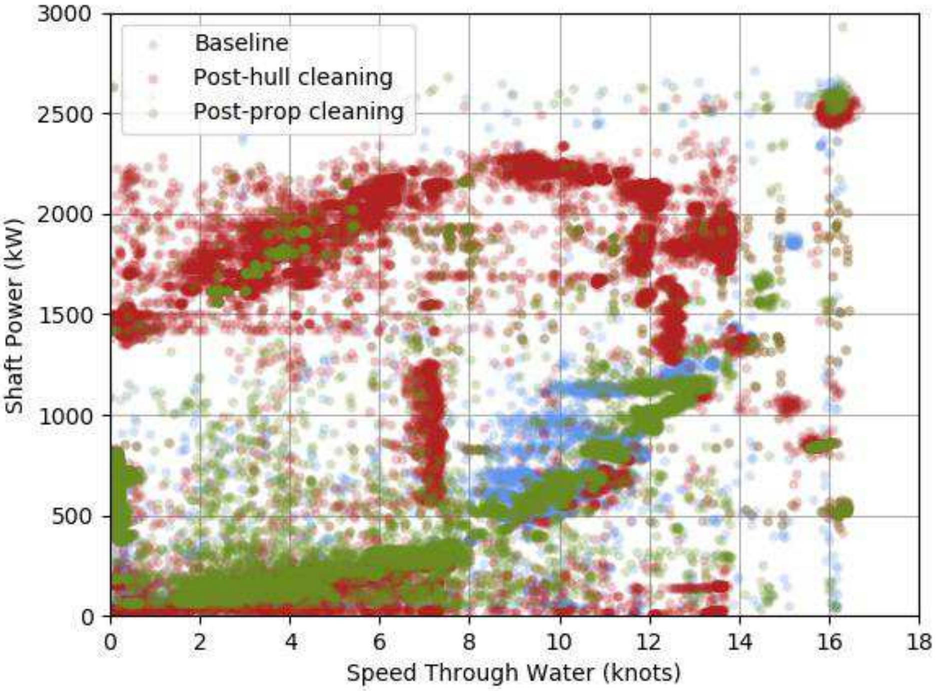


Fig.9: All operational data points throughout time period covering the cleaning trials. Scatter points occur due to operational activities, equipment and instrumentation fluctuation, and environmental condition.

The complete operational dataset is illustrated in Fig.9. This data covers all recorded data points throughout the operational period covering the cleaning trials (May-Aug, 2018). The data points are scattered due to operational activities, such as towing, equipment or instrumentation fluctuations, such as shaft power, and environmental conditions, such as large wind and waves. The open water power to speed relationship is visible, but not easily characterized.

To reduce the extraneous data points, the data set was clipped by a threshold of 300 kW about the approximate power to speed relationship. Fig.10 illustrates the data set with curve fits and comparison to the mean trial data. From this figure, it can be seen that the relationships are apparent, but the trial conditions capture the minimum power to speed curve from the operational data scatter. This is due to the relatively calm conditions under which the trials were conducted versus the typically rougher conditions encountered by the vessel under normal operation.

