

Reliability and accuracy of ship powering performance extrapolation

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ABSTRACT

The aim of this paper is to discuss factors that affect the reliability and accuracy of the ship powering prediction process from model experiments and to conclude with suggestions as to how the extrapolation process can be improved. Uncertainty exists in the experiments that are done to provide data for the ship powering performance prediction process and in the extrapolation method itself. Uncertainty analysis was used to address the sensitivity of the extrapolation process to uncertainty in the inputs and as a result to focus on those factors that contribute most to uncertainty in the results for a ship powering estimate. Questions are raised about the ship powering performance prediction process including: can experimental uncertainty be reduced; is it necessary to calculate wake fraction and relative rotative efficiency; how can uncertainty of the analysis method be minimised; how can frictional resistance of a ship model be most accurately subtracted from the total resistance; how sensitive is the powering estimate to uncertainty in the correlation allowance. Suggestions for improvements are made. The approach adopted is not prescriptive, but one of questioning standard practice in order to get practitioners to reconsider their analysis methods with a view to achieving improvements in accuracy.

Keywords

Ship powering performance; extrapolation; uncertainty

1. INTRODUCTION

Model ship extrapolation relies heavily on the work of W. and R.E. Froude from more than 100 years ago. According to (W.) Froude's *Law of Comparison* (e.g. van Manen and van Oossanen 1988, p.5; Rawson and Tupper 1984, p. 406), "The residuary resistance of geometrically similar ships is in the ratio of the cube of their linear dimensions if their speeds are in the ratio of the square roots of their linear dimensions". The *Law of Comparison* was established experimentally and is not a rigorous physical law.

The resistance of a ship and its model can be shown through dimensional analysis (e.g. van Manen and van Oossanen 1988) to be a function of the Froude number and the Reynolds number. This is effectively the justification for the practical use of the *Law of Comparison*. A geometrically similar model tested at the same Froude and Reynolds numbers to those of the ship would have the same coefficients of resistance and other non-dimensional

propulsion parameters, but as is well known, it is impossible to test the model at similar values of both the Froude and Reynolds numbers. As a result, in the resistance test, the model is normally tested at equivalent Froude numbers to the ship and a correction to the frictional resistance is made to approximate the effects of testing at different Reynolds number. As the Reynolds number variation from model to full scale is large (10^3 or more) any uncertainty in model ship extrapolation is exaggerated in the final result for ship power.

Ignoring additions and corrections such as the wind resistance coefficient, appendage resistance coefficient and ship model correlation allowance, the "residuary" resistance coefficient of the model and ship is found by subtracting the frictional resistance coefficient of the model (or $1+k$ times the frictional resistance coefficient if a form factor k is used) from the total resistance coefficient of the model. The frictional resistance coefficient of the ship (or $1+k$ times the frictional resistance coefficient), at the same Froude number, is then added to the residuary resistance coefficient to obtain the total resistance coefficient of the ship.

This process relies on the accuracy of frictional resistance coefficient values, but historically these values have themselves been found from experimental results. The friction lines, strictly representing the variation of turbulent flat plate friction coefficient values with Reynolds number, or in the case of the ITTC 1957 ship model correlation line (van Manen and van Oossanen 1988), a variation from turbulent flat plate friction values, are either curve fits to data of flat plate friction, or curve fits to corrected experimental values of flat plate friction, or the result of boundary layer analysis with coefficients obtained from experimental data. That there are several different lines with different values emphasizes that these values are not known exactly. Also, the values have been extrapolated to full scale ship values of the Reynolds number since it has not been possible to do experiments at these large sizes and speeds. Some examples of turbulent flat plate friction lines are the Schlichting/Prandtl line (Schlichting 1979, p.641), the Schoenherr or ATTC line (van Manen and van Oossanen 1988); a model ship extrapolator is the ITTC 1957 line; and examples of more recent work are the lines due to Grigson (1993; 1999) and Katsui *et al* (2003; 2005).

Uncertainty in the process is offset to some extent by the inclusion of model ship correlation coefficients which have been assembled from past practice of correlating full scale ship trials measurements of powering with predictions from model experiments using the same or similar process, but these correlation coefficients do not always effectively make up for this uncertainty. Indeed these model ship correlation coefficients themselves are uncertain in nature too.

