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WINDWARD PERFORMANCE OF THE AME CRC SYSTEMATIC YACHT SERIES

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SUMMARY

Since 1994 the Australian Maritime Engineering Cooperative Research Centre (AME CRC) has conducted an extensive set of towing tank experiments and theoretical predictions for calm and rough water, on a series of 11.3 metre IMS style racing yacht hulls with varying form parameters. In collaboration with Murray, Burns & Dovell (MBD), the AME CRC has developed a Velocity Prediction Program (VPP), and experimental procedures, with the intention of providing performance predictions to the highest international standards. A theoretical study has also been undertaken using the AME CRC developed non-linear vessel motions program, SEALAM.

The AME CRC systematic series for yachts is comprised of five "mini-series", corresponding to one series for each hull parameter investigated so far: length to displacement ratio; beam to draft ratio; prismatic coefficient; LCB - LCF separation, and; stern overhang. The parent hull is a development of the Delft Systematic Yacht Hull Series II. All the one-fifth scale models represent realistic yacht forms that could reasonably be expected to race as 11.3 metre IMS designs. Rough water test conditions were representative windward sailing scenarios corresponding to 6.5 knots full scale, 20 degrees heel and 3 degrees yaw.

This paper is written in two parts. Firstly, the paper will deal with the experimental procedures used by the AME CRC, highlighting the sources of errors and their magnitudes. The repeatability of the experiments has been exhaustively tested over three years, and the results of these studies are presented in this paper. The second part of this paper explains some of the results directly relating to the seakeeping predictions and experiments that have been conducted on the series of ten yachts over the past three years. To illustrate the accuracy of the results achieved, a comparison between the performance predicted from the investigation of prismatic coefficient variation, and that calculated from the 1996 version of the IMS VPP is also presented.

AUTHOR BIOGRAPHIES

Bruce McRae: Graduated from the Australian Maritime College (AMC) in 1991 with a Bachelor of Engineering (Maritime) degree with honours, and subsequently took up a position with the AMC to undertake a two year investigation into river bank erosion caused by tourist vessels. Following completion of this project, he moved to the Australian Maritime Engineering CRC Ltd. (AME CRC) to support commercial research which has included two America's Cup campaigns. He is now a Task Leader under the AME CRC's yacht technology program, and manages the AME CRC research carried out in the AMC towing tank.

Jonathan Binns: Jonathan received his Bachelor of Engineering (Naval Architecture) from the University of New South Wales in 1994. Following this he began postgraduate studies at the Curtin University of Technology dealing with hull - appendage interaction of yachts. He completed his Masters Degree in 1996 and since then has been seconded to Murray, Burns & Dovell as a design and research engineer. He is now the Task Leader for the AME CRC's project relating to the aerodynamic performance of yachts.

Kim Klaka: Kim Klaka is Regional Manager at the Perth Core of AME CRC. His first degree in Ship Science from Southampton University was followed by five years in the small craft industry and six years lecturing at Southampton Institute. In 1987 he completed a Masters Degree at Curtin University of Technology, working on performance prediction of America's Cup yachts. Since then he has been involved with commercially driven research mainly in seakeeping and yacht design, including work for five America's Cup syndicates. Kim is also Program Leader of the AME CRC Yacht Technology and Performance program.

Andrew Dovell: A Masters Graduate of Naval Architecture, University of California, Berkeley, Andy is an acknowledged worldwide leader in technical yacht design. His work has included testing for the victorious “Stars and Stripes” syndicate as well as for 5 other North American syndicates in the 1987 America's Cup. He has co-designed “The Whale” (Ultimate 30) and Charente Maritime (BOC single hander) with Bernard Nivelt.

With his background in classical naval architecture and emphasis on yacht hydrodynamics, MBD / AME has proven strength and depth in these areas. Andy worked alongside Iain Murray and John Reichel as a “Principal Designer” for the 1995 America's Cup Challenge “One Australia”.

NOMENCLATURE

AME CRC	Australian Maritime Engineering Cooperative Research Centre Ltd.
B_{WL}	Waterline Beam
B_{WL}/T_C	Beam to Draft Ratio
C_P	Prismatic Coefficient
C_T	Total Resistance Coefficient
MBD	Murray, Burns & Dovell Pty. Ltd.
IMS	International Measurement System
k_{yy}	Pitch Radius of Gyration
LCB	Longitudinal Centre of Buoyancy
LCF	Longitudinal Centre of Flotation
LR	Linear Random Course
L_{WL}	Waterline Length
$L_{WL}/\nabla_C^{1/3}$	Length to Displacement Ratio
RAO	Response Amplitude Operator
T_C	Canoe Body Draft
VPP	Velocity Prediction Program
V_{TW}	True Wind Velocity
V_S	Vessel Speed
WW/LW	Windward - Leeward Course
ΔP_{00i}	Performance Differential of ith Model
ΔR_{00i}	Rating Differential of ith Model
ΔRP_{00i}	Rating - Performance Differential of ith Model
∇_C	Canoe Body Volume of Displacement
σ	Sample Standard Deviation

1. INTRODUCTION

The distinguished Nathanael G. Herreshoff once paraphrased the rivalry between yacht design and yacht handicapping as “a subject never to be fully settled”. This is perhaps the fundamental principle underlying the sport of offshore yacht racing. The role of the designer is to produce a yacht which outsails its handicap. While conversely, the handicapper strives to produce a system whereby yachts of different ratings will finish in a corrected time dead heat, providing they are equally well sailed.

Technological advances in yacht design have occurred more or less continually for well over a century. Indeed, model tests have been used to predict the performance of sailing yachts since the late 1800’s when the America’s Cup challenger *Shamrock III* was tank tested to evaluate upright and heeled drag. The progress in yacht design has generally outpaced that of handicapping systems, which is proven by the number of different rules that have evolved over the years to try and level the playing field for competitors.

In 1976, a revolution in the form of the Velocity Prediction Program (VPP) occurred. Originally developed as a practical tool by Kerwin [1,2], at the Massachusetts Institute of Technology, the VPP revolutionised the way yachts are designed and handicapped. Put simply, the VPP attempts to predict the performance of a yacht for a given hull shape and rig design over a range of headings and wind velocities. The predicted yacht velocities are then used to calculate a handicap time allowance for the particular yacht in seconds per mile.

The introduction of the VPP has led to the world-wide adoption of the International Measurement System (IMS). The IMS VPP has provided significant advantages to the designer, handicapper and sailor alike in terms of performance data on all points of sail. This allows the designer to optimise for the particular weather conditions most likely to be encountered, the handicapper to construct a course from detailed weather reports, and furnishes the sailor with targets to achieve under the given conditions. However, the IMS VPP also has to be able to predict performance for the entire range of offshore racing and cruising yachts available. This situation dictates that the accuracy of the results is reduced for a smaller design space.

To rectify this problem, Murray, Burns & Dovell (MBD) developed their own VPP which is capable of using data from various theoretical and analytical sources. In this way, VPP results can be used to distinguish between subtle design changes. Enhancement of the MBD VPP has continued since 1994 in conjunction with the AME CRC.

In order to gauge the race winning potential of a design it is necessary to include calm water data in VPP studies. However, the presence of waves on the race course will also have a significant impact on a yacht’s overall performance. Wave motion will impart an additional regime of forces and motions on the yacht, which in hydrodynamic terms, manifests itself primarily as “added resistance”.

Gerritsma et al. [3,4,5,6,7] have conducted an extensive set of model experiments and theoretical predictions on the Delft Systematic Yacht Hull Series. The model data and predictions from a simple strip theory seakeeping program have enabled a polynomial expression for added resistance to be developed which is based on the main yacht parameters: length, displacement, beam, draft and prismatic coefficient. Using this polynomial it is possible to calculate the added resistance for a yacht as a function of the wave direction, wave frequency, and the Froude number for hulls within the envelope of shape parameters investigated.

The aim of the project described herein is to develop a VPP module which calculates the added resistance of a yacht in waves. The method described uses Response Amplitude Operators (RAO) for the added resistance in waves which are derived from theoretical predictions and towing tank experiments. The added resistance is simply the difference in total resistance between calm and rough water conditions. The RAO of the added resistance is then calculated by dividing the added resistance by the square of the wave amplitude.

2. INVESTIGATION OF ERROR SOURCES AND MAGNITUDES

2.1 SOURCES OF ERROR IN SAILING YACHT MODEL TESTS

Model experiments of sailing yacht hulls were first attempted in the late 1800's, but it was the groundbreaking work of Davidson reported in 1936 [8], which first made tank experiments useful to designers. Davidson developed test techniques and apparatus for towing models with heel and yaw, and methods for extrapolation of model data to full scale which remain in use today. However, it wasn't until the 1970's that extensive investigations into the possible sources of error involved with yacht model tests were reported [9,10].

In terms of a yacht model test program errors can be introduced from various sources: the model itself; test procedures; dynamometry and instrumentation, and; the experimenter [11].

2.1(a) Errors Due to Model Preparation

Of the possible sources of error, the preparation of the model is most critical to the success of any test program. Without due care being taken in the construction and tank preparation phases, it is pointless to test no matter how well controlled the rest of the experiment may be. Any asymmetry inherent in the model or appendages may require adjustment to the model alignment to achieve zero side force, which in turn can introduce errors in the calculated lift and drag. The quality of the model surface preparation will also influence the accuracy and precision of an experiment. Models need to be constructed with adequate stiffness to resist significant deformations caused by ballasting, and the whole ballasting process must be done carefully to avoid errors introduced by incorrect displacement and trim.

