Reliability assessment of ship powering performance extrapolations using Monte Carlo methods

Iwan M. Kamal, Jonathan Binns, Neil Bose, Giles Thomas

National Centre for Maritime Engineering and Hydrodynamics, Australian Maritime College, Launceston, Tasmania

ABSTRACT

This paper describes the application of a practical method for uncertainty analysis, in which the uncertainties in all error sources are considered individually and simultaneously in the extrapolation of ship powering prediction. Such uncertainty has been investigated by utilising the ITTC1978 performance prediction method and an application of Monte Carlo simulations. The error sources are: the torque, thrust, towing force, propeller revolution from the self-propulsion test; the resistance force and the model speed from the resistance test; and the torque and thrust coefficient from the open water test. A case study was conducted using available sea trials and towing tank experimental data of the RTV *Bluefin*, a research and training vessel owned and operated by the Australian Maritime College (AMC), see Table 1 for main particulars. The levels of uncertainty in ship powering were obtained by choosing a random sample from the error sources and repeating the calculation a large number of times. Then the distributions of the simulation results were used to determine the uncertainty in the total result.

Keywords

Monte Carlo simulations, model experiments, self-propulsion test, ITTC1978 extrapolation.

1 INTRODUCTION

One of the most important activities in a ship design process is the prediction of the full-scale power requirement. Even though the extrapolation of scaled model tests is currently the most reliable method available for the purpose, verification studies or uncertainty analyses are required to provide confidence in the accuracy of the results. However, the conventional uncertainty analysis recommended by the 22nd ITTC (ITTC, 1999) are almost prohibitive for ship model to ship extrapolation by the ITTC 1978 method, as the ITTC 1978 extrapolation procedures are complex and involve many steps. One alternative approach to such problems is by applying the Monte Carlo method in the uncertainty analysis (Bose et al., 2005). Furthermore with the computing power and speed available nowadays, it has become feasible to perform an uncertainty analysis directly using Monte Carlo simulation that could involve up to 100,000 iterations.

Table 1: Main particulars of RTV Bluefin

Length between perpendiculars	L_{pp}	(m)	32.00
Waterline length	L_{WL}	(m)	32.16
Molded breadth	B	(m)	9.75
Draft	T	(m)	3.93
Displacement volume		(m^3)	527.2
Wetted surface area	S	(m^3)	382.47
Block coefficient	C_B		0.427
Prismatic coefficient	C_P		0.616
Midship section coefficient	C_M		0.768
Waterplane coefficient	C_W		0.802
No. of propeller			1
No. of propeller blades	Z		4
Propeller diameter	D	(m)	2.20
Max. RPM propeller		RPM	240
Cruising speed		(knots)	10.0
Maximum speed		(knots)	11.5

The way Monte Carlo methods are used in uncertainty analysis is by assuming a variation in the inputs to a calculation or numerical method and then calculating the variation in the output for a given number of trials (Bose, 2008). The variation in the inputs is given an assumed range of a given normal distribution with a set standard deviation. This is achieved using a Gaussian random generator which is easily available in any computer program languages or spreadsheet (Coleman & Steele, 1999). Often 10,000 to 50,000 iterations are used for assigning new randomised inputs to the calculation or numerical method. Then the uncertainty of the output is obtained as the distribution in the values of the output from the iterations made.

The work carried out in this study was based on Molloy's (2006) work.

2 ITTC1978 SHIP POWERING PREDICTION

In the 1978 International Towing Tank Conference (Lindgren et al., 1978), a performance prediction method was presented and it is now generally accepted by all major testing facilities in the world. The ITTC 1978 method is used to extrapolate the results of three physical model tests to full-scale power. The three discrete tests are a resistance test, a propeller open water test and a self-propulsion test. The resistance test is a bare hull tow test; the resistance of the model, R_{TM}, is measured at a number of different carriage velocities, V_M, without the propeller installed. In the propeller open water test, the test is performed with the model propeller operating in uniform flow without the model hull. While in the self-propulsion test, a model complete with appendages and operating propeller(s), is towed at the ship self-propulsion point as in the continental method, whereas in the British method or the load-varied method, the model is towed at a number of tow force values and at the intersection of the non-dimensional K_{FD} curve using Equation 1 and the curve of the required towing force coefficient by using Equation 2, the towing force at the self-propulsion point is obtained (Bose, 2008). The non-dimensional form of the K_{FD} curve is given by:

$$K_{FD} = \frac{F_D}{\rho_M n_M^2 D_M^4} \tag{1}$$

where F_D = towing force; ρ_M = specific density of fresh water; and n_M = model propeller revolution and D_M = the diameter of the model propeller.