2. METHODOLOGY

2.1 Form factor

A ship hull is not a flat plate and physically, in estimating the frictional resistance, an allowance should be made for the departure of the shape from that of a flat plate. For streamlined bodies this can be approximated by use of a form factor, but the form factor itself is difficult to obtain accurately since it is necessary to obtain this from resistance measurements of the model at very low speeds. These low values of resistance are difficult to measure accurately and the uncertainty in the measurements is high. Many extrapolators prefer to avoid the use of a form factor for this reason and because for some ship hull geometries, for example those with sharp edges at an immersed transom, or those, normally fuller, forms that suffer from separation in the after body (summary by Tsutsumi in Stenson *et al.* 1996; Seo *et al.* 1978), the form factor approach does not accurately model the variation of frictional resistance with Reynolds number.

For streamlined bodies a form factor is an approximate way to proceed, but the above practicalities make it difficult to apply in practice. Even for streamlined aerofoil sections or bodies of revolution the drag coefficients do not follow an exactly parallel course to the friction line (e.g. Hoerner 1965: Chapter VI, figure 22) although turbulence stimulation improves the behaviour (e.g. Hoerner 1965: Chapter VI, figure 23; Chapter XI, figure 1). If the ship hull is not fully streamlined separation occurs and the use of the form factor is incorrect since a form factor cannot allow for the irregularities that occur in the drag coefficient with Reynolds number for this type of flow: note for example the large variations in average drag coefficient that occur with Reynolds number for a bluff cylinder (e.g. Hoerner 1965: Chapter III); and note also that drag coefficients are normally unsteady in nature for these geometries.

The conclusion is that there is no absolutely accurate way to separate the frictional resistance from the total resistance measured during a ship model test and so it is important to know the level of uncertainty that can arise in the powering prediction process from these sources.

2.2 The three tests

Ship powering prediction is normally done using the results from a resistance test; propeller open water test; and a self propulsion test. The propeller open water tests are sometimes done at different Reynolds numbers to those of the operation of the propeller in the behind condition in the self propulsion test (although this should be avoided). Sometimes stock propellers are used in the propeller open

water and self propulsion tests since the exact design of the actual propellers is not normally known at the time of the self propulsion test or even if known it may not be finalized. In fact the propeller design cannot be finalised before the powering estimate is made from the model tests. If there is a sufficient budget for testing, the propeller open water test and the self propulsion test should be repeated once the actual propeller design is known, but this is not often done for commercial vessels.

The propeller open water test is used in the ship powering procedure to estimate the wake fraction of the model. This is normally done by comparing the ship advance coefficient in the behind condition from the self propulsion test at the self-propulsion point of the ship with the advance coefficient at the same value of thrust coefficient found from the propeller open water test (although sometimes a torque coefficient identity is used in a similar way instead). This is an approximation since the propeller is operating in different inflow conditions in the two tests: one in uniform flow, the other in the wake of the model. Although the thrust coefficient is forced to match by this process, there is generally a mismatch in the propeller torque coefficients at these two advance coefficients and conditions and this is accounted for in the extrapolation process by introduction of the relative rotative efficiency. The wake fraction found is that of the model and is in general not equal to that of the ship. This wake fraction is used to approximate that of the ship using a process relying on the experimenters experience and previous knowledge; the method used in the ITTC 1978 method (Lindgren *et al.* 1978) is for a single screw ship (Toki 2004).

This process of using a propeller open water test and the thrust or torque identity introduces the need for a wake fraction, scaling of the wake fraction from model to full scale and the relative rotative efficiency, into the powering prediction process. The method develops a postulated full scale propeller open water performance curve from the model propeller open water test result. In addition, the uncertainty in the results from this test, add to the overall uncertainty in the powering prediction process.

The results of the thrust and torque coefficients from the model propeller open water test are modified approximately for Reynolds number differences, again using a turbulent flat plate friction line, to approximate the open water performance of the full scale propeller (this latter of course is never actually measured). These full scale values are used in the powering estimate for the ship.

The self propulsion test is used to obtain the propeller thrust and torque at the self-propulsion point of the ship. This is a required step in the ship powering extrapolation process.