2.1(b) Errors Due to Test Procedures

Turbulence stimulation always raises questions over its efficiency in producing turbulent flow. A system for applying turbulence stimulators should be developed, and the parasitic drag accounted for, to avoid increasing accuracy errors and uncertainty.

Assuming the quality of the model can be assured, the physical dimensions of the test facility, and the test medium may have some bearing on the test results. Blockage can become an issue if the immersed model cross-section is greater than 1/200th of the tank cross-section [11]. Test speeds also need to be governed to ensure they remain well below the intermediate water wave speed for the test water depth. As the data extrapolation requires the calculation of frictional resistance, the water temperature needs to be monitored accurately throughout the test period. In addition the turbulence level in the tank, and variations in viscosity due to chemical composition, will influence the uncertainty and precision of a test.

2.1(c) Errors Due to Dynamometry and Instrumentation

Another area where potential errors may arise is the alignment of sensors, which is critical to the overall accuracy of the measurements taken. If the sensitive axis of a force transducer is not precisely aligned with the direction of the force vector, the desired force component will not be fully measured, and other components will be introduced into the measurement. Cross-talk between the axes of the dynamometry can also introduce accuracy errors as a result of deflection of the sensors and test apparatus under the applied load. Even though misalignment errors may be small, the presence of these cross axis sensitivities can cause significant inaccuracies, since drag is typically small in comparison to lift.

While there are several other sources of experimental error, including those introduced through human fallibility, many of these will occur in isolated instances. Generally these errors can be dealt with simply by interpreting the data and repeating the experiment. This highlights the need to continuously monitor the data gathered and repeat suspicious tests if possible.

2.2 SUMMARY OF ERRORS IN PERFORMANCE PREDICTION

Since testing began on the AME CRC yacht series a substantial amount of data has been gathered which has enabled a thorough investigation of the errors associated with the experimental program. A summary of the random errors in the determination of the calm water resistance, added resistance in waves and performance prediction has been carried out and presented in the following sections.

2.2(a) Errors in Velocity Prediction

The errors in velocity prediction have been calculated for two cases. Firstly those present during a single testing session; and secondly those present between testing sessions.

The errors present during one test session have been calculated to be ±0.004 knots for the full scale boat speed over all of the conditions considered in the VPP. This error translates into an error of ±1.39 seconds per nautical mile for a Windward - Leeward (WW/LW) course and ±0.58 seconds per nautical mile for a Linear Random (LR) course. The errors grow when scrutinising those between test sessions to ±0.01 knots for V_S, ±3.57 s/nm for the WW/LW course and ±1.48 s/nm for the LR course. The difference has been attributed to incorrect temperature corrections, dynamometer alignment changes and transducer temperature dependencies. The growth in these errors between test sessions highlights the need to retest the parent model during each test session if the results are to be used for the fine tuning of designs.

2.2(b) Errors in Total Resistance

The error in total resistance coefficient (C_T) has been calculated by considering the repeatability of the extrapolated resistance results. The calculation of the repeatability has been explained in detail in Appendix A.1. It was calculated that the percentage error in extrapolated C_T varied from 1.6% (for low speeds) to 0.4% (for high speeds).

2.2(c) Errors in Added Resistance in Waves

For the calculation of error in the added resistance in waves measurements the reader is referred to Appendix A.2. It was calculated that the error was dependant on the wave period used for the tests, for the first full scale wave period of 2 s the error was calculated to be 68% whereas for all other wave periods the error was calculated to be 7.1%. The reason for the large change in error is thought to be due to the small wave amplitudes, and the significant increase in heave and pitch motions between the 2.0 s and 2.5 s wave period cases.

3. MODEL DETAILS

A standard yacht hull series has been designed by Murray, Burns & Dovell and tested by the Australian Maritime Engineering Cooperative Research Centre (AME CRC). The series presently comprises 9 models, which have been used to investigate 5 distinct hull form parameters: length to displacement ratio; beam to draft ratio; prismatic coefficient; LCB - LCF separation, and; stern overhang.

The parent hull in the AME CRC series, 004, is an IMS type yacht based on the Delft Systematic Yacht Hull Series II yacht form. A body plan of the AME CRC parent hull is shown in Fig. 1. Design of the individual hull forms follows a straight forward philosophy:

- The models should represent realistic yachts which would be built to race under the IMS rule.

- All parameters except for that under investigation should remain as consistent as possible.

A nominal scale of 1:5 has been adopted for all the models in the AME CRC Systematic Series, and the same keel and rudder combination has been used on all models tested. The full scale hull form particulars are given in Table 1.

3.1 LCB-LCF SEPARATION - MODELS 005 & 006

To examine the effect of LCB-LCF separation two models were constructed with a 2% variation in the separation distance. Model 005 has the LCB position moved aft, reducing the LCB-LCF separation, while 006 has the LCB moved forward to increase the separation between LCB and LCF [12].

3.2 STERN OVERHANG VARIATION - MODEL 004b

The effect of stern overhang variation on added resistance in waves has been investigated by attaching additional stern sections to the AME CRC parent hull. Each section is 750 mm long full scale and simply extends the lines in a straight run from the existing transom. Model 004b is the resultant hull form with two stern extensions added, giving an additional 1500 mm overhang.

3.3 PRISMATIC COEFFICIENT (C_P) VARIATION - MODELS 007 & 008

The investigation of prismatic variation was carried out using models with 2% higher and 2% lower prismatic coefficients than that of model 004 (C_P=0.535). The two models are designated 007 (C_P=0.513) and 008 (C_P=0.554).

The main design consideration for these models was that the initial stability of all three yachts should be held constant. This criterion was put in place to allow the same rig to be used in each hull, thus removing this variable in the comparison of performance between the three yachts.

3.4 DISPLACEMENT VARIATION - MODELS 009 & 010

In keeping with the overall design philosophy for the series, models 009 and 010 were designed such that the length-displacement ratio ($L_{WL}/\nabla_C^{1/3}$) was varied as much as possible without creating unrealistic designs which would not be built. The first step in the design process, was a survey of the Delft systematic series [8] to determine a suitable range for the length-displacement ratio. The survey identified Delft models 23, 25 and 28 as having consistent form parameters across the variation in length-displacement ratio. For these three models, $L_{WL}/\nabla_C^{1/3}$ was found to be 5.00, 6.01 and 6.99 respectively [8]. A further survey of yachts currently sailing in IMS in Australia was carried out, and it was found that length-displacement ratios varied from 5.87 to 6.52 for most yachts.

Initially, a full weight estimate for the parent model was conducted and the vertical centre of gravity calculated. This allowed a righting moment analysis to be performed from which the sail characteristics were derived. These sail characteristics were compared with realistic designs and internal ballast added to obtain the desired righting moment. The total internal ballast required for model 004 was calculated to be 1083kg, which is considered to be realistic.

In creating the hulls for the two new models, displacement was added by varying the internal ballast. This has the advantage that the keel, rudder and fit out are common to each model. A consequence of this methodology was that length-displacement ratio could only vary from 5.69 to 6.47. Unfortunately, this dictated that the variants could not investigate the same range of $L_{WL}/\nabla_C^{1/3}$ covered by the Delft series of models, but covered the population of IMS yachts sailing in Australia today.

3.5 BEAM TO DRAFT RATIO VARIATION - MODELS 011 & 012

A survey of the Delft series identified two distinct beam (B_{WL}) to draft (T_C) ratio variations, with a 50% variation in B_{WL}/T_C, while a survey of IMS yachts in Australia showed variations of up to 15% in beam-draft ratio. The AME CRC series parameters typically vary by significantly smaller magnitudes hence a 10% variation in B_{WL}/T_C was decided upon. Definition of the B_{WL}/T_C series hull forms was achieved by an initial modification of the midship section, varying the canoe body draft while maintaining the waterline beam. The hull lines were then faired along their length by maintaining a constant variation in curvature. This method proved extremely successful in that B_{WL}/T_C could be changed with only minor alterations in other form parameters.

A secondary characteristic generated by the B_{WL}/T_C variation was that the low B_{WL}/T_C hull exhibits a pronounced vee bow, whilst the high B_{WL}/T_C boat is extremely flat in the bow region. Hence, a measure of the influence of bow shape on seakeeping characteristics was gained.

4. EXPERIMENTAL PROGRAM

4.1 EXPERIMENTAL SETUP

4.1(a) Turbulence Stimulation

In order to stimulate turbulent flow, cylindrical studs were attached to each hull at stations 1 and 2 (station spacing equal to 200 mm). Each stud had a cross sectional area of 9.00 mm^2, and were fitted at a spacing of 25 mm. Additional studs were also applied to the keel and rudder at one third of the chord length from the leading edge. These studs had had a cross sectional area of 2.25 mm^2, and were fitted at a spacing of 12.5 mm.

4.1(b) Test Apparatus

All the systematic series experiments have been conducted in the towing tank at the Australian Maritime College's campus in Launceston, Tasmania. The tank has a rectangular cross section with the following principal dimensions:

Overall Length: 60.0 metres
Width: 3.50 metres
Water Depth: 1.45 metres

Situated at one end of the tank is a single flap, flat plate, hydraulically driven wavemaker. Whilst at the other end is a wet dock used for ballasting models. A steel carriage running on rails along the walls of the tank is used to tow the models, which has a maximum speed of 4.0 m/s.