Whereas the required towing force at the self-propulsion point is given by:

$$K_{FD} = \frac{C_{FD}.S_S}{2D_S^2}.J_P^2 \tag{2}$$

where C_{FD} = required towing force coefficient; S_S = wetted surface area of the ship; D_S = the diameter of the ship propeller and J_P = advance coefficient at the self-propulsion point.

2.1 Powering Prediction Procedure

In the prediction procedure, all the data from the three physical model tests are combined. The outline of the ITTC1978 method is described in detail by Bose (2008), where once the advance coefficient, J_P, at the model self-propulsion point is obtained using the curve of K_{FD} and K_{FD}/J_P^2, the values of the propeller coefficients, in the behind condition, K_{TP} and K_{QP}, can be found from the results of the self-propulsion test. Then using "thrust identity" method, the value of K_{TP} is used to find the value of advance coefficient, J_O in the results from the open water test of the propeller.

Some corrections have to be made to the model open water thrust and torque coefficients, K_{TO} and K_{QO}, to obtain the full-scale open water propeller thrust and torque coefficients, K_{TOS} and K_{QOS}. The operating point of the full-scale propeller can be found from the intersection of the curves of K_{TOS}, K_{QOS} and the requirement for thrust given in the form of $K_T/J^2 = S_S.C_{TS}/2D_S^2(1-t)(1-w_{TS})^2$ (Bose, 2008). This intersection leads to the operating values of K_{TS}, K_{QS} and J_{TS}, of the ship propeller. Then it is possible to calculate the delivered power, P_{DS}. The flow chart of this method is shown in Figure 1 in the dashed box at the right hand column of the chart.

3 RELIABILITY ASSESSMENT METHODOLOGY BY MONTE CARLO METHOD

The Monte Carlo method can be applied into uncertainty analysis in a complicated data reduction equation such as the ITTC 1978 extrapolations. Bose et al. (2005) described the methodology steps are:

(a) Determine elemental bias/precision error sources and their bias/precision limits

(b) Create Gaussian (or other) error distribution of bias/precision errors by assuming a standard deviation equal to half of bias/precision error limit (for 95% confidence)

(c) Create a calculation model by using data reduction equations. If an elemental bias/precision error source is shared among two or more variables, the same random value of elemental bias/precision error value is used in those variables.

(d) Setup simulations consisting of N number of simulations, in which elemental bias/precision error values are assigned randomly complying with Gaussian error distributions.

(e) Calculate the result and its distribution. i.e. calculate mean and standard deviation of result from N simulations.

(f) Determine the bias limit by taking twice the standard deviation.

(g) Perform repeat tests (minimum 10) and find standard deviation.

(h) Take twice the standard deviation to find the precision limit (for 95% confidence)

(i) Root-sum-square bias and precision errors to find the total uncertainty limit.

4 PROGRAMMING THE MONTE CARLO SIMULATION

In programming the Monte Carlo simulation, the initial approach was to program the ITTC 1978 method, with the three different sets of test data imported into the main body of the program, see Figure 1. The first input file contained the results of the resistance test: which contained the data of velocity of the model, V_M in m/s and the resistance of the model through the water, R_{TM}, in Newton (N). Using the MATLAB polynomial function, the resistance data were then converted into an equation using a 2nd order regression equation.

The second input file imported to the main program contained the results of the open water test. The test results were entered into the main program in the form of $J=V_A/nD$, $K_T = T/\rho n^2D^4$, $KQ = Q/\rho n^2D^5$ (Manen &

Oossanen, 1988). The coefficient of K_T and K_Q were also converted to 2nd order polynomial equations through regression.

