Fuel Conservation through Managing Hull Resistance

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Abstract
There are many good reasons for reducing marine fuel oil consumption. First and foremost is that fuel prices are rising beyond what analysts have predicted as recently as a year ago (315 USD per ton for IFO380). Furthermore, reduction in fuel consumption will have a corresponding positive impact in reducing airborne pollution and global warming. Ships are responsible for approximately 5% of the global oil consumption, and a considerable part hereof could be saved, if the ships' underwater hull and propeller were cleaned at economically optimum intervals. Many ship owners are not aware of the true impact that fouling has on vessel performance, owing to the inherent limitations of performance monitoring systems. In the following, an unprecedented method for monitoring the performance of ships, based on the standard measuring equipment onboard will be described together with some examples of the results, which may be achieved. Also, some of the precautions, which may be taken to improve fuel conservation, mitigate performance losses and benchmark the performance of hull coating systems will be mentioned.
Managing hull resistance may also contribute to mitigating invasive species attached to the hull.

Background on ship performance
For most ships delivered from a shipyard there is a diagram showing the relation between speed and required power for one or more loading conditions as shown below. This diagram has been prepared based on theoretical calculations and in most cases has been confirmed by model tests and by a speed trial immediately before delivery.
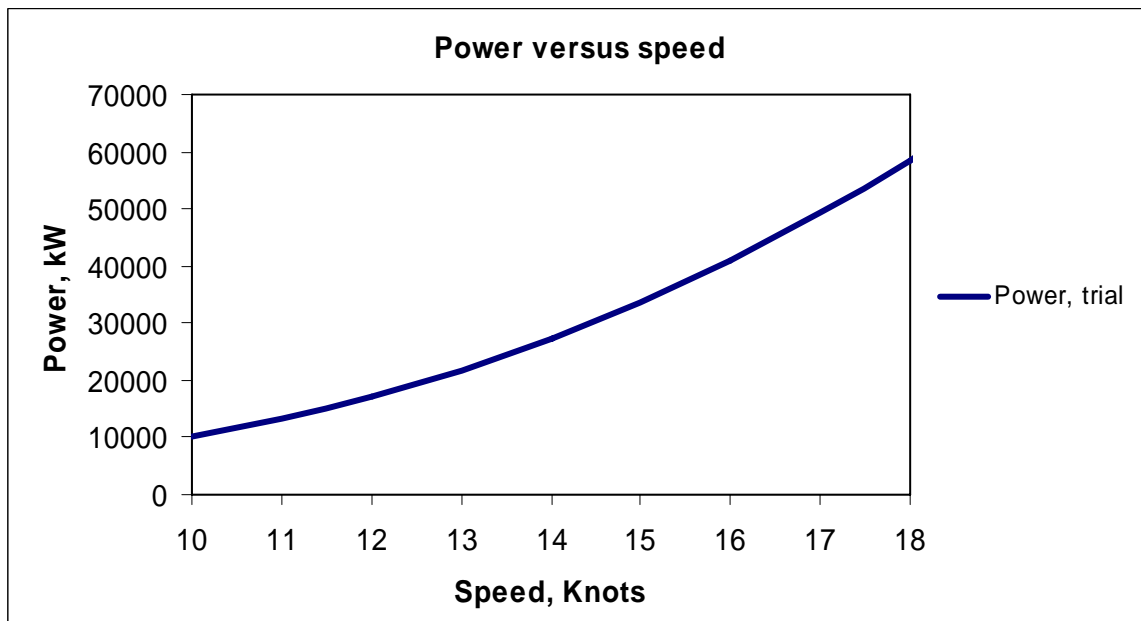

This speed trial is a complicated and time-consuming procedure. The ship must be loaded correctly, the weather needs to be reasonably good, and the trial has to take place in a test area with deep water at a time when there is no other immediate traffic. Time must be given to accelerate the ship up to a constant speed and, as a sea current may be present, each speed run has to be made twice, in opposite directions to compensate for this. Consequently, only a limited number of draft/speed combinations are tested, so the achieved speed/power results, properly adjusted for wind, waves, temperature, salinity, and draft differences, are used merely to confirm or adjust the already existing diagram.

If the engine's maximum continuous rating (MCR) is plotted in this diagram, the maximum speed for the ship may be found as illustrated below.

Power versus speed, trials
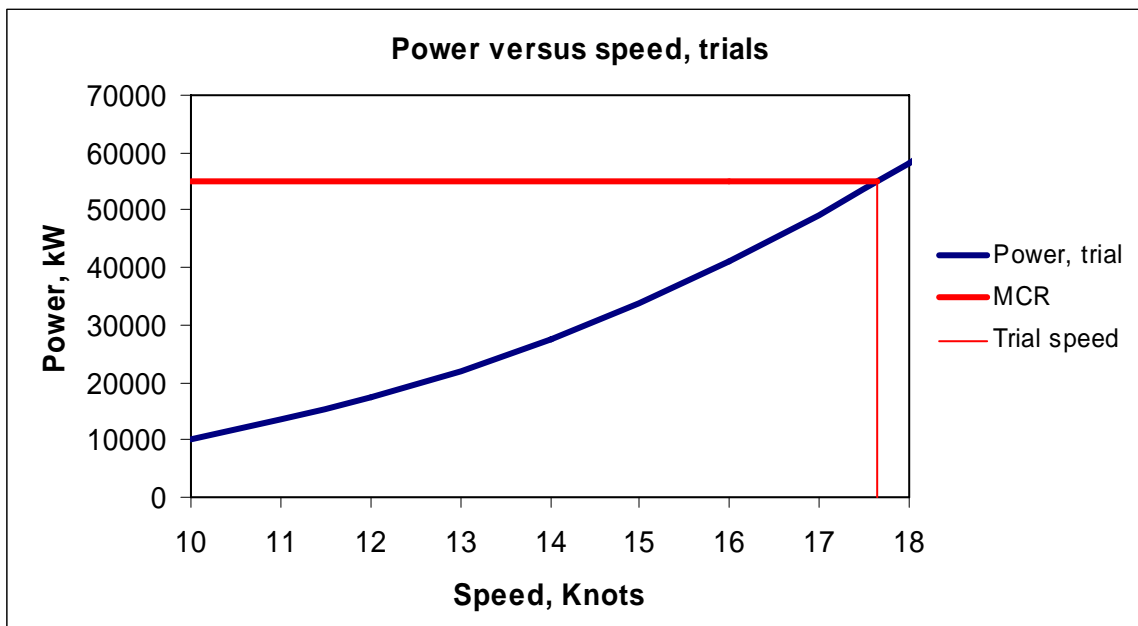
Ship owners know that this is not the speed they can expect in daily operation, and for commercial consideration, they define a so-called 'service speed'. This service speed is traditionally found by adding 15% to the power curve and subtracting 15% from the engine power line as shown below. The 15% added power is expected to consist of 5% for weather losses and 10% for losses due to hull and propeller surface roughness caused by marine growth and corrosion. For a well-organized introduction to ship propulsion, see Ref. 1.