The models are connected to the carriage using a single post yacht dynamometer, owned by MBD, and are free to pitch and heave, but constrained in surge, sway, yaw and roll. The dynamometer comprises: two flexures arranged orthogonally to enable lift and drag measurements, a torsion cell for measuring yaw moment, a strain gauge for measuring roll moment, a rotary potentiometer for determining pitch and a linear potentiometer for measuring heave.

In order to measure the wave height and also determine the motion phase relationships, a capacitance wave probe was fixed to the carriage, level with the bow of the yacht but clear of any wave disturbance from the model.

The data from the dynamometer and wave probe were processed using an analog to digital converter sampling at a rate of 20 Hz, and then recorded by a computer mounted on the carriage. The calibration and data acquisition was carried out using software developed by MBD and the Wolfson Unit.

4.1(c) Model Ballasting

Each model was ballasted to its required displacement and trim. This weight was then distributed along the model to achieve the necessary radius of gyration (k_{yy}), with $k_{yy}/L_{WL} = 0.220$. Since all models had the same design waterline length, their radii of gyration were identical. The bifilar method was used for estimating the pitch radius of gyration.

Prior to each test run, the ballast arrangement was modified to account for the pitch moment and vertical force applied by the sails. These forces and moments were calculated from the drag and lift results from the previous set of tests. The predicted results were continually checked during tests, and were found to be within the accuracy required to predict the trimming moments and vertical forces required.

4.2 TEST CONDITIONS

The test program for each model consisted of a comprehensive matrix of calm water resistance tests, followed by a series of rough water tests in one sailing condition.

Table 2 outlines the calm water test plan carried out over the speed range of the yacht for various angles of heel and yaw.

For both calm and rough water tests, the rudder angle relative to the yacht centreline, was set to the same as the yaw angle. The regular wave test plan employed is described in Table 3. All the wave tests were conducted at the full scale, design windward speed of 6.5 knots. The models were constrained at a heel angle of 20 degrees and yaw angle of 3 degrees. At least two runs were recorded at each wave height and period, to increase the confidence level of the means.

5. RESULTS OF PRISMATIC, AND LENGTH-DISPLACEMENT VARIATION INVESTIGATIONS

Of the five parameters investigated so far, the results from the prismatic variation, and the length to displacement ratio variation are presented herein. In addition to the experimental investigations carried out, theoretical predictions for added resistance in waves, heave, and pitch have also been conducted. Generally, the results achieved have shown that predicted trends agree well with experiment. However, in some cases the necessarily small variation in hull parameter has made the interpretation of results difficult, due to experimental errors.

For the analysis described, the added resistance in waves was calculated by taking the difference between a reference calm water drag, and the average drag from a rough water test. The added resistance RAO was then obtained by dividing the added resistance by the wave amplitude squared. Due to the dependency of the analysis on wave amplitude, a constant wave slope of 1/50 was used for both experiments and theoretical predictions.

5.1 THEORETICAL PREDICTIONS

The AME CRC has developed computer software for the prediction of motions, loads, and added resistance experienced by vessels in a seaway. The “SEALAM” software is based upon the strip theory method proposed by Salvesen, Tuck and Faltinsen [13], and incorporates the method attributed to Gerritsma and Beukelman [14] for calculating the added resistance of a yacht. Non-linear effects are addressed by calculating the hydrodynamic coefficients at the instantaneous dynamic “local waterline”. This allows the effects of the incoming wave pattern, immersion and emergence of overhangs, and phasing of the resultant motions to be considered. It should be noted however that the predictions were carried out for the yachts in an upright condition with no yaw angle and no appendages, rather than the sailing condition tested.

5.2 MEASUREMENTS AND PREDICTIONS OF HEAVE MOTION

The heave response operators presented in Fig. 2 for the prismatic variation, and Fig. 3 for the length-displacement variation, are calculated by dividing the heave amplitude by the wave amplitude. The figures plot experimental results from the rough water tests, and the response predicted using the SEALAM software, against the full scale wave period.

Inspection of the experimental results for heave suggests that the parent model (004) is located at, or near, a minimum when considering the effect of C_P variation. This effect is most pronounced around the peak response, where the heave response of the parent model is clearly lower than that for the high (008) and low (007) C_P models. The effect of high and low C_P is similar until large wave periods are reached, where the high C_P boat exhibits greater response. Both the experimental, and theoretical results show that for wave periods below 2.75 s, varying C_P appears to have little effect on heave. The major difference in trend between theoretical and experimental results, is the optimum value for C_P for wave periods between 2.75 s and 4.00 s. From the strip theory analysis, it is difficult to discern any difference between 004 and 008 in heave response predicted.

The variation in length - displacement ratio shows that the prediction method models the trends in heave response particularly well. At wave periods up to approximately 3.0 s, the experiments show the lighter boat (009) exhibits the greatest heave followed by the parent hull and then the heaviest boat (010). There is a crossover point at 3.0 s, above which the heaviest boat displays the greatest response in heave, followed by the parent and the lightest boat. Each of these features is predicted well by the strip theory. The magnitude of the heave response is reasonably well predicted by the theory in both prismatic and displacement investigations. Examination of the predicted response curves shows good absolute agreement apart from the region of the wave spectrum where resonance occurs.

5.3 MEASUREMENTS AND PREDICTIONS OF PITCH MOTION

The pitch motion RAO can be derived in a similar fashion to the heave RAO, whereby the pitch amplitude in degrees, is divided by the wave amplitude, which is given in Fig. 4 for the prismatic variation. The experimental results suggest that the parent model is located at, or near a minimum with respect to pitch response. From the experiments it is apparent that the low C_P boat has the largest pitch motion up to the peak response at a wave period of approximately 3.0 s, after which the high C_P boat pitches most. Note that, the high and low C_P boats both exhibit notably larger response than the parent model. The theoretical results for the C_P variation are much more confused and no clear optimum for C_P is apparent across the range of wave periods calculated. However, the magnitude of the variations is minimal compared with those in length-displacement.

The pitch response operators for the displacement investigation are given in Fig. 5. Once again the experiments show the parent model to exhibit the least response across the spectrum of wave periods tested. A similar crossover to that in the prismatic results is apparent at about 3.2 s wave period, where the greatest pitch response changes from the lightest boat (below 3.2 s) to the heaviest boat (above

3.2 s). The theoretical results give a somewhat different picture of the response operators. Examination of the predicted pitch response curves shows the parent model's response to be between that of the displacement variants across the range of wave periods tested.

In both the prismatic and displacement investigations, it is apparent that the theory consistently underestimates the pitch motion amplitude at wave periods above the crossover point located near the peak response.

5.4 MEASUREMENTS AND PREDICTIONS OF ADDED RESISTANCE IN WAVES

The RAOs for added resistance in waves are given in Fig. 6 for the prismatic investigation, and Fig. 7 for the displacement investigation. From the experimental results it would appear that the optimum C_P for minimising added resistance at low wave periods, is a high value close to that for model 008. Around the peak of the RAO , the parent model is the most effective at reducing added resistance, whilst at higher wave periods there is little discernible difference between the three variants.

The trends indicated by the theoretical results for the prismatic variation, are similar to those from the experiments. At wave periods between 2.6 s and 3.7 s the parent model will have the least added resistance, whilst at periods above 3.7 s there is no definite optimum for C_P. The main difference in trend between theory and experiment is for the region of wave periods below 2.6 s where the theory predicts the lowest C_P boat will have the least added resistance.

The experimental results of the displacement investigation show clearly that added resistance increases with displacement, across the spectrum of wave periods tested. However, the predicted response curves do not completely agree with the experiments. The predicted curves show a crossover point at approximately 2.7 s below which the heaviest boat (010) exhibits the least added resistance. The added resistance predictions also calculate a resonant period which is higher than that measured experimentally. It should be emphasised here that the rough water tests were conducted in a sailing condition of 20 degrees of heel and 3 degrees of yaw, whereas the added resistance predictions were carried out in an upright condition. Accordingly, the changed sailing condition may account for a large part of the discrepancy in both the magnitude of the added resistance predicted, and the position of the resonant peak.

6. COMPARISON OF AME CRC AND IMS 1996 VPP ROUGH WATER RESULTS

To illustrate the comparison between the AME predicted performance and the IMS predicted performance of the AME systematic series of yachts, the results of the C_P variation were examined and compared with those from the 1996 version of the

IMS VPP. This was done because it has been widely accepted that there was a flaw in the 1996 IMS VPP in its treatment of C_P variations (the 1997 IMS VPP has this flaw fixed). The flaw resulted in the speed of a high C_P yacht being under-predicted and the speed of a low C_P yacht being over-predicted. It shall be shown in the following section that this flaw was also predicted by using the AME VPP, which has allowed designers to use the AME VPP to predict with more accuracy the relative performance of sailing yachts.

6.1 RATING AND PERFORMANCE

Given a course to be sailed and the velocity prediction for a yacht it is possible to calculate the time a yacht will take to sail that course for a given wind strength. This parameter is commonly described in units of seconds per nautical mile (sec/mile). The IMS predicted values for this number shall from here on be referred to as the rating, while the AME VPP predicted results shall be referred to as the performance.