The third input file contained the results of the self-propulsion test in the form of velocity of the model, V_M in m/s, the propeller shaft revolution, n_M in rps, the propeller thrust, T_M in N, the propeller torque, Q_M in Nm and the towing force, F_M in N were also imported into the main program. There was also a fourth file of inputs containing other information such as the model particulars, the test temperatures and viscosities, the form factor and correlation allowance.

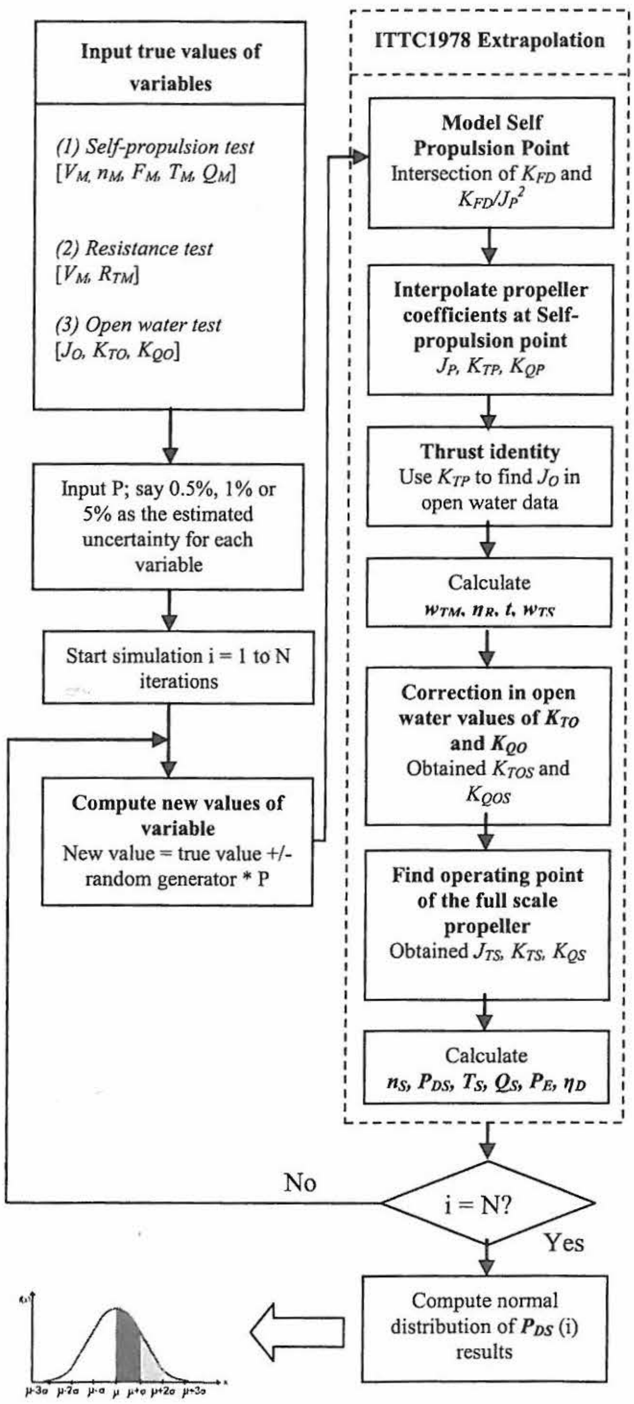

Figure 1: ITTC1978 Performance prediction uncertainty assessment methodology using Monte Carlo method

Then, the randomisation using the Monte Carlo simulation was applied directly to each input, and for this study the simulation only focused on the randomisation to inputs from the three discrete physical tests. In a Monte Carlo simulation, an input value to an equation is randomly varied by a predetermined uncertainty and a distribution of the output result is obtained (Coleman & Steele, 1999). The equation referred to in the previous sentence or this study will be the set of non-linear equations that form the extrapolation method itself. The original values of, for instance the propeller thrust, T_M, in the self-propulsion test, were assigned a standard deviation and distributed normally. The approach of this methodology is illustrated in Figure 1 at the left-hand column of the chart, where the randomisations of the error sources were introduced outside the extrapolation process.

The randomiser in the program randomly varied each test result with a standard deviation of for example 0.5%, 1% or 5% for each measured value. A sample of randomised results with a standard deviation of 1% for a resistance test is shown in Table 2 for two iterations.