2.3 Unsteadiness in testing

The resistance of a ship model is normally averaged from the drag values measured during a run at constant velocity when towing the model in a towing tank. In reality, the carriage speed may not be exactly steady, although modern carriage speed control systems improve the reliability of this, and the model may actually be accelerating and

decelerating during a run. The net result is that an inertia force is also measured by the drag load cell (e.g. Schmiechen 1991). Fluctuation in the measured resistance force may also result from flexibility in the connection between the carriage and the model.

Even small accelerations or decelerations can lead to significant changes in the measured resistance on the drag load cell. For example, for a ship model with mass plus added mass of 1,000kg accelerating at 1/10,000 of the value of gravitational acceleration, the additional load on the resistance load cell would be 1N (e.g. Bose 2008). This emphasizes the difficulty of getting reliable resistance results, especially at low speeds when the drag values may be only a few Newtons, but even at substantial model speeds this level of inertia force can mean a resistance error of several percent.

2.4 Uncertainty analysis

Uncertainty exists in the experiments that are done to provide data for the ship powering performance prediction process and in the extrapolation method itself. One way of estimating these is to follow the approach described by Coleman and Steele (1989, 1995) and adopted in the ASME standard (1986). These were adapted to the propeller open water test (Bose and Luznik 1996) and generally for resistance, propeller open water and self propulsion tests by the work of several committees of the International Towing Tank Conference (ITTC) (Stern *et al.* 1999; Day *et al.* 2002). The procedures to be followed have been documented in the ITTC Quality Manual, available on the ITTC web site at www.sname.org/ittc.

Insel (Bose *et al.* 2005) studied the comparison between the use of a Monte Carlo method for uncertainty analysis with the approach that propagates errors through explicit forms of the data reduction equations. This analysis was done to investigate uncertainty in the procedure for form factor estimation and included analyses both with and without correlated bias limits. The conclusions were that Monte Carlo methods can be used to effectively obtain levels of uncertainty and are especially useful in situations where the data reduction equations are highly complex and become unwieldy, such as in a full extrapolation method or full scale trials analysis. It was also found that inclusion of the correlated bias limits do not affect the results appreciably and can normally be neglected if the aim is to obtain general levels of uncertainty in tests or in an analysis method such as a ship powering extrapolation. Uncertainty analysis is by its very nature approximate since estimates are made of the input levels of uncertainty using the judgment of the analyst.

Molloy (2006) and Molloy *et al.* (2006) used a Monte Carlo method to study uncertainty in the ship powering extrapolation process. The method was used primarily to study sensitivity in the extrapolation process to uncertainty in test inputs and to the various assumptions used, such as the inclusion or otherwise of a form factor, uncertainty in friction lines, wake scaling, etc. Molloy (2006) used the results from sets of model tests for several ships; 21 ships were used for parts of the analysis and smaller subsets for

focused studies. The uncertainties in the tests were not estimated from the actual experimental details, but assigned arbitrary values so that consistency was achieved between the data sets: a normal distribution was assumed in the distribution of the test input values with a standard deviation of 1%.

Figure 1 shows the uncertainty in powering prediction in an extrapolation using the ITTC 1978 method when a 1% uncertainty (standard deviation) was assumed in all test inputs. Ten thousand (10,000) iterations were used in the method. Due to the root mean square nature of summation of the individual uncertainties and the influence of the extrapolation procedure, the average standard deviation of the uncertainties in the ship delivered power estimates was 2.09%. Further detailed study (Molloy 2006) showed that uncertainty in the self propulsion test and, usually, in the propeller open water test contributed a greater proportion of the overall uncertainty in the ship delivered power prediction than uncertainty in the resistance test. The only way to reduce this uncertainty is to reduce the level of the uncertainties from each test (increased attention to testing technique) or to reduce the number of test inputs needed in the extrapolation process.

Uncertainty arises in the extrapolation process not only from the results from the model tests, but also in the assumptions made in formulating the method (e.g. use of Froude's law and the choice of friction line); in the methods employed to obtain certain parameters in the analysis (e.g. Prohaska's method to obtain form factor); and in selection of variables (e.g. wake scaling values; correlation allowance). Molloy (2006) studied the influence on ship powering prediction of uncertainty in friction lines, form factor, wake scaling and correlation allowance.