Power versus speed, service
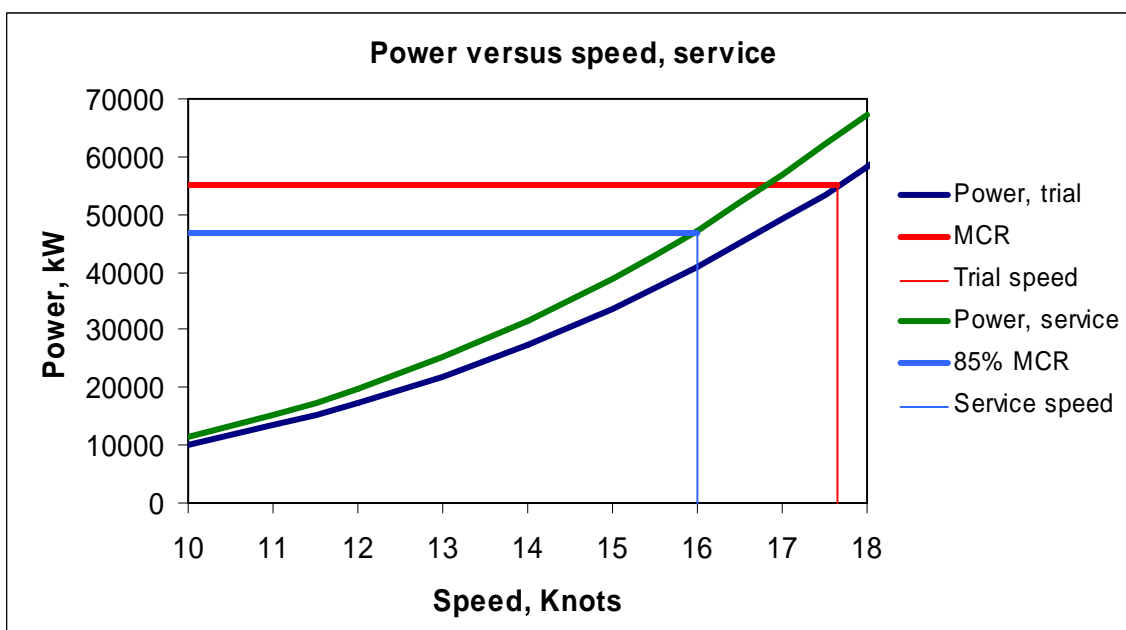
The actual situation with respect to marine fouling for any particular ship may be worse. This will only be discovered, if the fouling is significant, because it is very difficult in practice to get a reliable and accurate picture of the speed/power performance of a ship in service.

Degradation of the performance

The main reason for performance degradation is marine growth on the ship's hull. This subject is treated thoroughly in the technical literature, for instance in an excellent way in Ref. 2. Here it shall only be mentioned that ship owners are allocating a lot of time and money to prevent or mitigate the degradation. The main remedies are various types of hull treatment in dry-dock, coatings applied to the underwater portion of the hull at regular intervals, and in some cases, in-water cleaning of the hull and polishing of the propeller.

Altogether, the total costs of all ship owners' anti-fouling precautions are of the order of 1.5 billion USD per year or approximately 5% of the total marine fuel oil costs. Unfortunately, it is difficult to determine if this money is invested in the optimum way. There are many different types of hull treatments, and the price for the coatings varies greatly. In addition, each shipowner has his own way of handling coating selection and maintenance. Furthermore, it is difficult to evaluate and compare the effect of the different hull treatments, unless reliable methods of performance analysis are available.