The rating values can be normalised by subtracting the rating for the parent model 004, from the rating of the design under investigation. The rating differential can be calculated using the following equation

$$\Delta R_{00i} = R_{00i} - R_{004}, \qquad (1)$$

where R_{00i} is the rating for the ith model. This was done for models 007 and 008, the C_P variants. When this number is positive it indicates that the change in C_P has resulted in a decrease of predicted speed by the IMS VPP. The performance values can also be normalised in the same way, giving ΔP_{00i}.

A new quantity for each C_P variation can then be obtained using the following equation

$$\Delta RP_{00i} = \Delta R_{00i} - \Delta P_{00i}, \qquad (2)$$

where ΔRP_{00i} is a measure of the difference in predicted velocity between that obtained by using the AME VPP results, and that obtained by using the IMS VPP results. A positive result in this figure indicates that the parameter change has resulted in an underprediction of the velocity by the IMS VPP.

6.2 COURSES CONSIDERED

A standard set of courses has evolved which is used for handicapping of most offshore races; two of these courses shall be considered here. Firstly the Windward - Leeward (WW/LW) course, which is calculated by considering that the yacht is required to sail two legs of equal distance, one directly into the wind and one directly away from the wind. Secondly the Linear Random (LR) course, which is calculated by assuming that the yacht sails in a straight line and the wind varies evenly from directly in front of the yacht to directly behind the yacht.

6.3 COMPARISON OF RESULTS

Curves of the rating-performance differential (ΔRP_{00i}) against true wind speed are presented in Figs. 8 and 9, for the WW/LW course and LR course respectively. In both figures it can be seen that the AME VPP is predicting that the velocity of the high C_P model (008), will be underestimated when assessed using the IMS VPP, whereas the velocity for the low C_P model (007) will be overestimated.

This was also the conclusion from the yachting community during 1996 and resulted in the 1997 IMS VPP being altered considerably to rectify the problem.

7. CONCLUSION

The development of the AME CRC systematic series for yachts, has resulted in an enhanced knowledge of the effects various hull parameters have on the performance of IMS style yachts. A thorough investigation into the magnitude of experimental error has been undertaken which has shown the test techniques employed to be particularly good. Careful refinement of the experimental methods has resulted in excellent repeatability between tests, which in turn, has affirmed a high degree of confidence in the data collected.

In general, the trends predicted by the strip theory compare well to the measurements. There are regions where the theory breaks down, particularly in predicting the magnitude of the individual responses. A comparison of the AME CRC VPP and the 1996 IMS VPP has been presented as an example of the applicability of VPP studies to the overall design process. The AME CRC VPP is shown to correctly identify the effect of prismatic coefficient variation on performance rating.

In addition to the continuing analysis of existing results, anticipated future work will centre on the testing of two further hull form parameters, to complement the work carried out by Delft, and to further enhance the AME CRC VPP’s usefulness to designers.

8. ACKNOWLEDGEMENTS

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APPENDIX A

A.1 ANALYSIS OF ERRORS IN TOTAL RESISTANCE

Having calculated the total resistance coefficients (C_T) at each speed from the raw tank data, the error analysis proceeded by fitting a Bezier curve through the data points. Using a curve fitting routine developed by MBD, curves of C_T versus speed were generated and small variations in the test speeds accounted for. For this analysis C_T curves were defined for four upright resistance test series conducted between 1995 and 1997. The mean value of C_T over the four series was then determined for each speed.

An approximation of the random error can then be calculated by taking the standard deviation (σ) of the C_T values over the four series of experiments. Statistically, the true value of the total resistance coefficient will lie in an error band about the empirical mean, defined by $\pm 1.6449\sigma$ to a level of significance of 10% [15].

The results of the resistance error analysis are shown in Fig. 10 which gives the absolute error in C_T against the mean C_T. A linear fit to the data indicates a substantially constant magnitude for the random error in C_T. This randomness can be calculated from the linear regression shown in Fig. 10. This indicates that the percentage error in C_T ranges from 1.61% to 0.40%.

A.2 ANALYSIS OF ERRORS IN ADDED RESISTANCE MEASUREMENTS

A similar investigation to the calm water resistance analysis, has been conducted to assess the random errors associated with the measurement of added resistance in waves. During each series of rough water experiments, at least two runs were conducted for each wave frequency. Response operators were calculated for each run and then averaged to give the added resistance RAO for that wave frequency.

Data from three sets of rough water experiments conducted between 1995 and 1997 on the parent hull has been used for this analysis. The resultant mean RAO of the three series incorporates the average RAO from each set of measurements, which includes the added resistance plus a randomly distributed error. In the resulting plot of absolute error against the added resistance operator - Fig. 11, a zero offset has been assumed for the regression analysis, giving a percentage error of ±7.1%. This error model was chosen not only for its simplicity, but also because it did not significantly degrade the goodness of fit to the data.

The large magnitude of the errors associated with the calculation of the added resistance suggests there are numerous sources of error present. A consequence of the added resistance operator being a function of the wave amplitude squared, is that inaccurate measurement of wave height contributes a substantial proportion of the overall error.

A.3 ASSESSMENT OF ERRORS IN VPP ANALYSIS

Given that results from a VPP analysis are a crucial aspect of the design process, it was thought prudent to undertake an investigation of the variability of the VPP output. As in the added resistance analysis, the results from three test sessions conducted over a three year period, have been used to determine an estimate of the random errors in the VPP predicted yacht velocities (V_S).

For each set of experiments the VPP generates a velocity prediction for a given wind and wave condition. The wind conditions used were the same as those used to calculate a yacht's handicap under IMS, while the Pierson-Moskowitz spectrum was used to model the waves. All of the tank experiments accepted (ie. those experiments which did not fail running checks) are used in the velocity prediction. By comparing the velocity predictions from successive test sessions, the empirical average and standard deviation of the yacht velocity in each sailing condition can be calculated. Thus an estimate of the random error in predicted velocity can be determined in the same fashion as described in the previous sections.

The variation of absolute error in V_S with true wind velocity (V_{TW}) is given in Fig. 12. A linear regression for the error data is also plotted. Clearly, changing the true wind velocity changes the error in V_S by only a very small amount. Similar plots were examined for V_S error change with respect to heel angle and sail control parameters. From these plots it was concluded that there was no significant correlation between V_S error and the other VPP parameters.

Considering Fig. 12 and the other plots of variation of the error in Vs, it was concluded that the error was relatively constant, therefore a simple average of the error was taken over all the wind conditions considered. The resulting absolute error in Vs was then calculated to be ±0.01 knots.

An estimate of the random errors in the velocity predictions within a single test session maybe obtained by firstly considering the repeated resistance runs for each model. This has been calculated for repeat runs covering all test sessions to be ±0.39% for C_T. Then if it is assumed that a percentage error in C_T will be linearly proportional to the errors in velocity prediction the errors can be calculated to be ±0.004 knots for the full scale boat speed over all of the conditions considered in the VPP. This error translates into an error of ±1.39 seconds per nautical mile for the WW/LW course and ±0.58 seconds per nautical mile for the LR course.

Model No.	**004**	**004b**	**005**	**006**	**007**	**008**	**009**	**010**	**011**	**012**
L_{OA} (m)	11.30	12.80	11.30	11.30	11.30	11.30	11.30	11.30	11.30	11.30
L_{WL} (m)	10.23	10.23	10.26	10.34	10.24	10.21	10.28	10.20	10.26	10.21
B_{WL} (m)	2.691	2.691	2.706	2.702	2.716	2.662	2.538	2.820	2.645	2.720
T_C (m)	0.444	0.444	0.453	0.454	0.449	0.442	0.372	0.513	0.391	0.507
Δ (kg)	5100	5100	5280	5280	5100	5100	4100	6100	5100	5100
∇_C (m^3)	4.893	4.893	5.068	5.068	4.893	4.893	3.917	5.868	4.893	4.893
S_C (m^2)	20.30	20.30	20.52	20.72	20.24	20.40	18.96	21.51	20.71	20.23
LCB rel. to Stn. 0 (m)	-5.440	-5.440	-5.613	-5.282	-5.441	-5.412	-5.446	-5.438	-5.442	-5.420
LCF rel. to Stn. 0 (m)	-5.644	-5.644	-5.718	-5.629	-5.667	-5.648	-5.666	-5.638	-5.684	-5.643
LCB-LCF sep. (m)	0.204	0.204	0.105	0.347	0.226	0.236	0.220	0.200	0.242	0.223
L_{WL}/B_{WL}	3.801	3.801	3.792	3.825	3.770	3.836	4.052	3.616	3.881	3.751
B_{WL}/T_C	6.059	6.059	5.971	5.957	6.055	6.018	6.826	5.500	6.771	5.368
C_P	0.533	0.533	0.535	0.535	0.512	0.554	0.533	0.534	0.531	0.536
$L_{WL}/\nabla_C^{1/3}$	6.025	6.025	5.974	6.017	6.032	6.015	6.523	5.653	6.046	6.011
k_{yy} (m)	2.25	2.25	2.25	2.25	2.25	2.25	2.25	2.25	2.25	2.25
Scale	1:5	1:5	1:5	1:5	1:5	1:5	1:5	1:5	1:5	1:5