Figure 2. shows variation in ship delivered power resulting from an assumed variation in the turbulent flat plate friction or model ship correlation line (Molloy 2006). Again the extrapolation method is the ITTC 1978 and the model ship correlation line used is the ITTC 1957 line. Variation about this line has been assumed to be a standard deviation of ± 0.0001 at model scale and ± 0.00005 at ship scale because these values represent approximately $\pm 1/2$ the extreme differences found between the ITTC 1957 line and turbulent flat plate friction lines at these Reynolds numbers (Bose 2002, figure 3; Katsui 2003). The prediction emphasizes the large influence on the ship delivered power (standard deviation of uncertainty of 6.58% for six ships) of uncertainty in the friction line. Note that what is being modeled here is not the difference of using one line against using another line, but uncertainty in the values represented by a line; any line. In fact, studies have shown (Bose *et al.* 2005, section 7.1 and figure 7.4 from Toki; Steen *et al.* 2008) that there is only a minimal effect between choosing different lines in an extrapolation procedure, but these studies do not actually account for uncertainty in the knowledge of the coefficients of flat plate friction. The only way to reduce this error is to use a line which we know, as accurately as possible, represents the variation with Reynolds number of the turbulent flat plate friction values

and, together with the form factor or otherwise, accurately models the frictional resistance components of the model and ship as understood through the application of Froude's law.

Molloy (2006) investigated the uncertainty in ship delivered power when a variation, represented by a standard deviation of 10%, was made in the form factor. The uncertainty in delivered power from this cause is not large for this level of variation: on average for six ships investigated the standard deviation in ship delivered power is 0.76%. This does not really address the issue because a 10% variation is only a small variation for this parameter. Often, the issue of concern to the extrapolator is whether or not to use a form factor at all. Molloy (2006) investigated the uncertainty in ship delivered power for an assumed variation in form factor represented by a standard deviation of 100% and showed that, for the ships studied, uncertainty in ship delivered power was on average represented by a standard deviation of 7.63%. This result gives some idea of the uncertainty generated through the question of whether or not to use a form factor.

The prediction of ship delivered power is relatively sensitive to uncertainty in the wake fraction. Figure 3 (Molloy 2006) shows uncertainty in ship delivered power resulting from uncertainty in wake fraction, represented by a standard deviation of 10%; the extrapolation was done using the ITTC 1978 extrapolation method. The average uncertainty for the six ships investigated was 2.16%. Uncertainty in the wake fraction comes from two sources: uncertainty in the method (thrust or torque identity) used to obtain the wake fraction itself; and uncertainty in the scaling of the model wake to ship scale. Uncertainty in obtaining accurate values of the wake fraction itself can be avoided by not using the wake fraction in the extrapolation process. Uncertainty in wake scaling is unavoidable and can be minimized through, for example: results from the "experience" of many model to ship extrapolations; comparison of numerical simulations of wake at model and ship scales; and comparison of results from tests on large self-propelled ship models at increased Reynolds numbers (perhaps those done in large cavitation tunnels, e.g. Friesch and Johanssen 1994) with test results from towing tanks at equivalent Froude number scaled ship speeds.

The correlation allowance is strictly a correction factor applied to bring ship delivered power estimates from model tests in line with results from ship trials. Correlation allowances are usually assembled from past practice at a given model basin, by comparing results from a given extrapolation method with results from full scale trials after a ship is built; correlation allowances vary with the details of the extrapolation method used at a given institution and can vary with the source of the experimental data (i.e. the tank in which the tests were completed). The values of correlation allowances are often treated as proprietary information to a given model basin and have commercial value to that basin. Clearly,

there is uncertainty in the value of the correlation allowance (e.g. Bose *et al.* 2005, figure 7.4, from the work of Toki), but values of correlation allowances are not easily obtained due to the commercial-in-confidence nature of the data. To show the influence of uncertainty in the correlation allowance on ship delivered power prediction, Molloy (2006) showed how a variation in correlation allowance with a standard deviation of 50% caused an average uncertainty in ship delivered power estimates with a standard deviation of 6.14% for six ships studied (see Figure 4).