Monitoring of ship performance
Most ship operators have established a procedure for speed/power monitoring, for instance by measuring the daily fuel consumption and the daily distance covered. In this way, the daily mean power and mean speed may be calculated, and the result may be plotted in the speed/power diagram for comparison with the trial trip results. Unfortunately, results achieved in this way usually scatter so much that it is impossible to conclude anything directly from such a diagram, as it may be seen from the following plot for a well-maintained container ship.
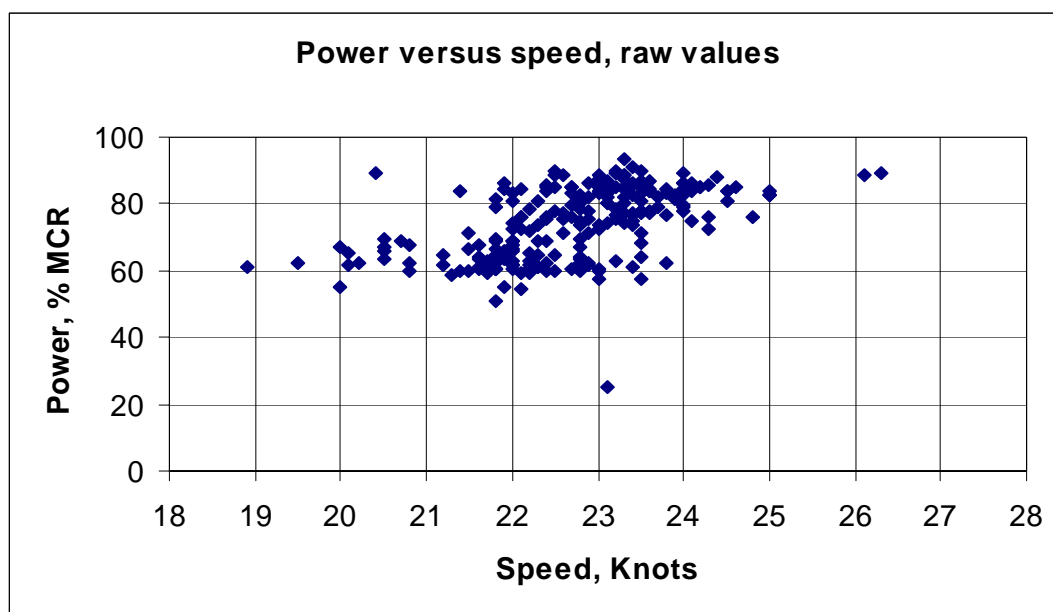
Procedures may also have been established for more precise measurements with longer intervals, for instance once a month. A day with nice weather may then be chosen. In such cases, and where the prime mover is a slow running diesel engine, the power may be measured more accurately by cylinder indication, and speed may be measured over a period of for instance two hours at constant power on a constant course. The result of such an exercise will be more accurate than one based on "noon data," however, even such monthly results may scatter to an extent that an accurate service speed prediction may be difficult or impossible.

Underwater inspections of the hull as a supplement to speed and power measurements are of course useful; however, they do not provide a meaningful metric between surface roughness and impact on vessel performance. For more information on the biological aspects of hull coatings, see Ref. 3.

Factors influencing the speed/power monitoring
There are many reasons why the directly obtained speed/power values are scattered as in the above illustration. The main factors, which need to be taken into account, are:

1. Drafts. Mean draft and trim has a great influence on the ship resistance. It is reasonably easy to adjust the results for differences in mean draft, but differences in trim are more difficult to deal with, especially when most ships today are equipped with a bulbous bow.

2. Weather. Wind and waves can seldom be totally ignored; therefore, the results will need to be corrected accordingly. It is not that difficult to measure and make corrections for the wind, but waves can neither be measured (by instruments) nor be easily corrected for.

3. Sea current. Today the speed over ground may be measured with great accuracy by means of the DGPS; however, this speed will not be the true speed due to the presence of sea current. The true speed, the speed through the water, is more difficult to deal with. The problem is that most speed logging devices are measuring the speed through water too close to the ship, so that the ship's boundary layer influences the result. Normally, it will not be possible to correct the speed for sea current, unless a reciprocal run is performed, and this is usually regarded as too time consuming to be done during commercial operation.

4. Temperature and salinity. These two factors do have some influence on the result, but they are seldom taken into account in performance analysis.

5. Last but most important: The lack of method for interpretation of the results. Even if reliable speed/ power values, corrected for all the above-mentioned factors are obtained and plotted in the speed trial speed/power diagram it may be difficult to accurately describe the degradation of the performance. The reason is that the ship's resistance may be roughly divided into frictional resistance and wave-making resistance. The fouling only influences the frictional resistance, and as the frictional resistance fraction of the total resistance depends on the speed and the draft, the additional power demand, expressed as percentage of the total power requirement, will not be the same for different loading conditions and different speeds.

[The specific fuel consumption of a well-maintained 2-stroke main engine will normally not change much during its service life. Therefore, a possible engine/bearings/propeller shaft degradation will not show itself in the same way as hull degradation, but in a number of other ways; for example as a high "residual resistance" and a high exhaust gas temperature. In the unlikely event that there is damage to the hull or propeller, these can usually be readily identified since the wake fraction coefficients are not influenced by damage to the hull or propeller, whereas, the wake fraction coefficient is directly influenced by hull and propeller resistance (type of treatment in drydock, coating system as well as fouling)].

Proposed measure for performance degradation

The effect of hull resistance on propulsion performance is complicated and difficult to describe in an unambiguous way. The primary effect is that more water is dragged forward along with the ship, and this will of course increase the ship resistance. The increased forward velocity of the water in the ship's boundary layer will also cause the inflow velocity to the propeller to be reduced. This has several effects. On one hand the efficiency of the propeller will decrease, on the other hand some of the power lost in the boundary layer will be re-gained. Altogether, the required power will increase, however, not quite as much as the resistance. Since it is not possible to state a fixed relation between added resistance and added power, for simplicity it is proposed to use the "added resistance" as a measure for degradation and *not* the added power.

Even a description of the hull degradation in the form of the added resistance as a percentage of the total resistance is ambiguous, unless it is specifically designated, for which speed and which loading condition (draft) this percentage is valid. Therefore, it is further proposed to refer the added resistance to "the design speed and the design draft." This is not a precise reference, but it works in practice and is quite useful, not only for evaluation of the condition of a single ship, but also for comparison of several ships, which not need to be of the same shape and size. The implication here is that different coating systems may be compared, even if they are applied to ships of different size or hull form.

