JAKeuning

Final Report

on

USSA Pitching Moment Project

15 October 1992

by

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ABSTRACT

The final Phase II of the Pitching Moment Project research has been successfully concluded, and the results are presented in a form suitable for inclusion in the VPP to allow for handicapping of effects of both weight distribution, and hull shape factors.

The research has been underway for 3 1/2 years, but by undertaking a step-wise program, provisions existed to make intermediate results available for handicapping, and races have already been run utilizing early results of the program. For example, the 1992 Newport-Bermuda Race sponsored by the Cruising Club of America was scored using experimental certificates which used the Phase I computer modules, and the United States Sailing Association IMS Certificates were modified in June of 1992 to incorporate some provisional seakeeping effects.

In this report, a summary of the development of a prototype measuring machine is presented, the results of improved computer computations to establish parameters of added resistance for a family of yachts are summarized, and these are blended with results[1],[2] of earlier phases of the research to produce a computer code module suitable for direct insertion into the IMS VPP which will allow for the prediction of the effects of added resistance in waves from shape and weight distribution variations.4

The work was accomplished in two Phases;

* Phase I was to investigate feasibility of rating weight distribution variations and to produce handicapping information for use to supplement the VPP, and

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[1]. Kirkman, Karl L., "Progress Report on USYRU Pitching Moment Project", 1 November 1990.

[2]. "Pitching Moment DELR", memorandum report to ITC by Karl L.Kirkman, 15 April 1991.

* Phase II in which a final measurement machine prototype was developed, and a more refined capability to actually represent added resistance in waves was compiled.

In predecessor projects of this type it has been traditional to turn the research results over to rule making bodies for implementation. To the extent that this implementation will require additional technical support from the Project, the Technical Collaborators remain available to assist in this work.

INTRODUCTION

Origin of the Project

In response to the widespread perception that yachts with stripped-out interiors enjoyed an unmeasured speed advantage when racing, a special project was initiated within the United States Sailing Association (USSA), then USYRU, to investigate whether practicable steps could be suggested to rulemakers which might account for this so-called "furniture" effect. The Project, started in 1989, was formed to try to backstop the Accommodation Requirements which were then beginning to be subjected to design pressure. While the Accommodations Requirements had served in a simpler time , the popularity of IMS on an international scale was expected to result in design pressures not present when the IMS was a secondary rule. Indeed, exotic material limitations were introduced into the rule at the same time to serve as a second level of defense against purpose-built racing boats.

Objectives

The pitching moment project was organized to:

"Plan, perform, interpret, report, and archive the necessary research to include the effects of weight distribution in yacht handicapping."

Organization of the Report

This report was written to present both the programmatic and technical aspects of the Pitching Moment Project so that these would be collected in a single reference for future use.

As a result, certain sections will be of more or less interest to readers.

For an overview of the Project, the earlier Sections provide a relatively non-technical summary of the work. However, I hope that the reader will be tempted to plunge into the technical sections in order to gain in understanding of the performance of yachts in waves. Study and comprehension of the technical work could be expected to lead to insight into the ability to sail to top performance levels in these conditions.

ORGANIZATIONAL & OPERATIONAL HISTORY

The project was administered within the Offshore Office of USSA, but with strong organizational support and encouragement from the Cruising Club of America, the International Technical Committee, and the Offshore Racing Council.

The research was conducted primarily by volunteer technical collaborators, but with some funded research performed by outstanding contributors not associated with the various organizations. The expenses were underwritten by contributions by individuals, and organizations. The Offshore Racing Council and the Cruising Club of America supported the work with substantial contributions which were supplemented by those of individual yachtsman. CRAY Research donated a block of computer time to the project. The Partnership for America's Cup technology made available the knowledge from an extensive research program into seakeeping including both computer code development and experiments.

The following individuals were the principal Technical Collaborators in the research:

Richard C. McCurdy
Richard S. McCurdy
John O'Dea
Professor Paul Sclavounos, MIT
James Teeters
Kenneth B. Weller
James A. McCurdy

NON - TECHNICAL SUMMARY

This section is presented so that a lay person can comprehend the magnitude and difficulty of the problem at hand, the general strategy used to attack this problem, the way in which the research will affect race results, and a feel for the uncertainties of the process.

The problem

An individual yacht proceeding to windward through wave action is one of the most complex hydrodynamic systems that scientists are called upon to analyze.

A few of the complex flows which are involved include the interaction of the wave train generated by the translating and pitching hull with incoming seas, the disturbed flows over oscillating keels and rudders undergoing complex motions, and the flow over sails which are moving and changing shape and being subjected to various angles off attack by virtue of flying from a pitching mast.

At the same time, experienced designers have found shapes and weight distributions that go well in waves. Sailors have developed, by trial and error, effective techniques for sailing in waves, a basic instinct as to under what conditions added resistance is important, and a feel for the magnitude of the effects.

This research did not undertake to solve the complete flow situation described above. Rather, we undertook to produce insight from predictions of parts of the problem believed to be important, studied the magnitude of the more complex effects not modeled, and demonstrated that this approach was substantially correct by checking results against the widely accepted notion that yachts tend to sail to slightly less than their calm water VPP predicted boat speeds, but at somewhat wider angles when encountering waves.