3. CONCLUSIONS – HOW THE EXTRAPOLATION PROCESS CAN BE IMPROVED

The following questions are raised about the ship powering performance prediction process:

1. Is the combination of the three tests (resistance; propeller open water; self propulsion) the most accurate and reliable way to do a ship powering extrapolation? (Note that this question does not preclude the need for use of individual component tests when studying particular aspects of design such as a particular propeller/propulsor design, to obtain current values of wake fraction or, say, to study the effect of hull shape comparisons.)
2. For powering performance prediction, is it necessary to calculate wake fraction and relative rotative efficiency?
3. How can experimental uncertainty and uncertainty of the analysis method be minimized in the ship powering performance prediction process?
4. How can the frictional resistance of a ship model be most accurately subtracted from the total resistance? Froude's "Law of Comparison" is normally used as the basis for this, but there is no way to accurately subtract and extrapolate the frictional resistance component; it can only be done approximately.
5. The form factor is arguably the only way to allow approximately for the departure of the frictional resistance from that of a flat plate. However, the form factor is not easy to obtain accurately. Should a form factor be used in the extrapolation process?
6. Should self propulsion tests be done (perhaps in large cavitation tunnels) at higher flow speeds, and hence Reynolds numbers, than possible using Froude number scaling in a towing tank, to get trends in propulsion factors, such as thrust deduction fraction, as the Reynolds number is increased, to values closer to full scale?

The following points are proposed as to how the ship powering extrapolation process might be modified and improved:

1. Uncertainty analysis should be used to investigate and minimize numerical uncertainty introduced in the extrapolation method in use, for example to find:
 - a. the ship self propulsion point;
 - b. the thrust deduction fraction;

- c. the full scale propeller operating point.
2. It is expected to be more accurate to obtain the thrust deduction fraction from load-varied, self-propulsion data by using the slope of the plot of towing force versus thrust, since this uses a linear curve fit to multiple data points, rather than just the one point obtained from the self-propulsion point of the ship in the self-propulsion test (e.g. Bose 2008, figure 3-1). (This value of the thrust deduction fraction is normally somewhat different in value by a few percent (e.g. Holtrop 2001) from that obtained using the thrust from the self-propulsion point of the ship and the resistance from the resistance test, but this is not a concern except when comparing values with those found from the conventional method.)
3. In the powering performance prediction process it is not actually necessary to obtain the wake fractions of the model and ship. What is required to be known is the scaling of the wake between model and ship. Accuracy in the powering prediction process is expected to be increased if the propeller coefficients in the behind condition are scaled directly to the ship values using a Reynolds number correction and an allowance for the scaling of the wake. The ship propeller operating point can then be found from the intersection of the required thrust coefficient with this ship propeller curve in the behind condition. Research is needed to formulate regressions for wake scaling, or values might be found from previous regression work such as that done by Holtrop (1977; 1978).
4. Avoid use of the relative rotative efficiency in the extrapolation procedure.
5. Use the most accurate turbulent flat plate friction line possible for the extrapolator. This might be either the Grigson line (Grigson 1993; 1999), or the work of Katsui *et al.* (2003; 2005), or more recent research. The choice of friction line affects the value of the correlation coefficients. However, the intention of choosing the "best" friction line is to minimize inclusion of a flat plate friction component correction into the correlation allowance.
6. If a form factor is used accuracy may be improved by using curve fits of form factor found experimentally against appropriate values of ship form coefficients, such as block and/or prismatic coefficient. This is likely to avoid inconsistencies found from the results from tests on one ship, since results would be averaged through the regression process. Research is needed to formulate these regressions for form factor, or values might be found from previous regression work such as that done by Holtrop and Mennen (1982) and Holtrop (1984).
7. Develop correlation allowances compatible with modifications in the extrapolation method.
8. Propeller open water tests and self-propulsion tests should be done using a propeller design that is as close as possible to the final design of the propeller to be used on the ship (i.e. not a stock propeller). Ideally these tests should be repeated once the final propeller design is known.
9. Propeller open water tests should be done at similar Reynolds numbers to those at which the propeller is operated in the self-propulsion test.
10. Consider using the self-propulsion test only method of ship powering performance prediction (Holtrop 2001; Molloy 2001; Molloy and Bose 2001; Bose 2008, Chapter 3).
11. Summarising, the steps taken in the extrapolation would then be:
 - a. Do a resistance and load varied self-propulsion test (the latter over a range of loading around the self-propulsion point of the ship; the variation has to be wide enough to provide propeller coefficients in the behind condition, when corrected, that cover the ship propeller operating point).
 - b. If wake values are required for reasons other than powering prediction, do a propeller open water test and obtain the wake values by thrust or torque identity, but do not use these in the powering prediction process. This is because the approach is normally ill-conditioned due to the low values of slope of the thrust and torque coefficient curves.
 - c. For the load varied self-propulsion test data, plot towing force against propeller thrust. This is normally a linear plot, the slope of which provides the thrust deduction fraction. This linear curve can be interpolated at the value of F_D to obtain the model thrust at the self-propulsion point of the ship.
 - d. The ship full scale resistance coefficient can be extrapolated from the model resistance using the most appropriate turbulent flat plate friction line and a form factor if desired (plus corrections for appendage and still air resistance, as well as a correlation allowance).
 - e. If a form factor is used consider using a value from a regression for form factors from many ship model tests rather than/or as well as doing a test for the individual ship.
 - f. The propeller coefficients in the behind condition can be corrected to the full scale by making an allowance for wake scaling and correction for the difference in Reynolds number. These propeller coefficients are plotted against an advance coefficient based on the ship speed, not the advance speed.
 - g. Find the intersection of the parabola representing the required propeller thrust coefficient with the full scale propeller curves