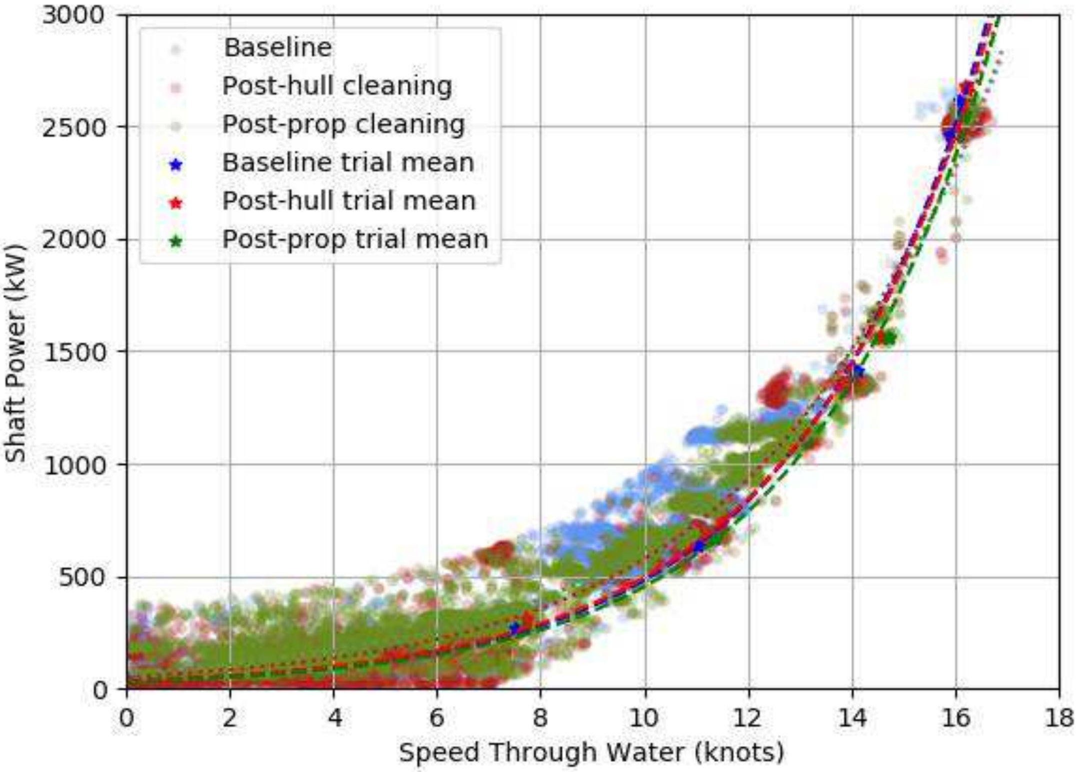


Fig.10: Reduced operational dataset covering trials period. Curve fits are applied for comparison. The mean trial data is shown for comparison with the operational data result.

8. Fuel Consumption and Speed

To identify the fuel curve for the vessel, total main engine fuel consumption versus shaft power was plotted for each trial. The fuel consumption versus power curve should be consistent for all trials since both fuel consumption and shaft power are not affected by external parameters such as environmental condition or hull and propeller condition. The speed attained however, does change as a result of variation in these external parameters. The measured total main engine fuel consumption versus power curve for all trials is shown in Fig.11. For each engine setting tested during trials, the baseline trials and post propeller cleaning trials data aligns well. However, there is an offset when it comes to the post hull cleaning trials data. For these trials there is less fuel required for a given power setting, particularly at higher power values. It is expected that there was some mechanical difference in the fuel measurement system that led to the discrepancy in the post hull cleaning fuel versus power data. A possibility is that one (or more) of the fuel flow meters surrounding one of the main engines was bypassed or partially bypassed or blocked during the post hull cleaning trials. However, the OpDAQ system bypass indicator did not highlight a complete bypass during this, or any of the trials.

The baseline and post propeller trials data for fuel consumption versus power are used to define the general fuel versus power curve for the Cygnus main engines. The post hull cleaning trials data was not used for this purpose due to the discrepancy from the other trials data. The general fuel versus power regression equation (regression equation corresponding to Fig.11) was used to calculate the "corrected" fuel consumption by adding the corrected power values at each engine setting for each trial. The power values corrected using the NavCad wind correction were used in this analysis. There is no quantifiable difference between the fuel consumption rate and speed through water for the different sea trials. This is due to the level of variation in data at single test condition within a given trial and how data from different trials fall within this variability range. For example, at a throttle setting of 8.0, the baseline trials speed through water ranges from 13.9-14.3 knots and the corrected fuel consumption ranges from 373-475 L/h. At this same throttle setting, the post hull cleaning trials speed through water ranges from 14.2-14.9 knots and the corrected fuel consumption ranges from 393-526 L/h. There is overlap in the speed and fuel consumption variability ranges between trials for each engine setting.