Thus, while we are unable to describe many of the complex details of the flows associated with the fully unsteady seakeeping problem we believe that the research is validated by what is known about the prediction of quantitative performance in rough water.

As an example of the kind of data which supports this confidence: Figure 1, shows the following collected on a single graph of boatspeed versus windspeed:

1. IMS target speeds for a particular yacht, <u>Anthem</u>, taken from the IMS certificate.

2. Individual points representing measured boatspeed for the yacht, corrected by an empirical relationship of calm water to rough water boat speed determined from actual sailing data, and resulting in the definition of an experimental "Calm Water VB" relationship.

3. An indication of the magnitude of the expected change in speed due to waves as computed in Phase I of the Project.

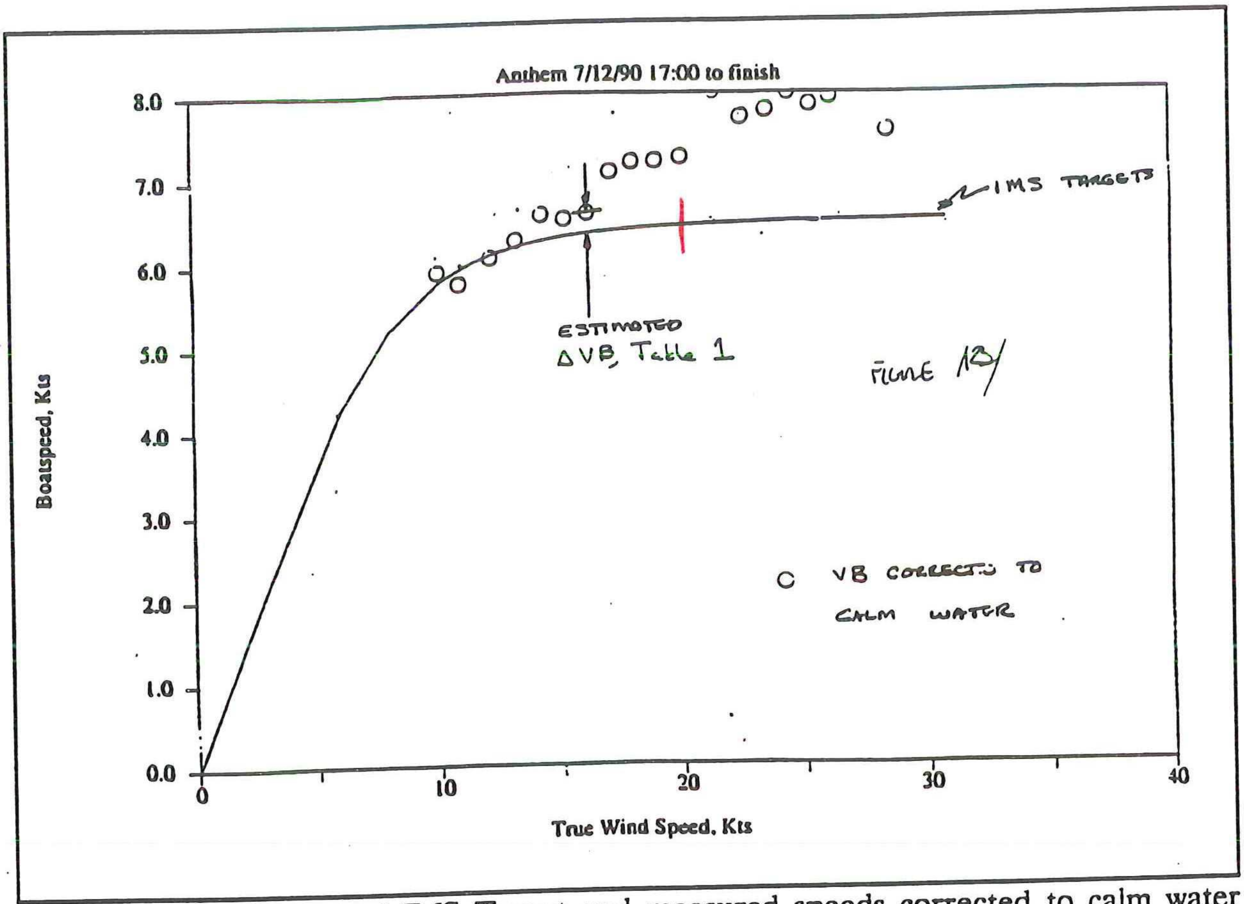

Figure 1 - Comparison of IMS Target and measured speeds corrected to calm water conditions for the yacht Anthem from the 1990 Hampton Race

These sailing data were taken using a Seastate Logger Subsystem (known as the "undulometer" in the Project) developed by OCKAM Instruments/Richard S. McCurdy for the Project. Subsequently, this capability has been made available as a commercial product and used to correct VPP predictions for rough water effects aboard racing yachts. The System, and the experiments summarized in Figure 1 were discussed in more detail in the Phase I Report of November 1990.