in the behind condition to find the ship propeller operating point (e.g. Bose 2008): i.e. the advance coefficient, thrust and torque coefficients.

- h. Hence find the revolutions, thrust, delivered power, torque, etc.

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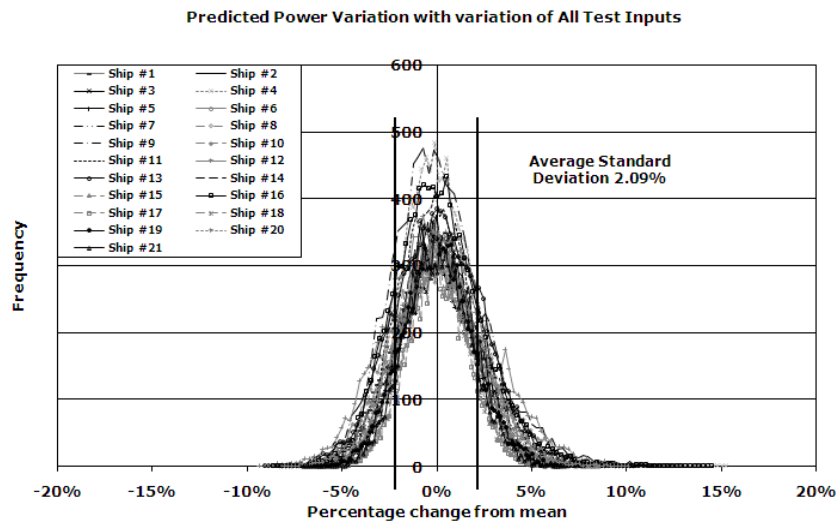


Figure 1. Uncertainty in ship power prediction in an extrapolation using the ITTC 1978 method when a 1% uncertainty (standard deviation) is assumed in inputs from all model tests (Molloy *et al.* 2006).