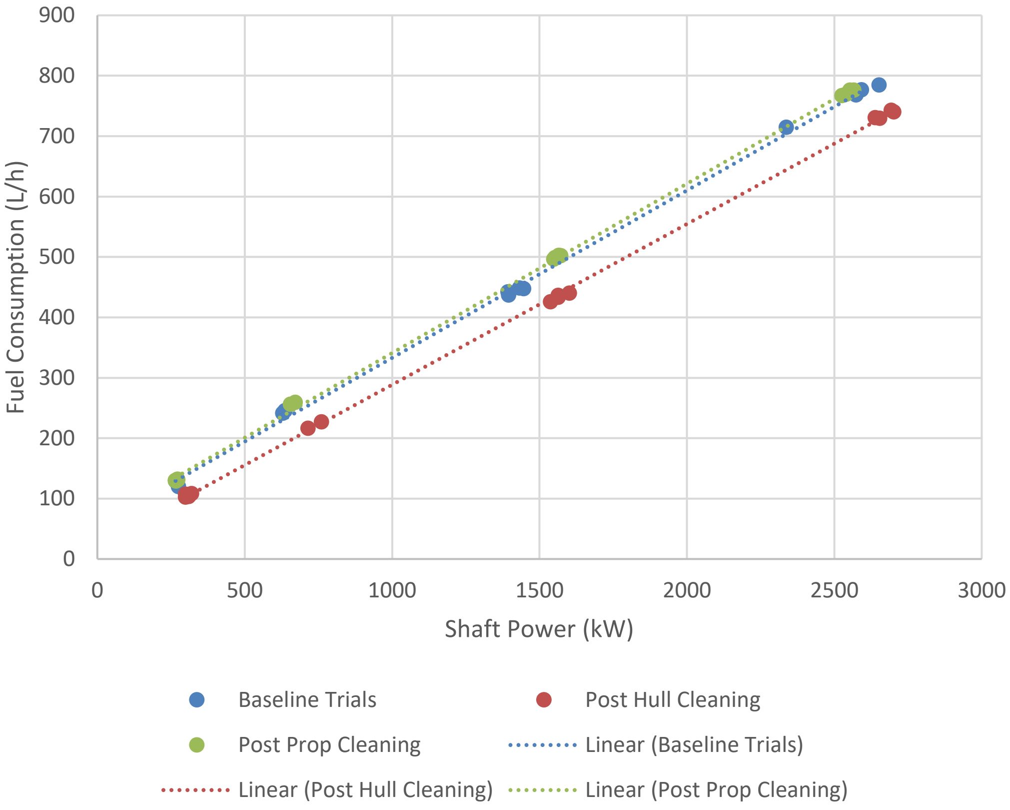


Fig.11: Uncorrected total main engine fuel consumption rate versus shaft power

9. Condition of Cygnus Hull in September 2018

The CCGS Cygnus was taken into dry dock on September 11, 2018 to perform vessel maintenance. When in dry dock, the hull was observed to have a relatively high level of fouling on one side in particular (port). The level of fouling present on the port side was similar to the amount that was present during the underwater survey conducted in May, 2018, prior to cleaning the hull. Specifically, there was slime and sea grass covering a large portion of the underwater hull (Fig.12). These observations were unexpected for two reasons. The first relates to the speed of fouling taking place on the Cygnus hull. Prior to the May hull cleaning, the Cygnus hull had not been cleaned in two years. It was anticipated that the level of fouling present in September, just 3.5 months post hull cleaning, would be much less than that observed during the May survey. Some reasons that could have led to rapid fouling growth during this short period include the relatively warm temperatures during summer 2018 in the region and a depletion in anti-fouling coating.

It is observed that the September hull condition level of fouling differs on the port and starboard sides of the vessel with the starboard side having a higher level of fouling. The May survey results indicated that the starboard side of the hull had a slightly worse level of fouling. It was anticipated that if one side was more fouled than the other in September, it would have been the starboard side to be consistent with earlier results. Increased fouling on one side of the vessel could result from frequent docking on one side (fouling occurs more on side subject to sunlight) or lower quality of anti-fouling coating on one side of vessel. Cygnus Captains were consulted and it was confirmed that the docking side varies. The anti-fouling paint was noted to be highly depleted in September, on both sides of the vessel (see Fig.13). This likely played a role in the high fouling accumulation rate during the summer period.

11/09/2018

Fig.12: Images of port side of hull during September, 2018 dry dock. The level of fouling is similar to that encountered in May, 2018.

Fig.13: Images of Anti-fouling coating after biofouling was removed. The anti-fouling coating is deteriorated in large swatches across much of the hull.

Note that the anti-fouling paint is the black paint that can be observed in Fig.13. This image indicates the level of depletion of the anti-fouling paint after the biofouling was removed using a pressure washer in dry dock. The anti-fouling paint adhesion was investigated by brushing it lightly by hand using a scouring pad. This resulted in the anti-fouling paint flaking off as a result of the brushing. It is possible that the May and September hull cleaning events enhanced this level of depletion.

The status of the anti-fouling paint was considered further by consulting with the Canadian Navy. A Canadian Navy biofouling Subject Matter Expert (SME) noted that the level of depletion of anti-fouling coating on the CCGS Cygnus was not typical given that the anti-coating was applied to the vessel only two years prior. The Canadian Navy SME indicated that this level of depletion was not seen on Navy vessels even after 5 years of use. They suggested to check on conditions during application and noted that application during high humidity levels could lead to faster depletion of coating. They also indicated that the type of coating used on the CCGS Cygnus was different than that used on Navy vessels and recommended that the CCG use an alternative coating.