It should always be kept in mind that the added resistance as defined here is *not* equal to the actual increase of power. Even at "design speed and draft" the increase of power will normally be a few percent lower than the "added resistance". At deep draft and low speed the power increase will be more than the "added resistance", and in ballast condition at full speed it may be less than half of the "added resistance". Note that it is always possible to calculate the actual power increase for any draft/speed from the found "added resistance".

Collection of performance data

As mentioned above, performance data may be collected daily or, in a more detailed form, with an interval of a month or so. Some ships have an automatic data logging system, which files performance observations continuously.

In principle, any of these methods may be relevant and useful, as long as the observations are made carefully. These different methods do have their advantages and disadvantages:

1. Continuous data logging excludes all human errors, but some data, for instance wave data, are normally not available in this way. Furthermore, this method produces a lot of data, which means that some kind of data reduction and data selection has to be introduced together with the system. Still it is difficult to assure that only data for valid navigation conditions are further processed.

2. Daily observations, the so-called 'noon-data', are useful for some purposes, if carefully dealt with. Daily reports can only be used for reliable performance analysis, if all conditions have remained unchanged during the 24-hour noon-to-noon period, and this is seldom the case.

3. Monthly, detailed observations over a time interval of a couple of hours are normally as reliable as such observations can be and quite useful. It will however be described later that these observations cannot "stand alone", but have to be treated together, and 12 sets of observations a year are therefore too few to establish a reliable "time history" for the development of the added resistance for a ship.

4. A reasonable solution seems to be a procedure, where observations are made once a week. This interval is so short that the routines are not forgotten, but on the other hand so long that the temptation of just repeating the latest data is avoided. In addition, it is usually possible to find a two-hour period with constant navigation conditions within a time interval of a week, and +/- 50 observations per year is still enough for a detailed time history of the propulsion efficiency.

Processing of performance data
One way of processing the performance data is to compare the observed power and RPM values to those, which are found for similar weather and loading conditions from a mathematical model of the ship's propulsion performance. It can then be determined, at which speed through the water and with which added resistance the calculated values matches the measured values, and both speed through water and added resistance are then determined.

This method requires that such a mathematical model is available or can be established, however, this is not as easy as it sounds. There are complicated, theoretical methods for the calculation of resistance, propulsion system performance, weather resistance, and influence of hull resistance for a specific ship, but in practice a simple and robust general mathematical model, which can easily be adapted to any ship, is needed. Such a model may be established by means of a combination of theoretical considerations and approximation formulas with empirical constants.

The number of empirical constants in a model, which is developed in this way, is quite high, but fortunately, some of these values are valid for all ships or for large groups of similar ships. Other constants are specific for the individual ships. The value of some of these latter constants may be found by careful analysis of the tank test and/or trial trip results, whereas, other constants can only be found by statistical analysis of a large number of performance observations for the ship *in service.*

An example of a solution (called CASPER, Computerized Analysis of Ship PERformance)
CASPER® is based on a general mathematic model; a build up by well-known, state-of the art elements for the calculation of ship resistance, propeller performance, weather resistance, etc. The general model, based on the type and main dimensions of ship and propeller, may stand alone and may be used directly for comparison to actual performance data, but a more reliable model can easily be established by an adjustment of the general model, considering tank test/trial data. Even this model will not normally reflect all changes in the operational conditions, and the model is therefore not used for performance evaluation until it has been adjusted further by means of a statistical analysis of a number of performance observations. In general, 10 – 12 sets of performance observations are required (in some cases, the standard noon reports can be utilized) for this purpose, and the model will then be used for performance analysis and predictions. The adjustment of the model continues weekly, as more observation data are received. Normally, the basic constants of the model will remain unchanged after 30 40 sets of observations, but the constants describing the condition of the hull and propeller resistance are updated in real time as service performance data from the ship is acquired.

Accuracy of the analysis

In practice, the accuracy of the analysis results is more dependent on the accuracy of the observation data than of the mathematical model itself. Experience shows that the actual "added resistance" as earlier described may be found with an accuracy of approximately 1%, and that the result from a single set of observations normally not will deviate more than 3% from the mean value. The actual speed/power diagrams, which may be produced from the adjusted mathematical model, are therefore fully valid for all practical purposes (transport cost calculations, cost-benefit decision for coating selection, optimal maintenance intervals, et cetera).
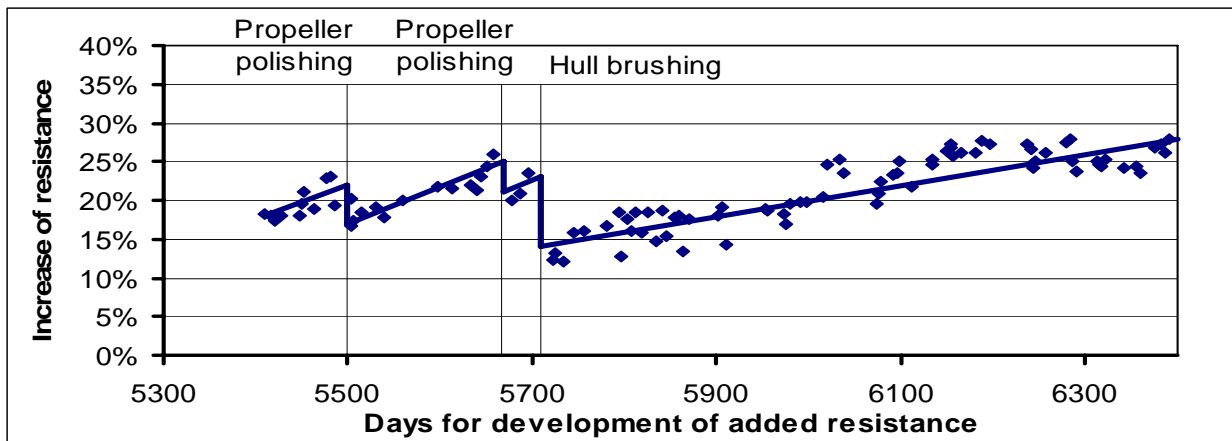
Examples of Added Resistance diagrams

In the following, a number of diagrams are shown in order to illustrate the described method. The individual analysis results are shown, and a 1st order curve (a straight line) is faired through the points in order to show the development. For each ship, there is a direct relationship between added resistance and speed/fuel penalties.