Approach

The approach taken was to make certain simplifying assumptions early in the study which are noted immediately below, to collect limited data on race course waves and then to see whether calculations on the simplified basis gave insight into handicapping differences between yachts. In line with the name of the project, the item identified intuitively as the driver to added resistance was weight distribution; "pitching moment"

The important simplifying assumptions made at the outset were:

* "Pitch Moment" character of a yacht could be measured in situ,

* The effects of weight distribution differences on added resistance in waves could be estimated accurately using existing strip theory codes developed for naval ships and a calm water VPP,

* Handicapping could be effective by associating a single wave wind condition with each certificate wind speed

We were not betrayed by any of these assumptions.

The work in Phase I of the Project was concentrated in three areas:

- Development of a practicable measurement experiment,

- Development of a zeroth order code for added resistance in waves, and

- Adjustment to certificate handicapping information to represent wave effects.

That work was completed in winter 1991, and made available to rulemakers at that time. However, the following unresolved issues were identified as requiring additional research:

- The measurement machine was judged to be too expensive for widespread acceptance,

- Provisions did not exist to provide for handicapping of seakeeping effects other than those related to weight distribution, and

- The research had shown poor validation of strip-theory code prediction methods with published experimental results.

As a result a Phase II, reported herein, was undertaken to confront these deficiencies.

In Phase II, the Project:

- Identified and prototyped a minimum cost machine,

- Obtained the results of advanced prediction tools which had been validated by high-quality model tests of yacht hulls, and

- Developed a new added resistance module, DELR2, which could handle hull form as well as weight distribution effects, and could do so in the context of a VPP, rather than off-line handicapping.

The effect on race results

The research when applied to race scoring will be sensitive to two new parameters; the effects of hull shape and weight distribution, and the sea conditions used to estimate added resistance.

The major effects of added resistance are expected to be related to pitch gyradius, and slenderness. Thus, yachts with stripped out accommodations in the ends, and yachts with fine waterline entry angles should be expected to be speeded up by the VPP.

Lesser effects are associated with weight and longitudinal distribution of hull volume. Yachts with extraordinarily large differences in displacement or separation between center of gravity and center of flotation will experience modest speed corrections.

too few

The wave spectra that were determined by buoy measurements to apply to typical race courses show more wave energy in light air conditions than would be associated with the wind alone. The research shows that this is consistent with effects of the wakes of passing vessels, and the immature nature of the waves from increasing winds frequently encountered. However, the consequence to handicapping is that differences in performance of yachts will be substantial in light air even though one not familiar with the wave data might not expect this to be the case.

Uncertainties in Application

Part of any research is to understand the potential weaknesses of the results.

1. A likely uncertainty in applying the research is related to the practical requirement to use a zeroth order code to predict added resistance, and to neglect some complexities of the unsteady flow and dynamics. We believe that the zeroth order approach is robust enough to minimize the opportunity for rule beating for now. If it becomes necessary to introduce a more complex model of performance, the knowledge exists to do so. The ability to blend sailing data rough water effects with VPP predictions such as in Figure 1 should encourage the notion that the simplifying assumptions predict differences correctly, and seem to get approximate magnitudes about right.

2. An additional uncertainty will inevitably arise related to the determination of gyradius values. Until a practicable machine is in hand and we have experience with measuring on a production basis, it is impossible to predict all the possible paths for exploitation, but this must be watched closely so that careful preparation of a yacht for measurement does not allow for manipulation of the gyradius measurement in a manner that defeats the added resistance prediction.

3. At some time, it may be necessary to adjust the assumed wave spectra, and to add off-wind added resistance (which is probably negative) to the VPP prediction scheme to handle surfing performance of lighter yachts. There is no reason to expect that the codes used to date would not predict this aspect of added resistance properly, but no experimental data is in hand to validate such a prediction.

TECHNICAL APPROACH

It has been recognized for a long time that yachts performance in waves was an important discriminator between different hulls; perhaps no better example existed in modern racing experience than the ill-fated America's Cup challenger SCEPTRE which demonstrated horrible performance to windward in waves in the 1958 match. The capability to rate effects of weight distribution has existed, in principle, since the development of computer codes in the 1960's for the estimation of added resistance in waves for yacht forms.

However, certain critical technical deficiencies and practical limitations have discouraged the introduction of this capability into handicapping rules until now:

* The inability to practicably measure minute differences in weight distribution observed to cause major speed effects, and an ignorance about the actual values of weight distribution for existing yachts,

* Lack of data regarding details wave conditions to be expected for typical race courses,

* A lack of validation of seakeeping computer codes for sailing yacht hulls.

On the other hand, it was expected that with certain simplifying assumptions, positive results could be produced, and the Project was undertaken with the following initial assumptions:

* With the developments in modern instrumentation and computer capability, the pitch moment of inertia of a yacht, Iyy, could be measured in the water by a reasonable measuring device.