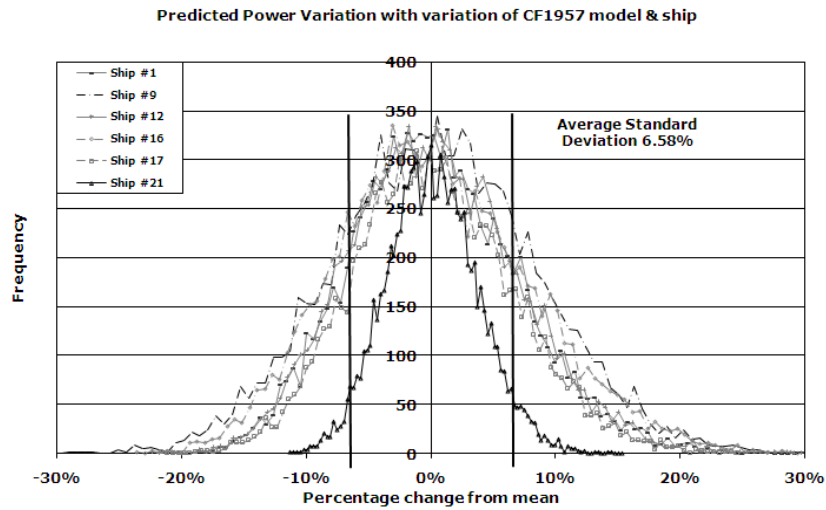


Figure 2. Uncertainty in ship delivered power resulting from uncertainty in the turbulent flat plate friction line or ship model correlation line (ITTC 1978 extrapolation) (Molloy *et al.* 2006).

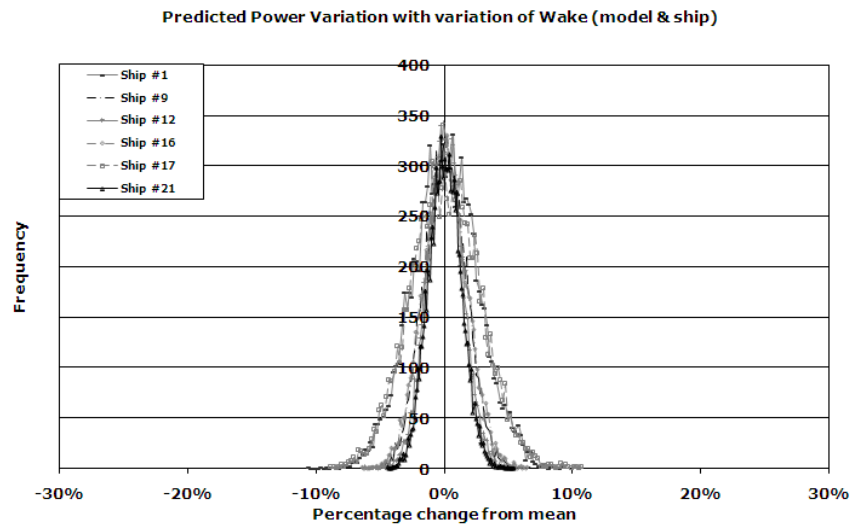


Figure 3. Uncertainty in ship delivered power resulting from uncertainty in the wake fraction (standard deviation 10%; ITTC 1978 extrapolation) (Molloy *et al.* 2006).

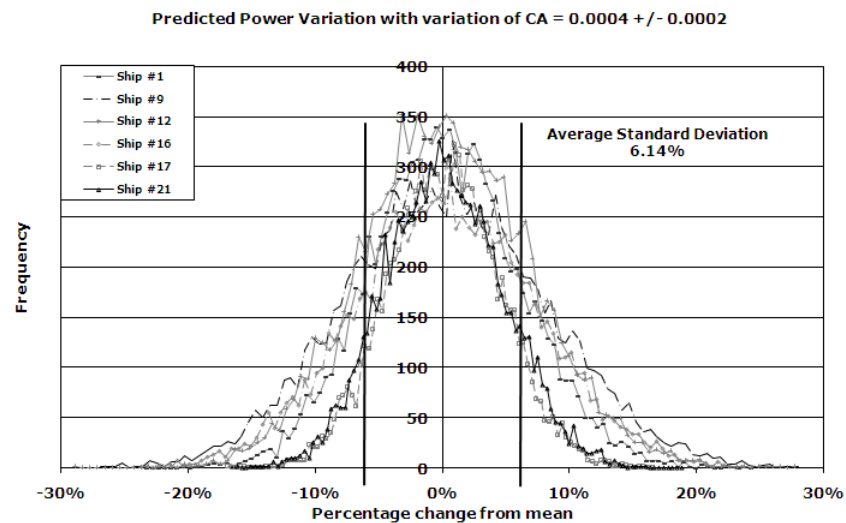


Figure 4. Uncertainty in ship delivered power resulting from uncertainty in the correlation allowance (standard deviation 50%; ITTC 1978 extrapolation) (Molloy *et al.* 2006).