1. Typical example (below) of development of added resistance. It is seen that the added resistance of the hull and propeller in this case develops very slowly, less than ½% per month.
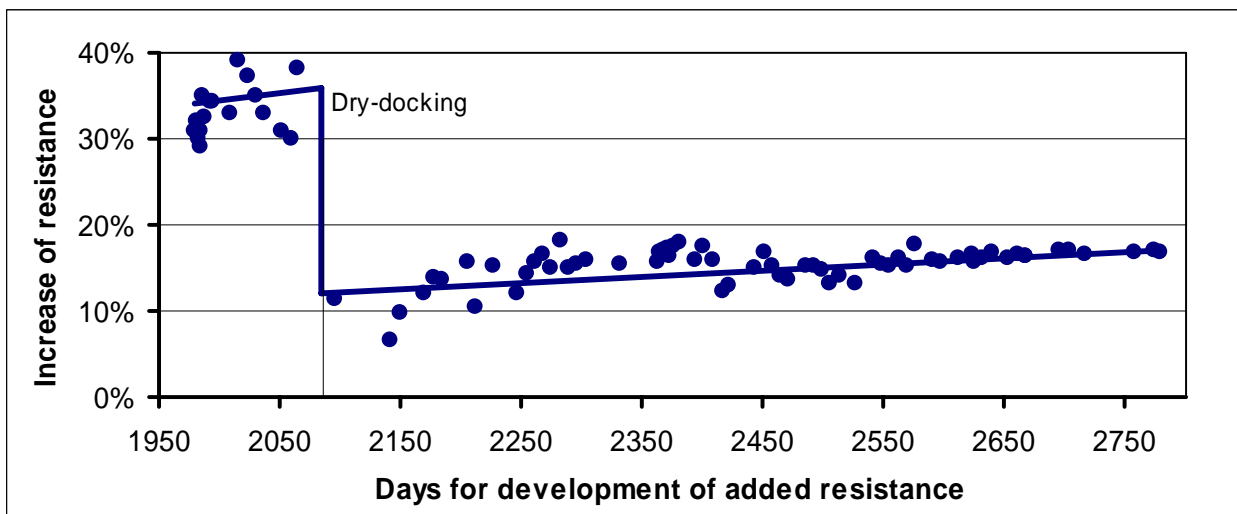

2. Example (below) of a more pronounced development of the added resistance. Here, the propeller polishing at 6 month intervals resulted in a 5 ton per day fuel saving and the hull cleaning resulted in approximately 10 tons per day fuel saving. The development of resistance of the hull and propeller is 0.7 – 1% per month.


Use of the diagrams

In the following, four examples of the use of the diagrams will be shown.