Table 2: Example of randomised resistance test values

Original true values		Randomised values, Iteration #1		Randomised values, Iteration #2	
$*V_M$	$**R_{TM}$	$*V_M$	$**R_{TM}$	$*V_M$	$**R_{TM}$
0.222	0.142	0.222	0.142	0.220	0.143
0.340	0.315	0.339	0.314	0.337	0.315
0.459	0.583	0.458	0.580	0.454	0.584
0.578	0.918	0.577	0.914	0.572	0.920
0.685	1.634	0.684	1.627	0.678	1.637
0.803	1.941	0.802	1.933	0.795	1.944
0.862	2.411	0.861	2.400	0.853	2.415
0.921	2.570	0.920	2.558	0.912	2.574
0.949	3.025	0.947	3.012	0.940	3.030
0.971	3.219	0.969	3.204	0.961	3.224
0.972	3.159	0.970	3.144	0.962	3.164
0.981	3.277	0.979	3.262	0.971	3.282
1.009	3.505	1.007	3.489	0.999	3.511
1.039	3.789	1.037	3.771	1.029	3.795
1.089	4.209	1.087	4.189	1.078	4.215
1.149	5.131	1.147	5.107	1.138	5.139
1.207	6.161	1.205	6.132	1.195	6.170
1.275	7.444	1.273	7.410	1.262	7.456
1.383	9.576	1.381	9.532	1.369	9.591

$*V_M$ in m/s and $**R_{TM}$ in N

This process was repeated for a large number of times specified by the user, and in this study, 10,000 numbers of iteration were chosen as this number are usually sufficient (Coleman & Steele, 1999). For every iteration on the resistance test values of V_M and R_{TM}, a new regression equation was calculated using the new data and this new regression equation was the new input into the ITTC1978 extrapolation program.

A similar process was applied to randomise the open water test data. These data were converted into a regression equation, and at each randomisation, a new regression equation was calculated and this new regression equation was input to the program. This process was also repeated 10,000 times.

Similarly the self-propulsion test data was randomised although the test runs were less numerous than the resistance test or the open water test. The data for K_{QP}, K_{TP}, J_P, K_{FD} and n_M were also converted into a regression equation, and a new regression was calculated at each randomisation. A sample of randomised values with a standard deviation of 1% for self-propulsion test is shown in Table 3 for two iterations.

Table 3: Example of randomised self-propulsion test values

	V_M	F_M	n_M	Q_M	T_M
Original true values	1.152	5.849	300.0	-0.543	0.064
	1.150	4.281	400.0	1.279	0.102
	1.152	2.201	500.0	3.727	0.171
	1.150	-0.865	600.0	7.111	0.278
Randomised values, Iteration #1	1.151	5.836	300.8	-0.541	0.064
	1.149	4.272	401.1	1.274	0.102
	1.151	2.196	501.4	3.713	0.170
	1.149	-0.863	601.6	7.085	0.277
Randomised values, Iteration #2	1.151	5.856	299.6	-0.545	0.065
	1.149	4.286	399.4	1.284	0.103
	1.151	2.204	499.3	3.742	0.173
	1.149	-0.866	599.2	7.139	0.281

*V_M in m/s, n_M in rps, F_M and T_M in N and Q_M in Nm.

5 METHODS OF UNCERTAINTY ANALYSIS

In this study, only the three physical test inputs were varied by a standard deviation in a normal distribution while the propulsion factors such as form factor k and correlation allowance C_A were not varied. Nevertheless, further work will be carried out in order to assess the uncertainty when the propulsion factors are varied. The output result of interest is the ship delivered power P_{DS}. As the randomisation was performed 10,000 times, the output results of the ship delivered power P_{DS} also numbered 10,000. Therefore the results were presented in standard deviation as a percentage change from the output mean.

5.1 Variation of propeller open water test inputs

The values of the advance coefficient J, thrust coefficient K_T and torque coefficient K_Q in the open water test were varied with standard deviation of 0.5%, 1% and 5%. The resulting standard deviation in predicted power are 0.75%, 1.5% and 7% when all the open water test inputs were varied at 0.5%, 1% and 5% respectively. The comparisons of predicted power variation are shown in Figure 2 as percentage change from mean for inputs varied with standard deviation of 0.5%, 1% and 5%.