The relatively high level of fouling present in September likely has an impact on the results presented in this report since there may have been a level of fouling present on the hull during post cleaning trials. This is particularly true for the post propeller cleaning trials which were not conducted until August 1, 2018. Unfortunately, there is no way to quantify the amount of fouling present during the post hull cleaning and post propeller cleaning trials. In general, if fouling was present during the post hull cleaning trials the analysis would indicate a lower level of power and fuel savings than the actual values. Also, if more fouling was present during post propeller cleaning trials than during post hull cleaning trials, the discrepancy between the measured savings potential and the actual savings potential would differ between trials and be larger for the post propeller cleaning trials. This could relate to the unexpected result of the post propeller trials found from the ITTC analysis methods.

10. Discussion and Recommendations

The measured results indicated an approximate 4% improvement in terms of required power to attain a given speed as a result of cleaning the hull and approximate 5% improvement as a result of cleaning the propeller, for speeds between 12.5 and 16 knots. However, there were variations in the environmental conditions and condition of the vessel between trials and these differences have an influence on vessel performance. The wind, wave and water temperature variations between trials were corrected based on ITTC guidelines. The wind correction was also made using two variations of the ITTC recommended wind resistance correction method for comparison. The discrepancy between vessel displacement during the different trials was not corrected for since there was no standard guideline available to correct for this when the displacement varied by more than 2%. It was estimated that the displacement between trials varied by approximately 8%. The lhull condition also varied between trials in that there was likely some level of fouling present during both the post hull clean and post propeller clean trials. Therefore there is some uncertainty in level of fouling between the post hull and post propeller cleaning trials. Based on the data that was corrected for wind (NavCad correction method), waves and water temperature, there is an average of 5% savings in terms of power required to attain a given speed as a result of cleaning the hull, for speeds between 13.5 and 16 knots. The performance decreases after the propeller polishing in this same speed range based on this analysis. To correct for wind, wave and temperature variation a number of parameters (e.g. wind resistance coefficient, propeller pitch for each trial, hull underwater area) had to be estimated. As a result, there is uncertainty involved in the corrected power values.

In terms of fuel consumption, there appeared to be a measurement error during the post hull cleaning trials which led to lower fuel consumption rates for a given power setting. This could be a result of partially closed fuel valve(s) surrounding one of the main engines. Therefore, it was impossible to quantify fuel savings resulting from cleaning the hull directly from the measured data. The general fuel consumption rate versus shaft power regression equation was used to calculate the corrected fuel consumption rates for each trial using the corrected (NavCad wind, ITTC wave and sea temperature) power values. This resulted in a corrected fuel consumption rate versus speed through water plot for each set of sea trials. The results for each trial were very similar and there were no quantifiable differences in the three curves.

10.1 Recommendations to Reduce Uncertainty and Gain Result Clarity

There were a number of recommendations identified for conducting a similar study in the future which would lead to lower uncertainty in the data and more clarity in the results. These are summarized in point form below.

1. Conduct all tests in very low wind and wave conditions. In this project the baseline trials and post hull cleaning trials were conducted in similar conditions which were high in terms of the environmental condition limit. The post propeller cleaning trials were conducted in relatively mild conditions. The methods to correct for wind and wave conditions lead to uncertainty in the results since certain parameters need to be estimated. In mild conditions these corrections are much smaller and therefore less significant.
2. Conduct all tests at the same displacement. Variations in displacement lead to changes in vessel performance. In this project it was attempted to complete all trials at the same draft levels. However, since the Cygnus is an operational vessel and trials were completed weeks apart this was difficult to manage. As such, there was a variation in the draft (and displacement) and the effect of this on the results was not quantified. Trials at the same displacement would not have this source of variation and would lead to increased confidence in results.
3. Select vessel that has available propeller open water curves, wind tunnel test data and model resistance test data. This would reduce the number of parameters estimated in the data correction analysis and lead to lower uncertainty in the results.
4. Conduct tests closer together in time. The three tests involved in this test were completed between May – August of 2018. During this time there was some level of fouling that developed on the hull between trials and subsequent to the hull cleaning. This leads to a lower level of confidence in the results since there may have been some fouling present during both post hull and post propeller cleaning trials. If the trials had occurred closer together in time (e.g. days apart rather than months) this would limit the potential for fouling to develop on the hull or propeller between trials.
5. Conduct study on a vessel that has an off-season or longer alongside duration. The CCGS Cygnus is continuously in operation throughout the year and has a short, 2 day, layover period between operations. This gives limited time for the accumulation of biofouling and as such it was expected that the amount of fouling present initially on the Cygnus would be relatively low. The performance increase as a result of cleaning the hull and propeller would be larger for a vessel with more fouling in the baseline condition. A good candidate would be a vessel that does not operate for a portion of the year, during which time fouling would accumulate faster than during operations.