* Added resistance in waves could be estimated for handicapping purposes by a simple computer model called a zeroth[3] order code, which could be accommodated by the present computer hardware used

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[3]. The term "zeroth" order code is technical shorthand for a code which is based upon using fewer parameters to estimate the added resistance than were necessary to make an estimate of added resistance for a particular hull in even the simplest physically meaningful, or "first" order code. The ability to do this is based upon using the more sophisticated code to estimate the effects on a family of hulls, and then generalizing the effects into a few simple relationships, in much the same manner that standard series of ship models have been used for nearly a century to estimate the resistance of a new hull form.

to produce rating certificates,

* Direct substitution into a VPP of added resistance[4] would provide correct handicapping results; that is, neglecting unsteady effects on the hull and rig,

* Tuning of the response of a yacht to a particular wave spectra would not dominate overall handicapping to the extent that an additional handicapping variable: spectral content, would be required to handle weight distribution effects.

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[4]. In Phase I, an even more restrictive assumption was made and validated: two additional conditions: head seas and upright hull form.

RESEARCH ON MEASUREMENT

The research in this slice was carried out primarily by Richard S. McCurdy.

At the initial planning meeting for the project of March 1989, initial specifications were formulated for a method of "measuring" the pitch moment of inertia of a yacht:

* The measurement would best be accomplished in-the-water in order to allow for confirmation that the yacht was in measurement trim, and to minimize expense,

* It would suffice to measure a "wet" value for moment of inertia, that is including hydrodynamic added mass and damping effects in real time and without reference to hull measurement data,

* The measurement system should be able to detect differences equal to "one man on the bow", an amount perceived by sailors to affect performance in waves by a distinguishable amount,

* The measurement system should include sufficient integral data quality assurance features to minimize the occurrences when remeasurement would be required,

* The target cost of the measurement system was set at less that $5,000.00 [5], with a desire that it be minimized consistent with the other constraints, and

* The pitch motion analysis at the time of measurement could be adequately modeled by a simple damped spring-mass system.

These specifications were satisfied by the machine previously reported by McCurdy[6], and summarized in Reference 1. This measurement system was designated a Pitchometer.

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[5]. This cost was agreed at the ITC meeting in the fall of 1991 to be exclusive of computer hardware on the basis that measurers could be expected to possess a PC-type machine.

[6]. McCurdy, Richard S., " Feasibility Study of the Measurement of the Mass Moment of Inertia in Pitch for Cruiser/Racer Yachts", NESYS, 1990.

Indeed, it was expected that this Pitchometer could be produced in quantity for approximately $3,000.00.

However, concern that the cost impact of making such a machine available to each measurer arose after completion of this development. Accordingly, the project then spent significant effort attempting to identify a less costly system. In particular, development of micro-electronic based instrumentation was investigated based upon preliminary indications that such a system might be produced in quantity for a fraction of the cost, ex development costs.

Unfortunately, this advanced technology turned out to be insufficiently mature at the time for introduction.

For Phase II, a number of alternative Pitchometers were surveyed, and a concept selected for refinement which was designated Mark IIB. This configuration is shown in schematic form in Figure 2. The upper portion of the Figure shows the setup for longitudinal inclining, and the lower portion the setup for dynamic pitching.

Prototyping of this Pitchometer concept was undertaken in Spring 1992 to the following specification:

* Based upon simple damped spring mass system with chirped frequency variable,

* Heave motion ignored (based upon experience from Phase I research),

* Traditional longitudinal inclining to get pitch stiffness was introduced,

* Pitch motion time history was assumed sufficient, and force at time of release was deleted from system,

* Error budget considerations indicated that inclining weights should be measured on an electronic digital scale. Water bags were proposed to deal with larger weights necessary to longitudinally incline large yachts,, and the ability to accomplish transverse inclining using same system was provided.

McCurdy then developed such a machine based upon an inclinometer utilizing the instrument meter balance principle, and