Table 1 AME CRC Systematic Series Full Scale Particulars - Test Condition

Speed Range (knots full scale)	**Speed Range (m/s full scale)**	**Heel Angle (degrees)**	**Yaw Angle (degrees)**
4.5 → 11.0	2.31 → 5.66	0.0	0.0
5.0 → 9.0	2.57 → 4.63	0.0	1.0
5.0 → 8.0	2.57 → 4.12	0.0	3.0
5.0 → 8.0	2.57 → 4.12	0.0	5.0
5.0 → 9.0	2.57 → 4.63	10.0	1.0
5.0 → 8.0	2.57 → 4.12	10.0	3.0
5.0 → 8.0	2.57 → 4.12	10.0	5.0
5.5 → 9.0	2.83 → 4.63	20.0	1.0
5.5 → 8.0	2.83 → 4.12	20.0	3.0
5.5 → 8.0	2.83 → 4.12	20.0	5.0
6.0 → 9.0	3.09 → 4.63	25.0	1.0
6.0 → 8.0	3.09 → 4.12	25.0	3.0
6.0 → 8.0	3.09 → 4.12	25.0	5.0

Table 2 Calm Water Test Matrix

Wave Period (s)	**Wave Height (mm)**
2.00	124.8
2.50	195.0
2.75	236.0
3.00	280.8
3.25	329.6
3.50	382.2
3.75	438.8
4.00	499.2
5.00	575.0

Table 3 Regular Wave Test Plan (Full Scale values)