10.2 Comparisons to Similar Publically Available Data

A brief literature search was completed to compare the results of this study to data available in the public domain. There were no directly comparable results identified in the literature in terms of comparable vessel size or initial level of fouling. However there were guidelines identified that provided insight as to what performance increases could be expected from cleaning the hull based on different initial levels of fouling (Schultz, 2007). These guidelines are based on model scale drag measurements and boundary layer similarity law analysis and were made for a mid-sized naval combatant at two speeds, 15 and 30 knots. Different fouling ratings (FR) as per the Naval Ships Technical Manual (2006) were used in this study. Table 8 summarizes the results of this study for a vessel speed of 15 knots in terms of increase in shaft power resulting from different levels of fouling. The fouled (baseline) condition of the CCGS Cygnus was mostly FR 20 with some areas having FR 30 (~15% of vessel). The corrected (for wind, wave and temperature) results indicate that the baseline trials required approximately 5 % more power than trials during which the hull was clean, for speeds greater than 13.5 knots. This is smaller than the 11% estimated increase in power for FR 10-20 as outlined in Table 8. However, the baseline condition was not a hydraulically smooth surface and was better described as a somewhat deteriorated coating. Therefore, it is reasonable to expect a lower power savings when comparing the two conditions.

Table 8: Expected performance changes as a result of hull fouling

NSTM Rating	Description	Increase in SHP
0	Hydraulically smooth surface	0%
0	Typical as applied antifouling coating	2%
10-20	Deteriorated coating or light slime	11%
30	Heavy slime	21%
40-60	Small calcareous fouling or weed	35%
70-80	Medium calcareous fouling	54%
90-100	Heavy calcareous fouling	86%

Giorgiutti et al. (2014) conducted a study to investigate the impact of fouling on a crude oil tanker. This study investigated the effects of fouling on the hull and propeller separately and involved several sea trials. The data from sea trials was analyzed using ITTC analysis guidelines and complimented with other recommended methods. The analysis involved corrections for wind, wave, sea temperature and displacement variation. Details on the displacement during each trial or how this was corrected for were not provided. In this study the level of fouling at baseline condition was much higher on both the hull and propeller than that which was present on the Cygnus. The fouling was not rated as per Naval Guidelines however it was indicated that there was severe hard, calcareous fouling that was difficult to remove covering the majority of the propeller and underwater hull surface. The savings resulting from cleaning the hull and propeller were approximately 45 % in terms of reduced power at cruising speed. This study included both propeller cleaning and polishing.

A Computational Fluid Dynamics (CFD) based study was presented by *Demirel et al. (2016)* in the Journal of Applied Ocean Research. This investigation predicted the effect of biofouling on resistance and power requirements of a container ship based on full scale simulations. These predictions indicated an increase in power by 18% for the ship fouled with light slime and an increase by 38% for the ship fouled with heavy slime. There were no sea trials used to compare or validate the CFD results. However, model test data was compared to the non-fouled predictions and they compared well.

In general, there is limited comparison data available in the public domain for this type of study, particularly data resulting from sea trials. The data that does exist can be compared generally but not directly since the hull forms and initial level of fouling vary. In addition, there are gaps in the methodologies applied for data analysis and trial corrections for the comparative data that is available in the literature.

11. Concluding Remarks

The primary goal of this study was to quantify the effects of cleaning the hull and propeller on the vessel performance in terms of speed and power, for the CCGS Cygnus. The corrected sea trials data indicated a reduction in power required to attain a given speed by an average of 5% between the speed ranges of 13.5-16 knots. However, these results were not corrected for variation in displacement across trials or the presence of slight fouling during the post cleaning trials. The results compare reasonably to estimations of power increase for a mid-sized Naval frigate for similar baseline and fouled conditions.

This study provided insight towards steps that could be taken to increase the value of future tests of a similar nature. These recommendations should be considered when planning future work to increase the level of confidence in results.

Acknowledgement

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