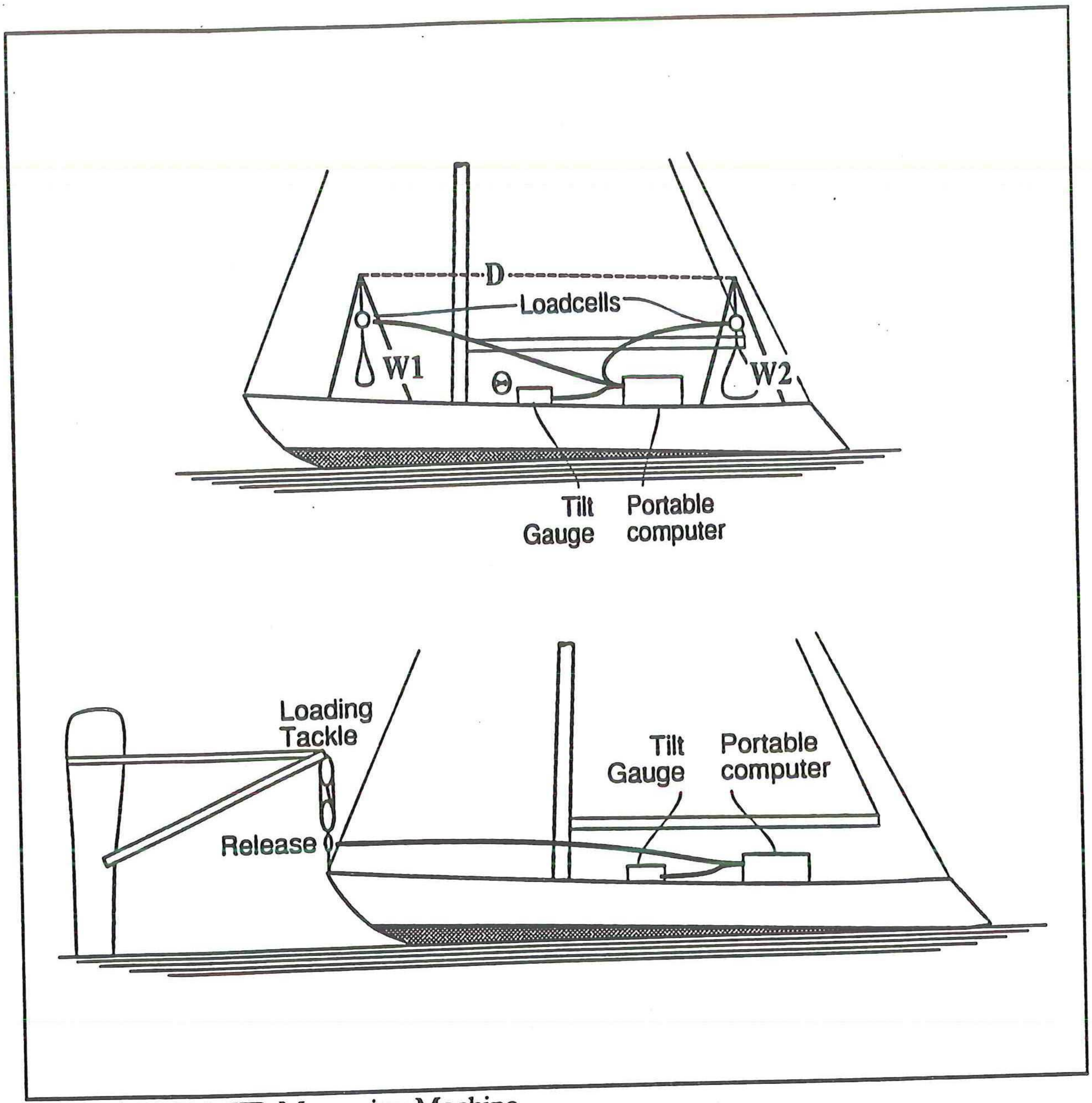

Figure 2 - Mark IIB Measuring Machine

delivered this machine to the Chief Measurer for evaluation in August 1992. Since that time, the USSA Staff has begun evaluating the machine and the measuring process associated with it. That evaluation and refinement process is explored in more detail in a later section of this report.

In cooperation with PACT, experiments were conducted at the University of Michigan Towing Tank by Cohen and Beck using a carefully ballasted and instrumented model of an IACC yacht model under test by PACT for other research. The purpose of these experiments was to provide data which exactly emulated a pitchometer output signal so that advanced computer prediction codes developed by Sclavounos could be utilized to validate the assumption that a gyradius could be extracted from the pitchometer output. The results of this analysis, presented by Scalvounos[7] to the ITC at the fall 1992 meeting indicate that the Pitchometer signal can indeed be translated accurately to a value of gyradius for the yacht. Figure 3 shows a comparison of the predicted and measured time history of pitch angle as presented by Scalvounos. In fact, additional research and development of signal processing has already been investigated which promises to allow extraction of the gyradius value. In practice, this more elegant processing is expected to be made a part of the processing of data for production of sa certificate by the national authorities rather than being embedded into the Pitchometer software, but the validity of the Pitchometer assumptions is confirmed by the result shown.