5.2 Variation of resistance test inputs

The simulation was next run with only the values from the resistance test varied, which are the measured resistance R_{TM} and the velocity of the carriage V_M. These values were also varied with standard deviations of 0.5%, 1% and 5%. The resulting standard deviations in predicted power are 0.20%, 0.41% and 2.06% when the inputs were varied at 0.5%, 1% and 5% respectively as plotted in Figure 3.

5.3 Variation of self-propulsion test inputs

The self-propulsion data then were varied alone. The values of carriage speed V_M, propeller revolution n_M, towing force F_M, model propeller thrust T_M in N and model propeller torque Q_M were varied at standard deviation of 0.5%, 1% and 5%.

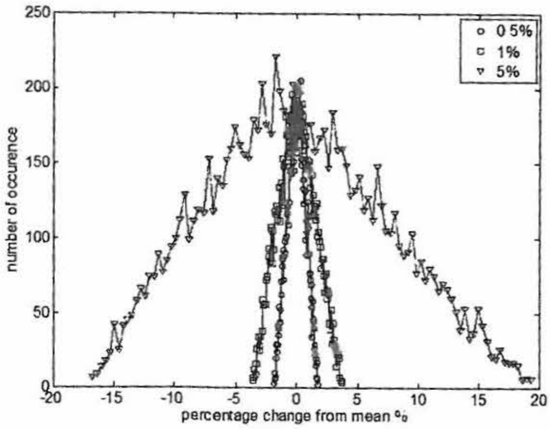

Figure 2: Variation of open water test inputs - K_{TO}, K_{QO} and J_O were varied simultaneously with standard deviations of 0.5%, 1% and 5% at a corresponding speed of 10 knots

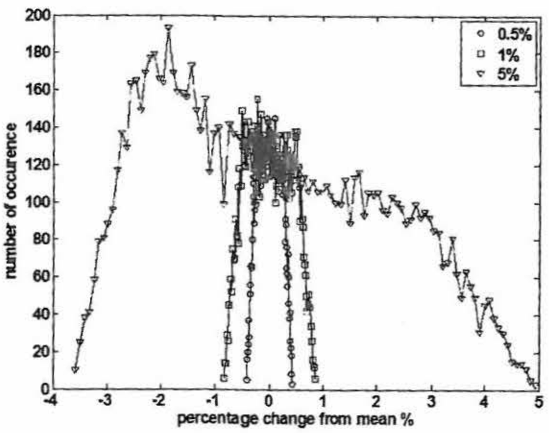

Figure 3: Variation of resistance test inputs - V_M and R_{TM} were varied simultaneously with standard deviations of 0.5%, 1% and 5% at a corresponding speed of 10 knots.

The resulting standard deviation in predicted delivered power P_{DS} when the inputs of self-propulsion test were varied with standard deviations of 0.5%, 1% and 5% are 0.72%, 1.42% and 7.08% respectively as plotted in Figure 4.

5.4 Variation of All Measured inputs

All the measured input values from self-propulsion, resistance and propeller open water test were also varied simultaneously with standard deviations of 0.5%, 1% and 5%. The simulation was run with variation in all of the measured values together.

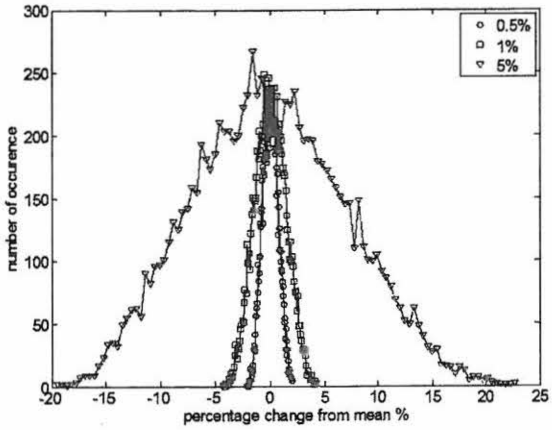

Figure 4: Variation of self-propulsion test inputs - V_M, n_M, F_M, T_M and Q_M were varied simultaneously with standard deviations of 0.5%, 1% and 5% at a corresponding speed of 10 knots.