1. This ship (below) had initially a high added resistance, approximately 50%. When this was discovered, the propeller was polished and the ship's sides were brushed. It is seen that the effect of this was marginal. The Operator was advised to have the ship dry-docked, but as this was inconvenient at that time he decided to clean the sides and bottom of the hull thoroughly a few weeks later. The result of this cleaning was remarkable, but as the anti-fouling was apparently depleted, the result did not last long, as indicated by the steep slope and the ship was dry-docked on schedule. Subsequent to the dry-docking, the hull was cleaned in-water, when the added resistance exceeded 20%.
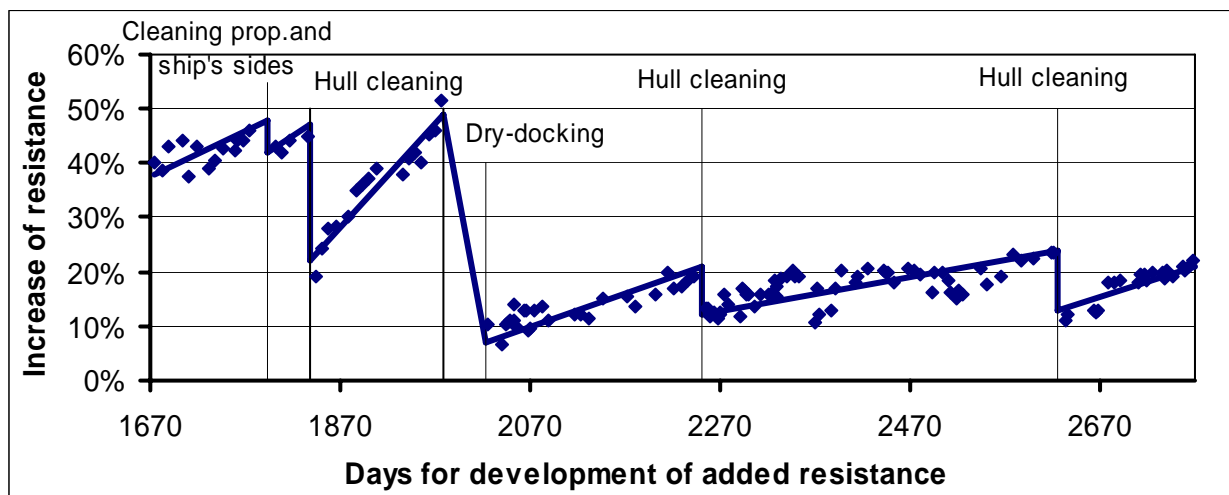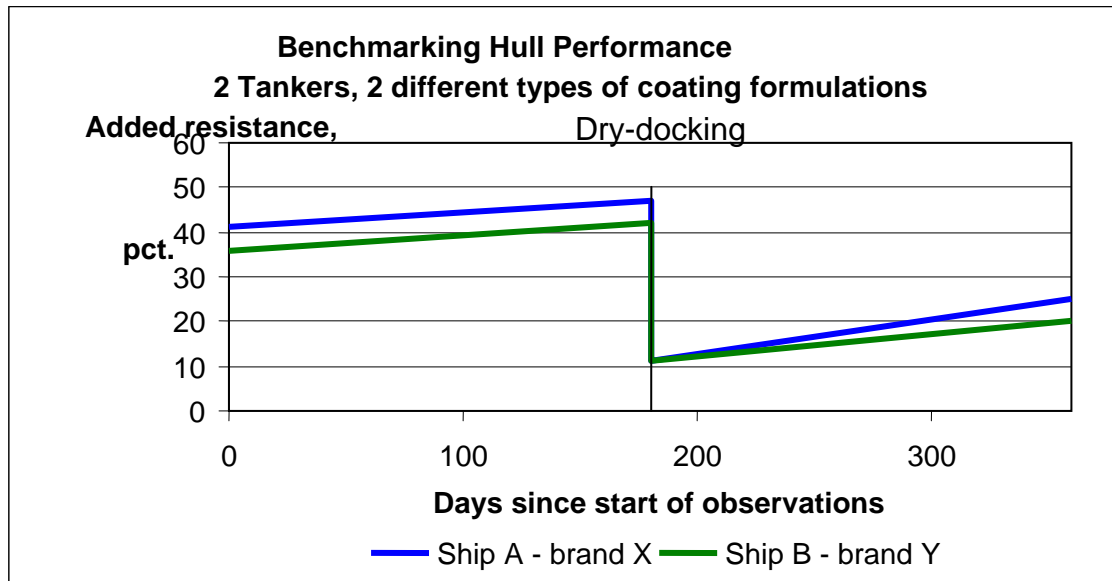

2. This ship (below) came out from the dry-dock with a remarkably high added resistance (40%), and this resistance was constant for a period, until it suddenly dropped. After this the added resistance developed very fast (6% per month). A hull cleaning removed approximately half of the added resistance, but the resistance is developing fast again after the cleaning. It is a clear example of a poor treatment in the dry-dock.
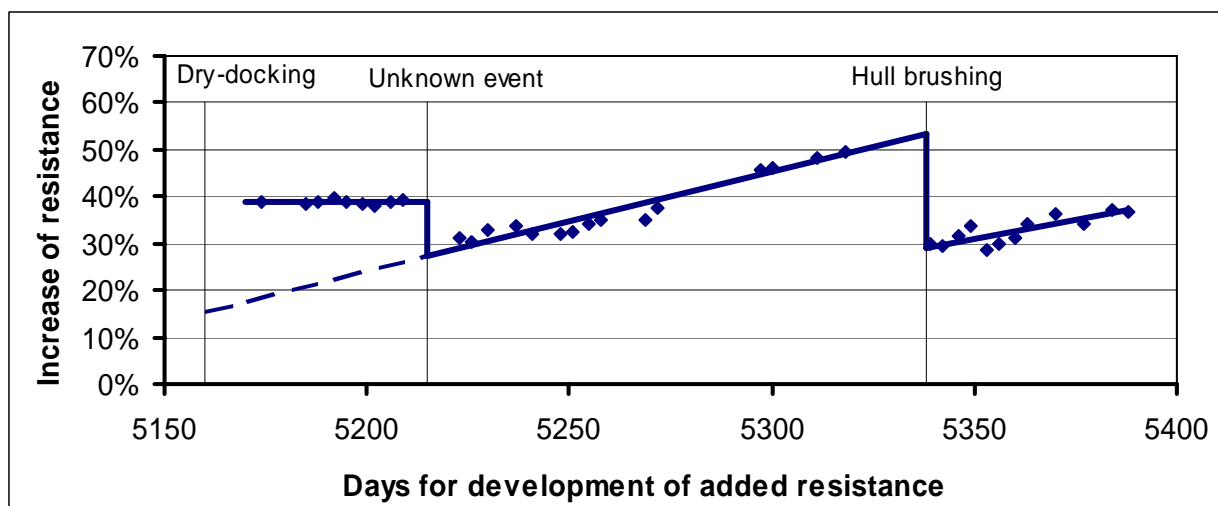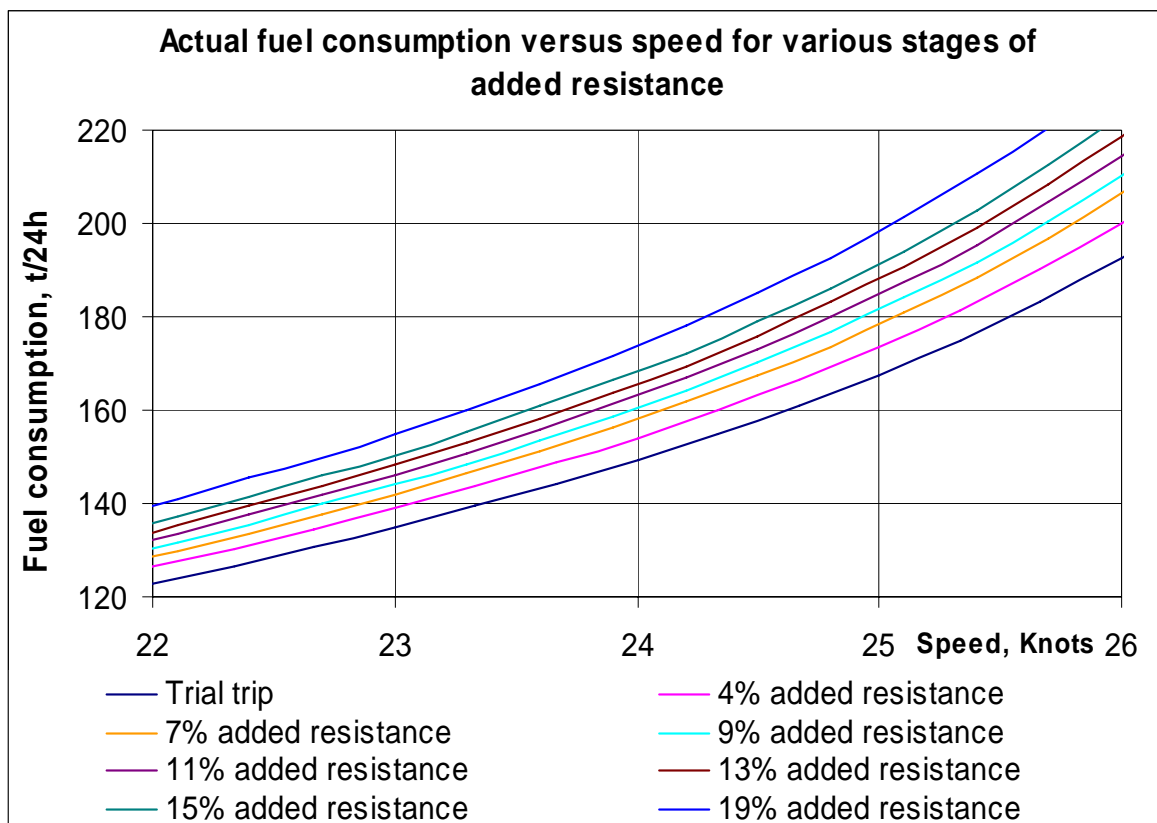