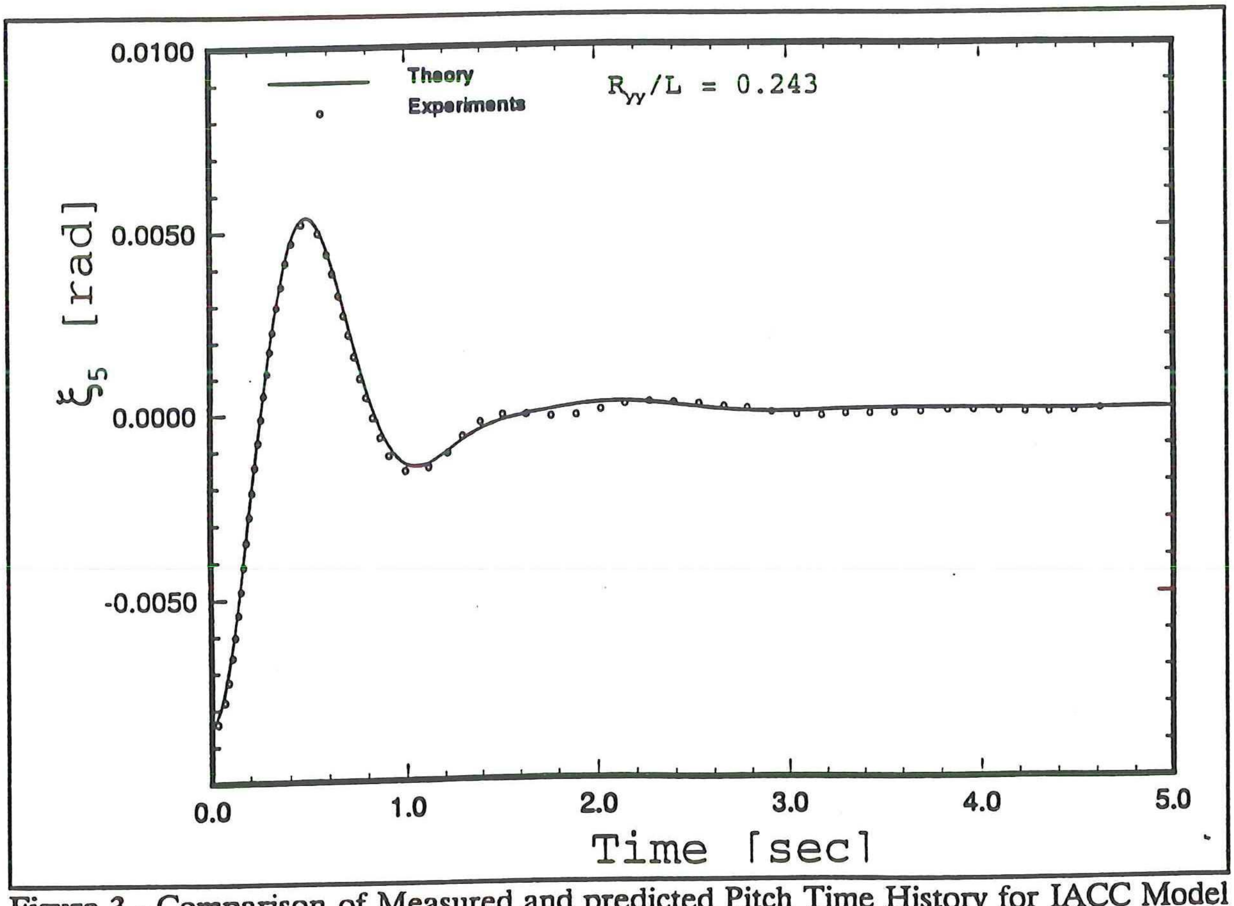

Figure 3 - Comparison of Measured and predicted Pitch Time History for IACC Model

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[7] Sclavounos, Paul D., "Radius of Gyration Identification from Pitch Decay Measurement and Theory", ITC, 25 September 1992.

RESEARCH ON ADDED RESISTANCE

The research in this area was primarily conducted by Professor Paul Sclavounos, of MIT, and James Teeters. However, significant credit must go to PACT for important underlying fundamental research including both experiments and estimating methods. Professor Sclavounos briefed the ITC in detail on his work at the September 1992 meeting, and the technical details of his work will be reported[8] at the forthcoming 1993 CSYS.

At the submission of the report on Phase I of the research, the need to pursue added resistance calculations with more advanced techniques was identified as requiring further research. This conclusion was based upon the poor level of correlation between published model test data on added resistance and "strip theory" codes for estimating added resistance; the predictions did not agree with the model data, but even more important, the discrepancies changed with hull type.

SWAN validatie nu wel? gedaan

This situation led us to suspect that any prediction involving hull form differences would be questionable, and the DELR module presented at that time was suited only for predicting the effects of a weight distribution change for a yacht.

Fortunately, the Partnership for America's Cup Technology (PACT) chose to make seakeeping one of it's priority projects for research, and the results of this research are now available for handicapping purposes.

PACT choose to foster development of advanced seakeeping prediction methods by pursuing both 2-D and 3-D codes, and by providing experimental data on motions and added resistance of a yacht hull conducted to a very high standard of experimental uncertainty.

AC boat

Professor Sclavounos then utilized one of these codes: SWAN, to perform a parametric study of added resistance for an IMS base

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[8]. Sclavounos, Paul D., and Nakos, D.E., " Seakeeping and Added Resistance of IACC Yachts by a Three-Dimensional Panel Method", to be presented t at CSYS 1993.

boat, Figure 4, and presented the results of that study to the ITC[9] at the Fall meeting in Newport.