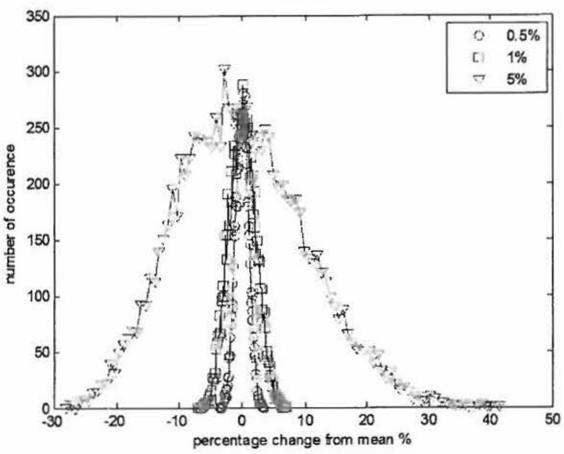

Figure 5: Variation of all measured inputs – all tests inputs were varied simultaneously with standard deviation of 0.5%, 1% and 5% at a corresponding speed of 10 knots.

The predicted delivered power when all the inputs were varied together was normally distributed as plotted in Figure 5 with standard deviations of 1.04%, 2.1% and 10.55% for inputs variation of 0.5%, 1% and 5% respectively.

The summarised standard deviations of the predicted delivered power are shown in Table 4. In comparing the three discrete physical tests, it is observed that the predicted power is very dependent on the self-propulsion test results as the uncertainty of the output results in the predicted power were twice the value of the uncertainty of the error in the inputs. The results obtained from this study with input varied with standard deviation of 1% has relatively similar results in comparison with Molloy's (2006) averaged results for 6 different ships with the inputs also varied at 1%. However the resistance test result in Molloy (2006) was higher than the result from this study; see Table 4, last row.

5.5 Variation of Individual Measured Values

The influence of individual test measurements was also examined. In each run of the simulations one of the measured parameters was varied while the other parameters remained constant.

5.5.1 Propeller Open Water Test Results

The resulting standard deviation in predicted power P_{DS} when the propeller open water test parameters were varied individually was small except for the torque coefficient as shown in Table 5.

Table 4: Standard deviations in the predicted delivered power with the three separate physical test inputs were varied

Inputs	OW*	RT*	SP*	ALL*
Inputs σ	P_{DS} (W)	P_{DS} (W)	P_{DS} (W)	P_{DS} (W)
0.5%	0.75%	0.20%	0.72%	1.04%
1%	1.5%	0.41%	1.42%	2.1%
5%	7%	2.06%	7.08%	10.55%
Results from Molloy (2006) **				
1%	1.37%	0.91%	1.36%	2.22%

*OW = Open water test inputs varied, RT = Resistance test inputs varied, SP = Self-propulsion test inputs varied, ALL = All measured inputs varied

**Average results for 6 ships with inputs varied at 1%

Table 5: Standard deviations in the predicted delivered power with individual test inputs of the open water test were varied

Inputs	J	K_T	K_Q
Inputs σ	P_{DS} (W)	P_{DS} (W)	P_{DS}(W)
0.5%	0.04%	0.48	0.58%
1%	0.08%	0.95%	1.15%
5%	0.4%	4.77%	5.82%
Results from Molloy (2006) **			
1%**	0.21%	1.00%	0.66%

**Average results for 6 ships with inputs varied at 1%

The standard deviation of the predicted power when the torque coefficient was varied with a 1% standard deviation was 1.15%, whereas the standard deviation in the predicted power was small when the advance coefficients were varied by 0.5%, 1% and 5%. Therefore it can be concluded that the most influential parameters in the open water test is the torque coefficient. However, the standard deviation in the predicted power from Molloy (2006) when the torque coefficient was varied standard deviation of 1% was low at 0.66%, see Table 5, last row.