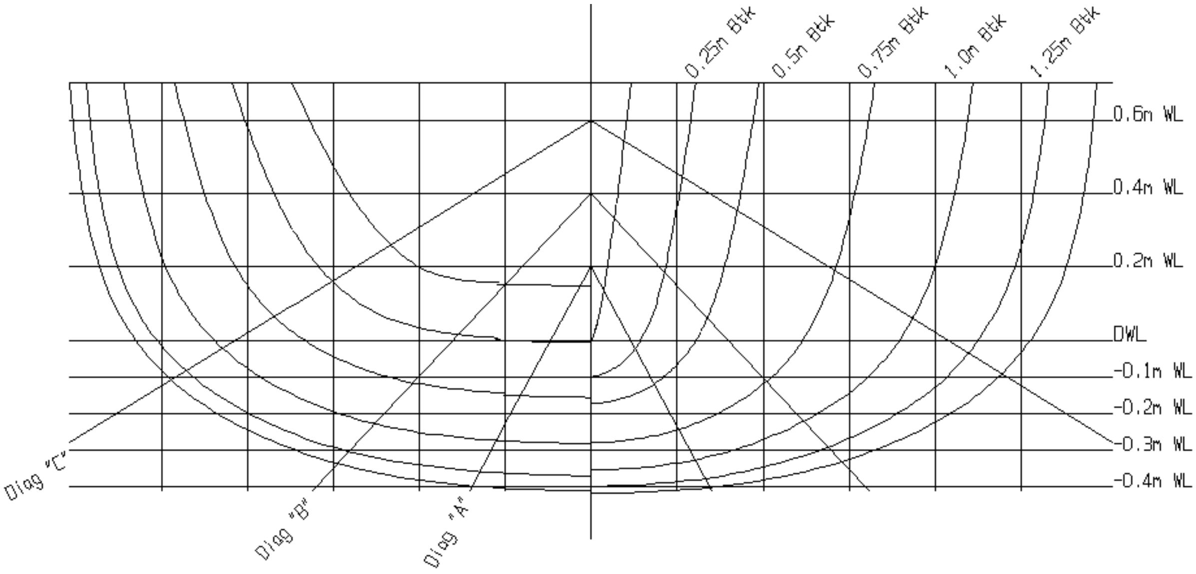

Fig 1 Body Plan of the AME CRC Systematic Series Parent Model

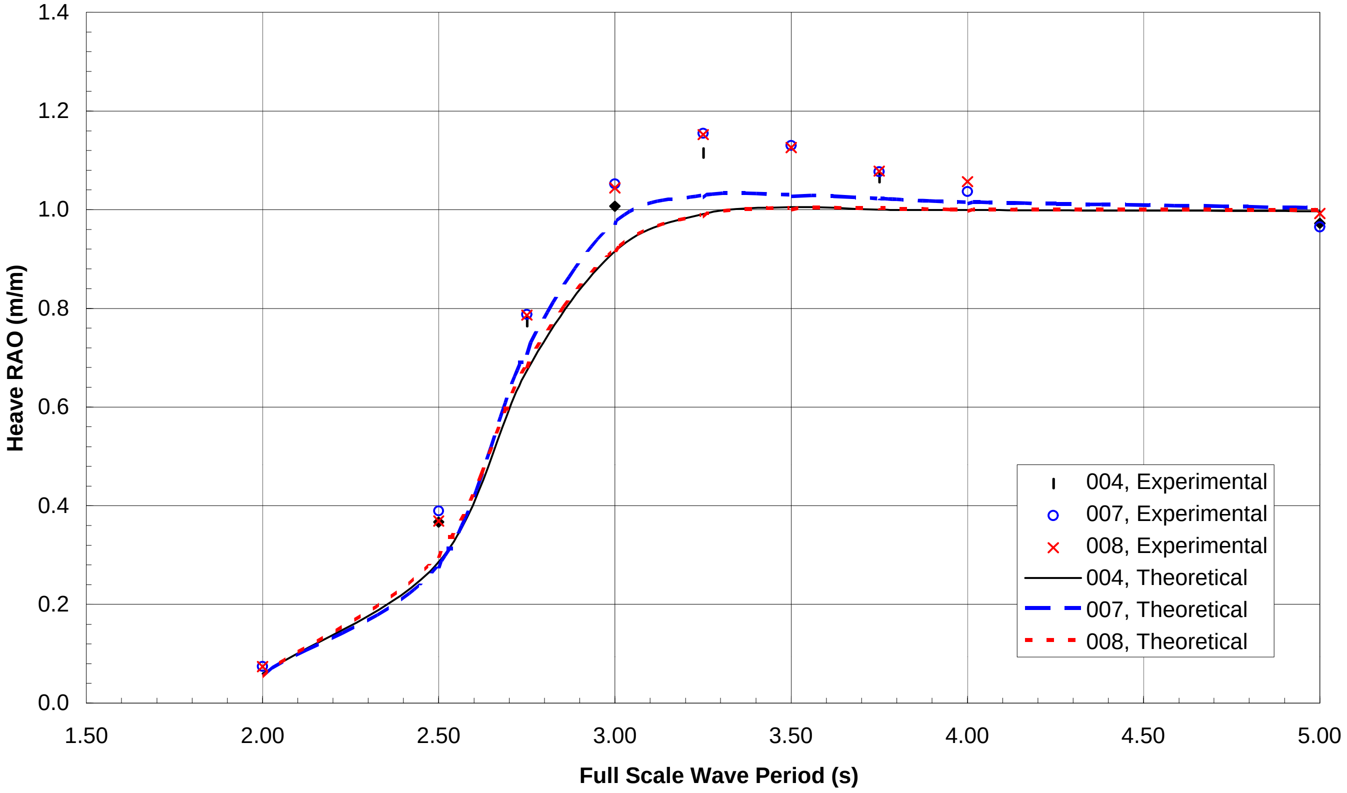

Fig 2 Predicted and Experimental Results for Heave - C_P Variation

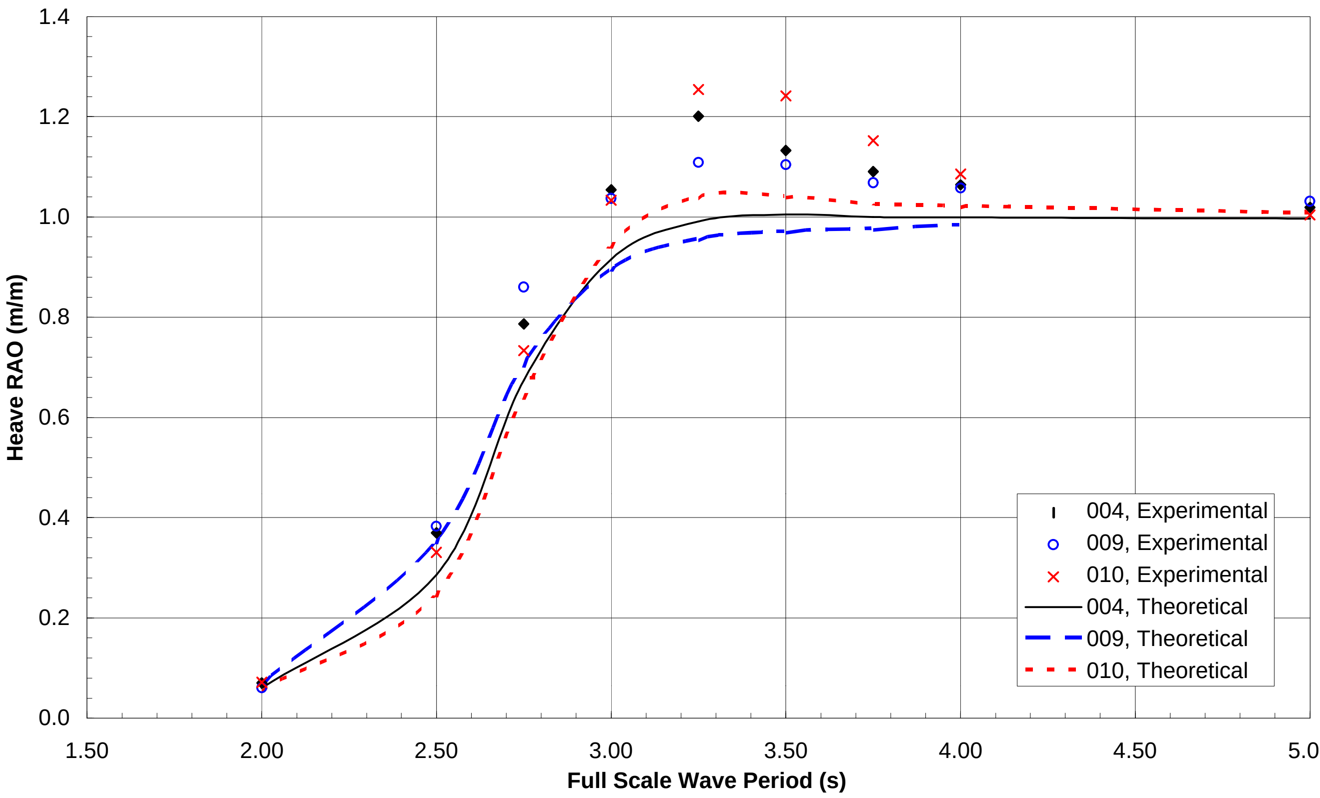

Fig 3 Predicted and Experimental Results for Heave - $L_{WL}/\nabla_C^{1/3}$ Variation

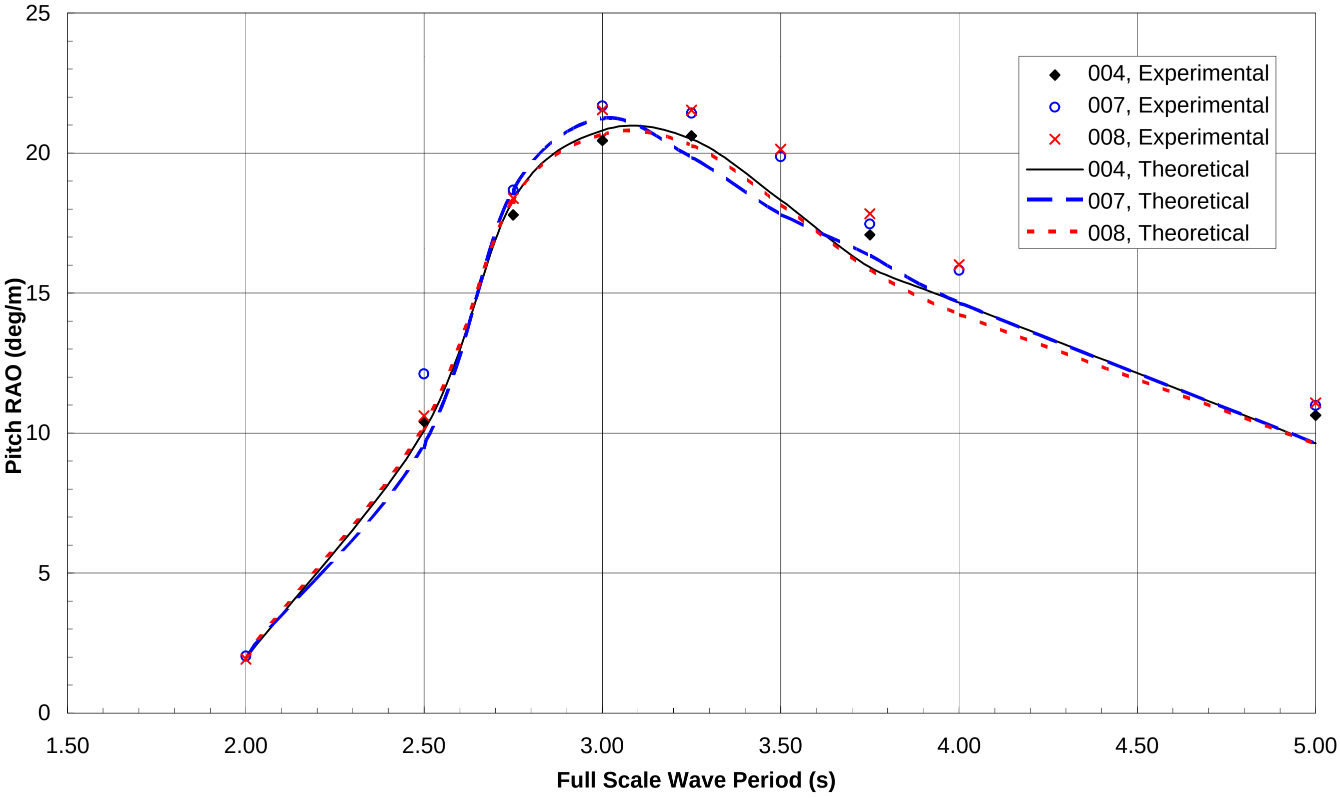

Fig 4 Predicted and Experimental Results for Pitch - C_P Variation

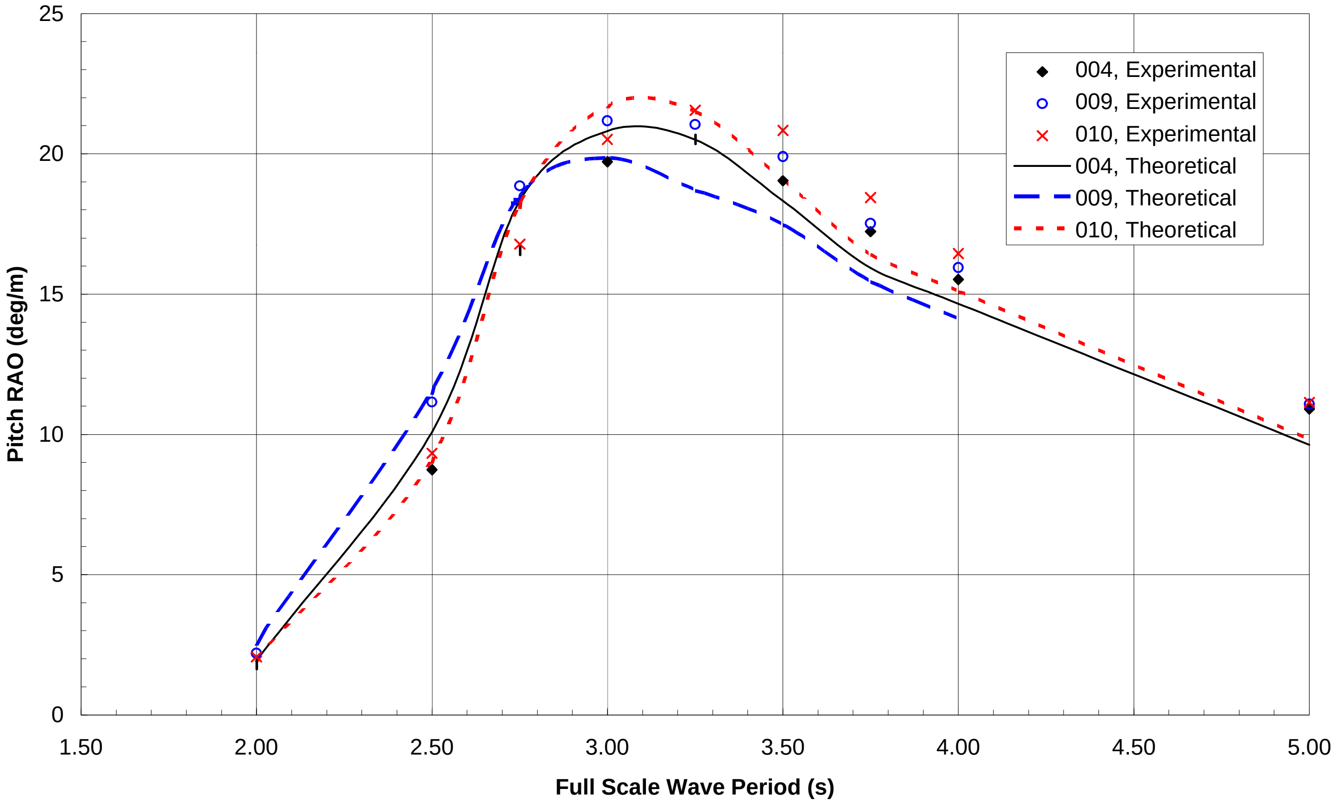

Fig 5 Predicted and Experimental Results for Pitch - $L_{WL}/\nabla_C^{1/3}$ Variation