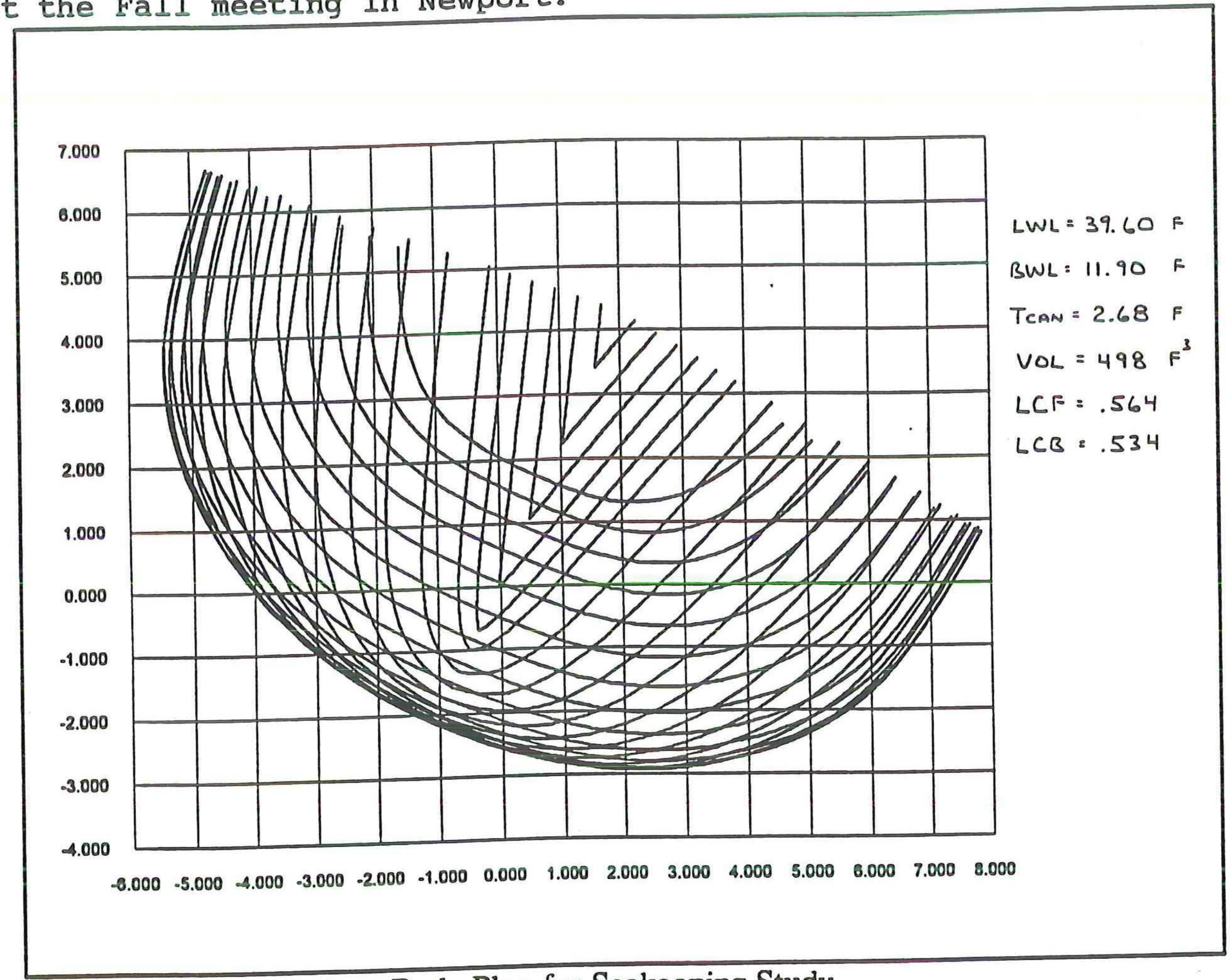

Figure 4 - IMS Base Boat Body Plan for Seakeeping Study

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daan?

His work consisted of performing exploratory calculations on the base hull to identify a set of parameters which dominated the added resistance of the type, and then conducting computations for systematic variations of Length-Beam Ratio (L/B), Figure 5, Displacement-Length Ratio, Figure 6, Longitudinal Center of Buoyancy Location (LCB), Figure 7, Longitudinal Center of Flotation Location (LCF), Figure 8, and gyradius, Figure 9.

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[9] Sclavounos, Paul D., " Parametric Study of Added Resistance of IMS-40 Base Boat with 3-D Panel Code SWAN ", ITC, September 1992.