The explanation for the high, constant added resistance (above graph) after dry-docking can only be that something adhered to the hull. It could be keel blocks, plastic sheets or other objects, which may have been present under the bottom of the ship before docking out. Whatever it was, it disappeared suddenly, and the resistance dropped down to a usual development line. Assuming this was the case, the added resistance after dry-docking was as high as 16%, which indicates that not much treatment had been done (in dry-dock) to make the hull smooth. Further, the fast development of the added resistance indicates a very inefficient anti-fouling paint had been applied. It is seen that for this particular case a hull cleaning at least every half year will be advisable to mitigate what would otherwise be even higher fuel penalties.

3. These 2 ships (below) came out of dry-dock at different times. The effect of the hull efficiency before and after dry-dock is clearly shown, where ship A exhibited higher added resistance before dry-dock. After dry-dock, (similar hull preparation in drydock) the two different

coating systems exhibit differing developments of resistance, hence, Ship B is now consuming 5 tons per day of fuel *less* than Ship A or thousands of nautical miles further on same amount of fuel over a 3 year period. Individual data points were removed for clarity and the drydock date was zero-adjusted.

Benchmarking Hull Performance
2 Tankers, 2 different types of coating formulations

Added resistance, pct.

Dry-docking

Days since start of observations

Ship A - brand X   Ship B - brand Y

4. Fleet monitoring. The graph (below) shows a fleet of 7 ships of similar design, plotting the actual performance due to present state of fouling, with all other variables corrected. This illustrates that performance losses due to fouling are seen as an increase in consumption to maintain a speed or as an incremental speed loss at a maintained power (no change in fuel consumption!). Another benefit of this analysis is for determing precise speed-fuel metrics for slow sailing in service. Note that in this speed window, the fleet if 7 ships varies in fuel consumption from 156 tons per day to 174 tons per day (at 24 knots) due solely to fouling and type of treatment in drydock.

Actual fuel consumption versus speed for various stages of added resistance

Fuel consumption, t/24h

Speed, Knots

Trial trip   4% added resistance
7% added resistance   9% added resistance
11% added resistance   13% added resistance
15% added resistance   19% added resistance