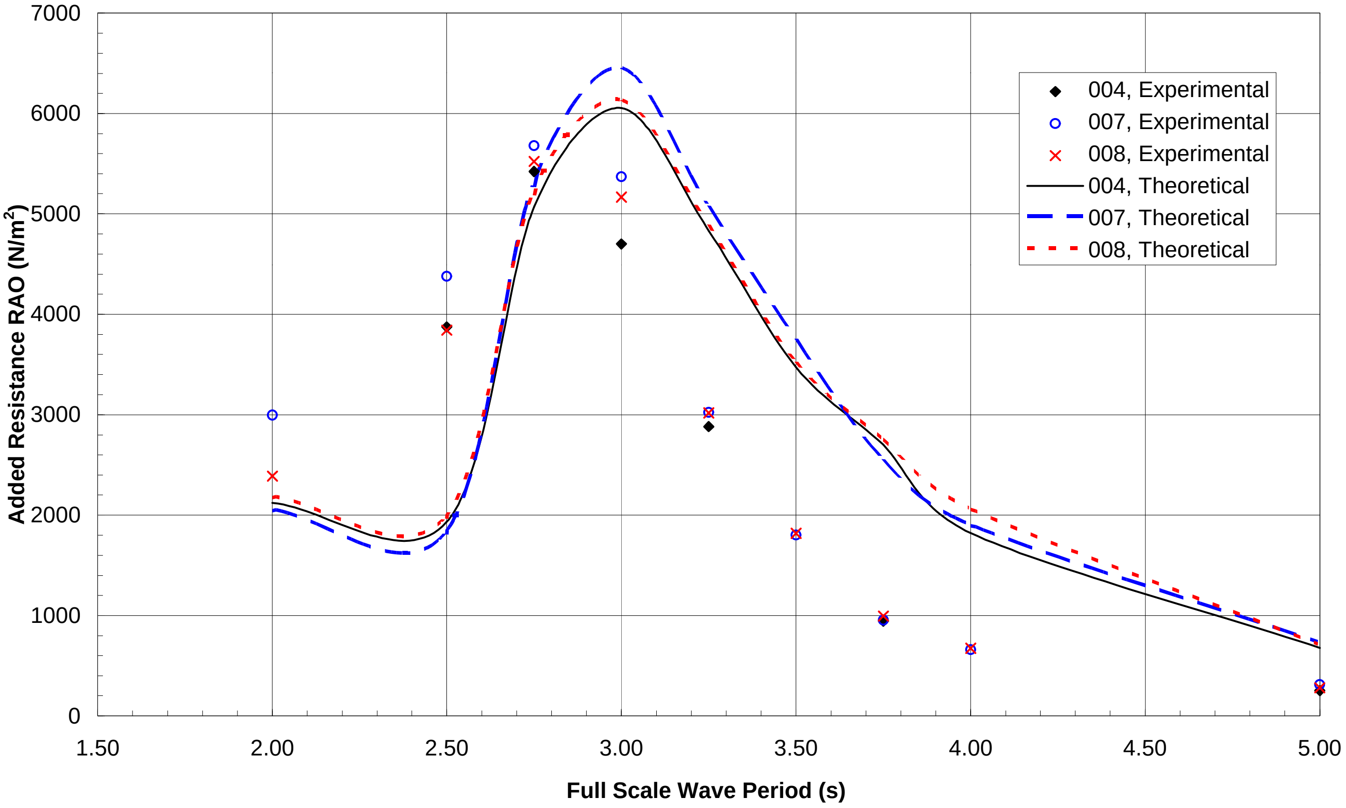

Fig 6 Predicted and Experimental Results for Added Resistance - C_P Variation

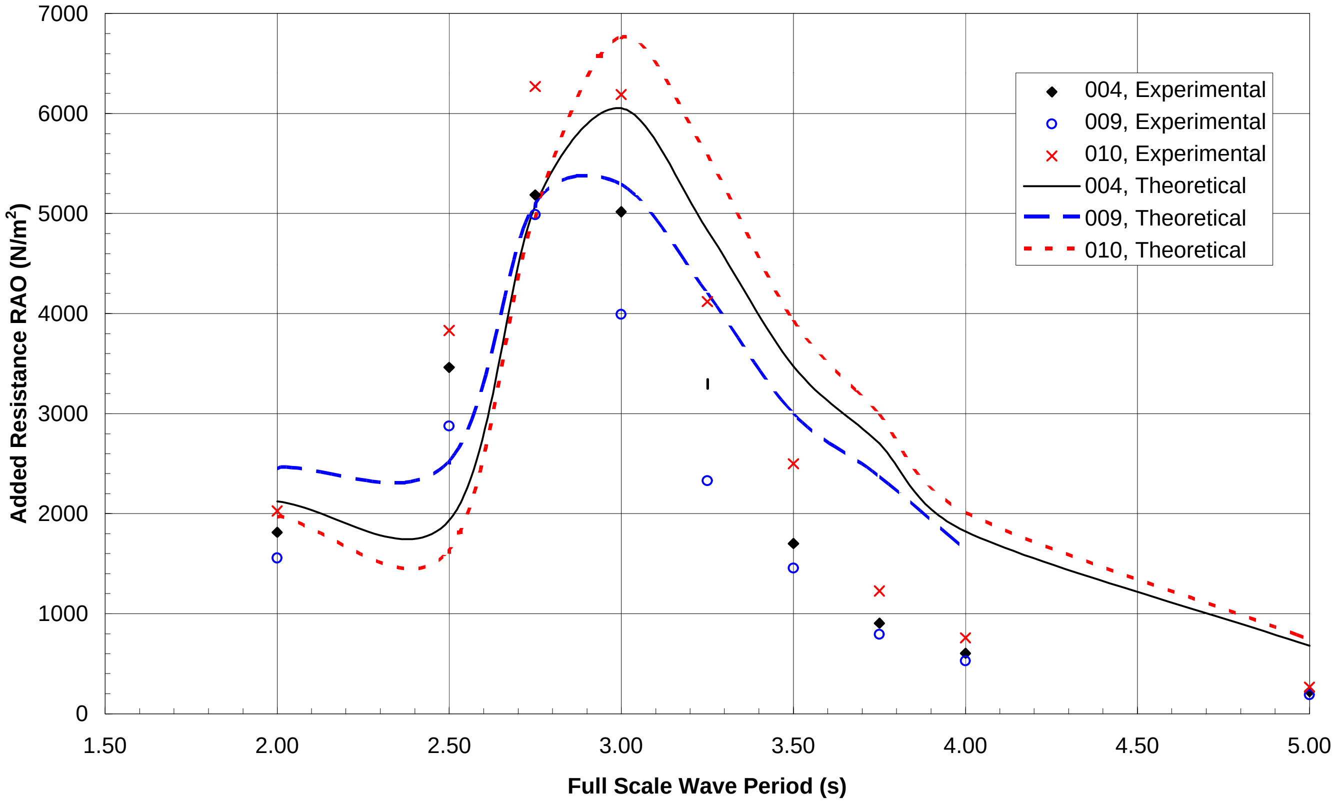

Fig 7 Predicted and Experimental Results for Added Resistance - $L_{WL}/\nabla_C^{1/3}$ Variation

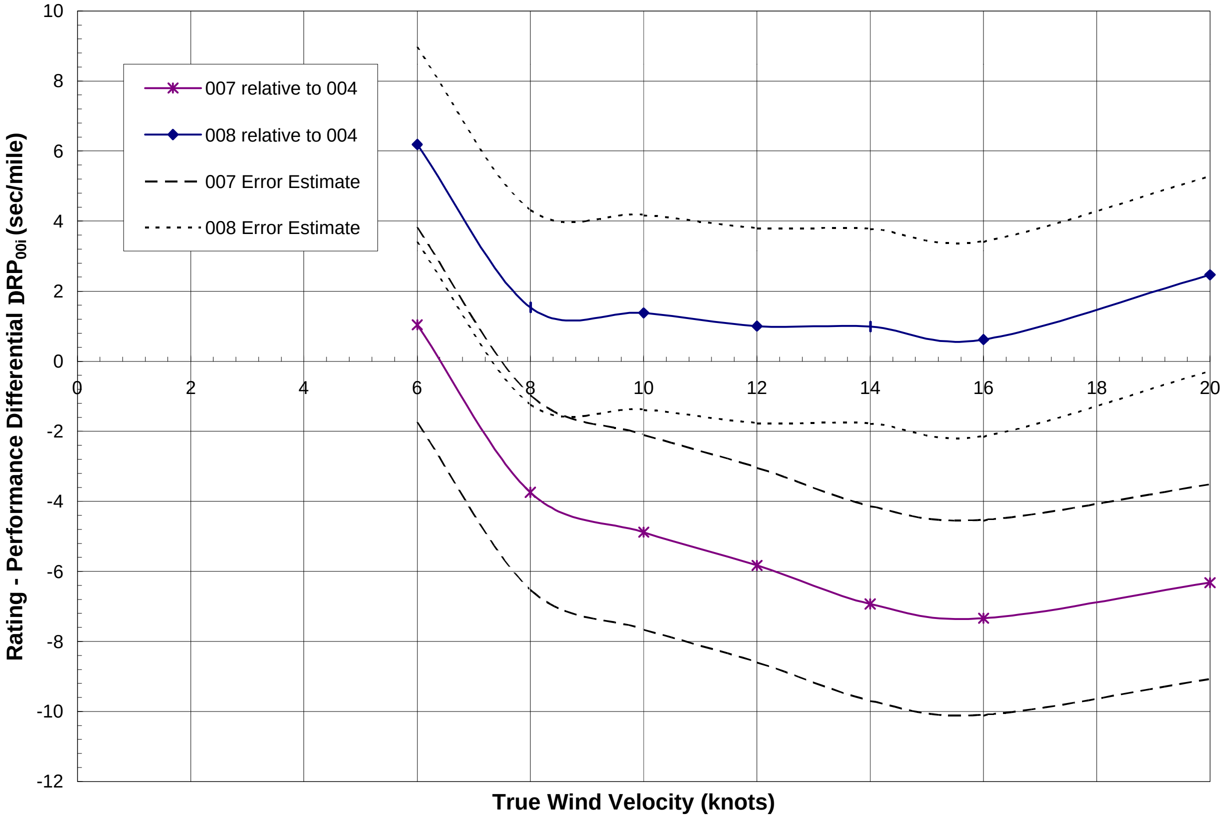

Fig 8 Rated Performance Curves for C_P Variations Relative to Parent Hull - Windward / Leeward Course