Table 6: Standard deviations in the predicted delivered power with individual test inputs of the resistance test were varied

Inputs	V_M	R_{TM}
Inputs σ	P_{DS} (W)	P_{DS} (W)
0.5%	0.20%	0.05%
1%	0.39%	0.1%
5%	1.99%	0.5%
Results from Molloy (2006) **		
1%**	0.86%	0.32%

**Average results for 6 ships with inputs varied at 1%

5.5.2 Resistance Test Results

Then the resistance test velocity and the resistance force data were individually varied by a standard deviation of 0.5%, 1% and 5% and the standard deviations in the predicted power was relatively small as shown in Table 6.

Table 7: Standard deviations in the predicted delivered power with individual test inputs of the self-propulsion test were varied

Inputs	V_M	n_M	F_M	T_M	Q_M
Inputs σ	P_{DS} (W)	P_{DS} (W)	P_{DS} (W)	P_{DS} (W)	P_{DS} (W)
0.5%	0.16%	0.45%	0.05%	0.43%	0.29%
1%	0.31%	0.91%	0.09%	0.87%	0.58%
5%	1.57%	4.51%	0.46%	4.35%	2.89%
Results from Molloy (2006) **					
1%**	0.89%	0.65%	0.38%	0.49%	0.89%

**Average results for 6 ships with inputs varied at 1%

This shows that the resistance test has a small influential factor to the overall result of the predicted power from the ITTC1978 prediction method although uncertainty in the resistance test results can cause the predicted power to skew as shown earlier in Figure 3. Molloy (2006) mentioned that the reason of the skew, was due to the steepness of the resistance curve slope itself, where at the values that corresponded to the higher operating speed, which was at the steepest portion of the curve, the varied values tend to be more at the higher values of the input data, thus giving higher predicted power, which led to skewing to the higher side.

5.5.3 Self-Propulsion Test Results

Then the self-propulsion test data such as carriage speed V_M, propeller revolution n_M, towing force F_M, model propeller thrust T_M and model propeller torque Q_M were varied individually at the same standard deviations as in previous simulations. The resulting standard deviations in the predicted delivered power were relatively small except for two parameters which were the propeller revolution and the model propeller thrust, see Table 7. The standard deviations when the propeller revolutions were varied at 1% was 0.91%, whereas when the propeller model thrusts were varied at 1% it was 0.87%. The results when the inputs were varied individually with a standard deviation of 1%, is not in agreement with the averaged results for 6 ships (Molloy, 2006), see Table 7, last row.

In this study it can be concluded that the propeller revolution n_M and the model propeller thrust T_M, were the most influential parameters to the predicted delivered power in the self-propulsion test.

6 CONCLUSIONS

As seen from the summary results of the standard deviations of the predicted delivered power in Tables 4 to 7, the most influential test to the predicted delivered power results was the self-propulsion itself and the most influential parameter in the three physical test was the torque coefficient in the open water test. Individually the standard deviation of all of the tests data varied at 0.5%, 1% and 5% was small and all the individual tests do not have a large effect on the uncertainty in the predicted power, except for the torque coefficient in the open water test. A large effect can be defined as when the standard deviation in the predicted power is more than the standard deviation of the input itself which indicates that the ITTC1978 extrapolation equation amplifies the uncertainty of that parameter. In this study the only amplification observed was in the self-propulsion test, and the contributor to the amplification was the combination of two parameters: propeller revolutions and model thrust. Some suggestions could be made from these findings, that the value of the uncertainty in the predicted power can be reduced with additional test points in the resistance, open water and self-propulsion test programs. This can be clearly observed on why the self-propulsion test has the higher standard deviations in predicted power when compared to resistance test is that the number of test points in the self-propulsion test was limited to only 4 or 5 points, whereas there were 19 test points in the resistance test data. In addition to that, Molloy (2006) recommended that repeating and replicating the experiments could reduce the uncertainty in the predicted power results.

Further work will be carried out in order to assess the uncertainty when other parameters are varied. The other parameters that will be of interest are the coefficient of friction and propulsion factors such as the correlation allowance, the wake fraction, the thrust deduction fraction and the form factor. Molloy (2006) reported that the standard deviation of the predicted power was larger when the coefficient of friction and the propulsion factors were varied. Further work will also be carried out in the reliability assessment on another extrapolation method that uses only the self-propulsion tests data to predict full scale powering from model tests as described in detail in Bose (2008).

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