Lessons learned
Since this technology has been utilized for more than 10 years, and on more than 100 ships (prior to commercialization in 2002 as CASPER®) it is possible to draw some general conclusions from the results.
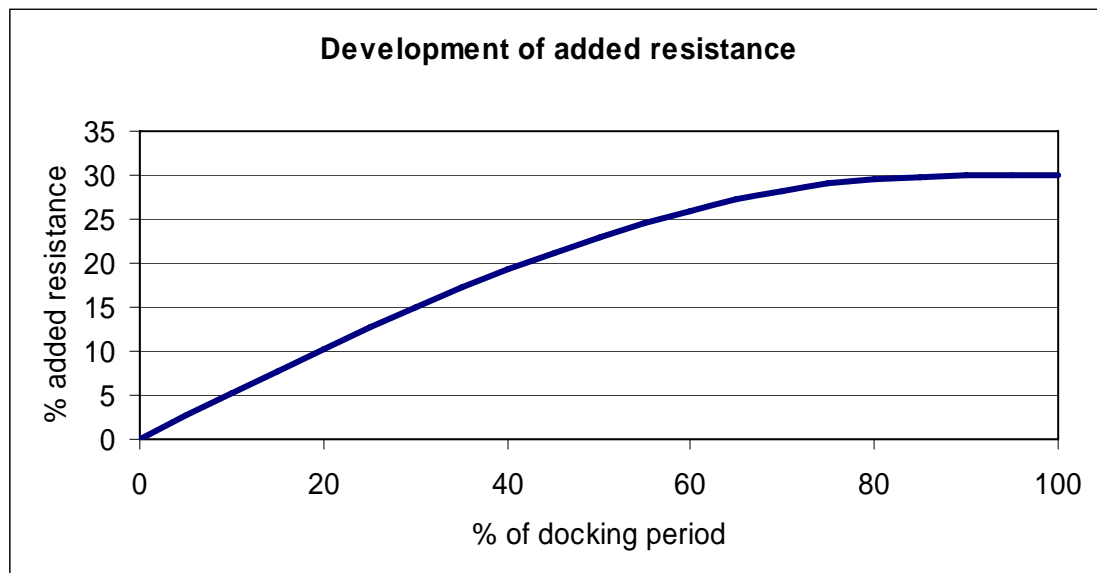
1. The added resistance (due to fouling of the hull and propeller) varies from around 6% and up to 80% in the worst cases. *In average, the added resistance for a ship is approximately 30%, if no special attention has been paid to the ship. 30% resistance on an Aframx tanker equates a speed penalty of 1.0 knots are an increase fuel use of 12 tons per day at design speed.*
a.) Roughly, one third of all ships are in a good condition with added resistance less than 20%;
b.) Half of all ships are in a reasonable condition, but in a condition, which easily could be improved, with an added resistance between 20% and 40%, but exhibit no unusual fouling pattern. For these ships, improvement in performance can be achieved by some standard maintenance procedures without interfering with the normal course of operations;
c.) The remainder of the world fleet (over 10,000 dwt) is in poor condition, where the added resistance is over 50% (with a good likelihood of bio-risk from the higher level of hull fouling).

2. The development of the added resistance normally follows a curve like this:

Development of added resistance

A line graph with the y-axis labeled "% added resistance" ranging from 0 to 35, and the x-axis labeled "% of docking period" ranging from 0 to 100. The curve starts at 0 and rises steeply, gradually leveling off to reach approximately 30 at 100% of the docking period.

The increase will normally be between 0.5% and 2% per month in the beginning of a dry-docking period. For some cases, 5% - 6% per month for a limited duration have been seen. Later in the period, when the added resistance has reached a certain level, the development may be more restricted. *The slope of the lines for development of resistance are a good business tool in determining future performance penalties due to fouling.*

3. The basic hull treatment in the dry-dock has a pronounced influence on the added resistance after the dry-docking. In the best cases, the base-line added resistance will only be 0% to 4%. A partial treatment in drydock has been seen to result in an added resistance of 5% - 20%, while in the worst cases there is no benefit at all from the dry-docking.

4. The type of coating has a pronounced influence on the development of the added resistance. It is not only a question of type of coating, it is also important that the coating is applied in correct thickness, and that the dissolution speed or, for self-polishing paint the polishing speed, is carefully adjusted to the service speed and operational patterns of the ship. Insofar as the performance of silicon coatings, the treatment in dry-dock is even more critical than with paint systems.

5. Hull cleaning between dry-dockings may have a remarkable effect, especially if one of the less active types of antifoulants has been used. Hull cleaning may to a certain degree compensate for low efficiency of the antifoulant.

It is advisable to clean the hull _before_ the slimy layer of bacteria and algae has turned into a layer of seaweed. In that case, very soft brushes (for example, softer than the bristles of a toothbrush) can be used, and the anti fouling paint will not be damaged. This stage corresponds to approximately 12% of resistance added to the resistance after dry-docking. At a later stage, harder brushes are required, and though they easily can remove the seaweed they will most probably remove some of the anti-foulant, and this may result in an increased development of the added resistance after the cleaning.

Conclusion

Economically optimum precautions can only be taken, if the propulsion condition of the ship is well defined, and this requires not only a reliable performance monitoring system, but also rigorous methods of analysis. Any shipowner may establish such a system; however, it requires strong hydrodynamic and statistical expertise to develop and to extract actionable information for prudent business decisions.

When rigorous methods of analysis have been established and in use for some time, it will be possible:

- To evaluate dry-docking treatment such as water-blasting, robotic systems and other emerging technologies;

- To follow the development of hull and propeller resistance for individual ships and to take action when economically justified on a ship-to-ship basis. This includes evaluating the before-an-after effect of hull cleanings, water pressure cleanings, propeller polishing, as well as the mitigation of invasive species introduced through the ship's hull.

- To benchmark the efficiency (Total Ownership Cost) of any coating system by comparing ships with different coating systems. Ships need not be identical in hull form.

Experience has shown that at least 10% may be saved in average on the fuel costs. For a ship, which burns 100 tons of fuel per day, at least 10 tons per day may be saved. This represents a value of approximately 3,000 USD per day or approximately 800,000 USD per year.

Other advantages may follow, such as the ability to:
- Optimize trim characteristics for maximum propulsion efficiency;
- Correlate Average Hull Roughness to added resistance;
- Controlling invasive species from hull growth, by controlling the added resistance;
The aforementioned advantages are worthwhile, yet outside of the scope of this paper.

Looming on the horizon is volatile fuel prices (as of this writing, fuel is $315 USD per ton for IFO380), greater demand to reduce emissions and the need for defining true lifecycles of new coating systems. It is in all parties' interest that ship operators do their utmost to establish accurate and reliable methods of analysis for maximizing fuel conservation, reducing emissions and improving vessel performance.

This paper was slightly modified from its original presentation and is for informational puposes only and cannot be construed as technical or financial advice whatsoever.

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