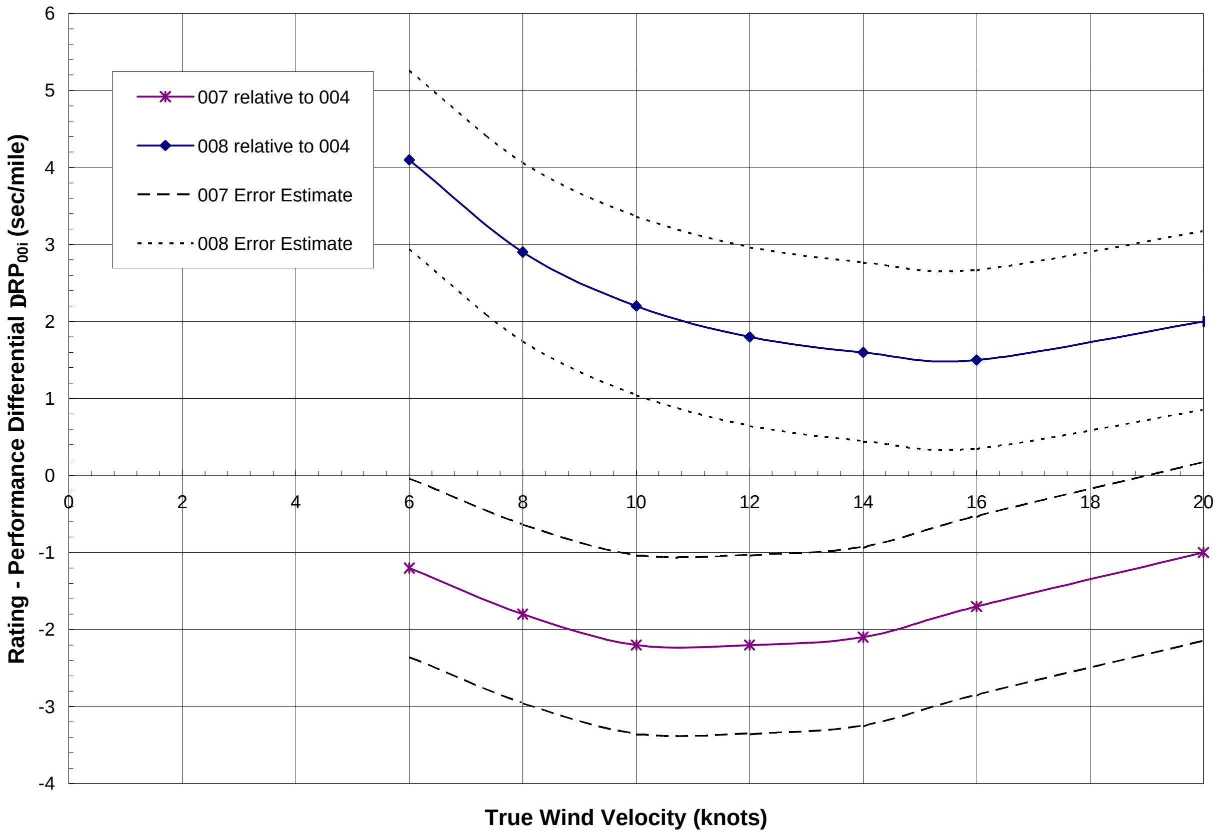

Fig 9 Rated Performance Curves for C_P Variations Relative to Parent Hull - Linear Random Course

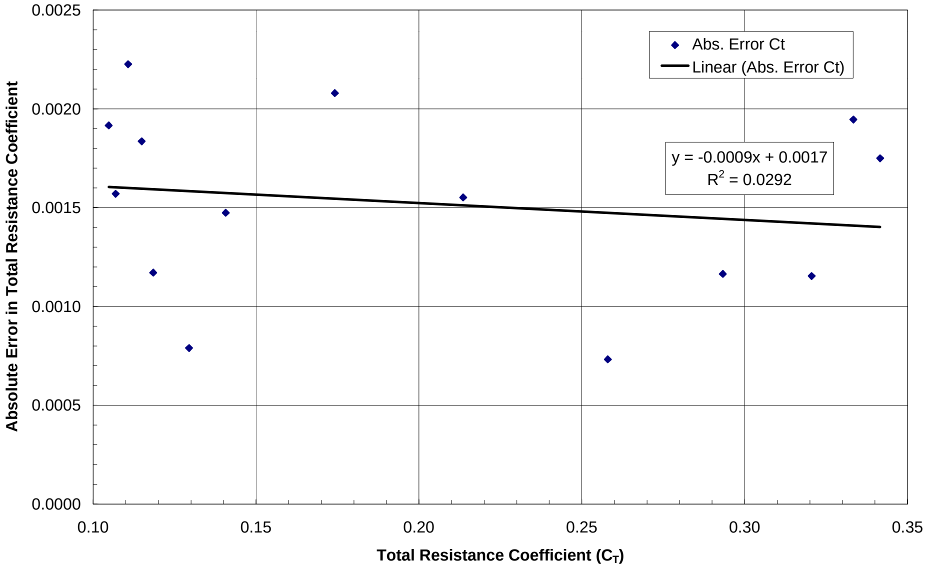

Fig 10 Linear Regression of Absolute Error in Total Resistance Coefficient

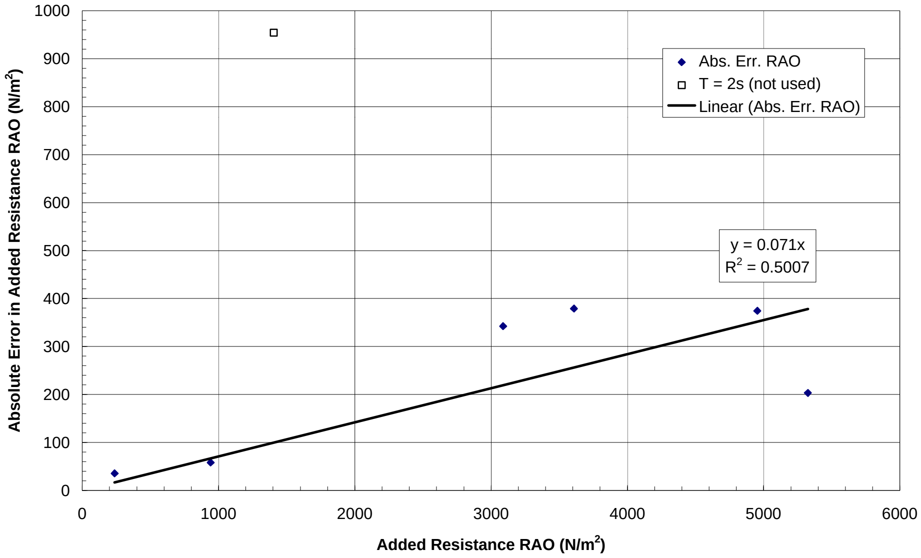

Fig 11 Linear Regression for Absolute Error in Added Resistance RAO

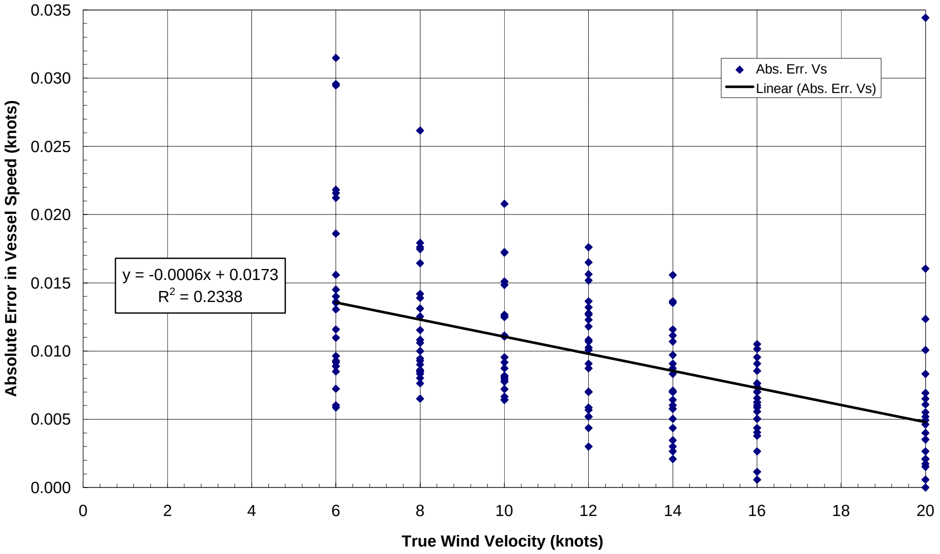

Fig 12 Linear Regression for Absolute Error in Sailing Velocity Versus True Wind Velocity