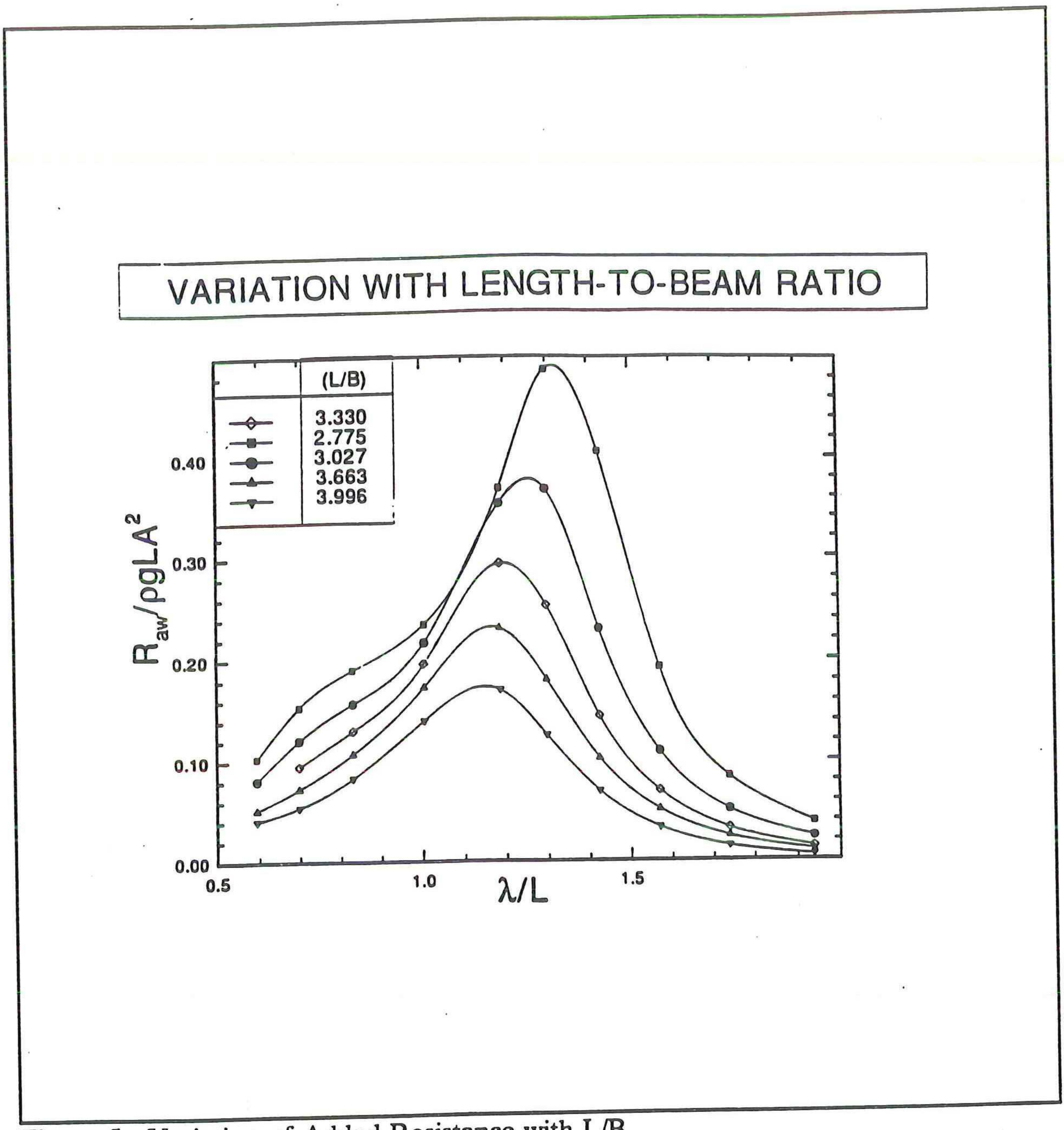

Figure 5 - Variation of Added Resistance with L/B

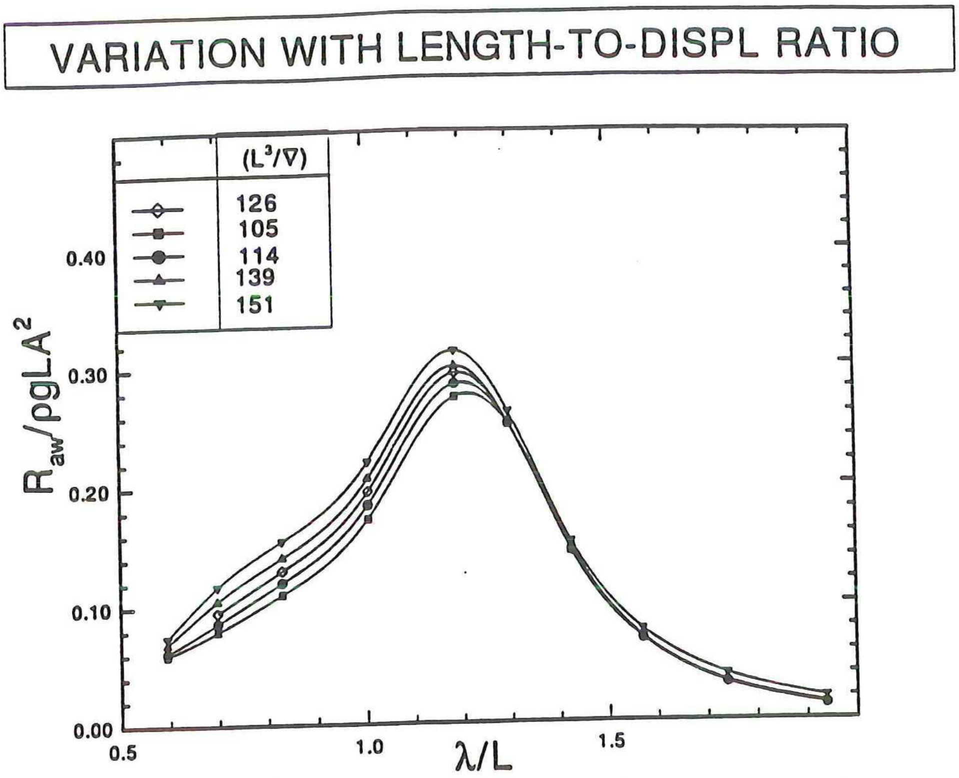

Figure 6 - Variation of Added Resistance with Length-Displacement Ratio.

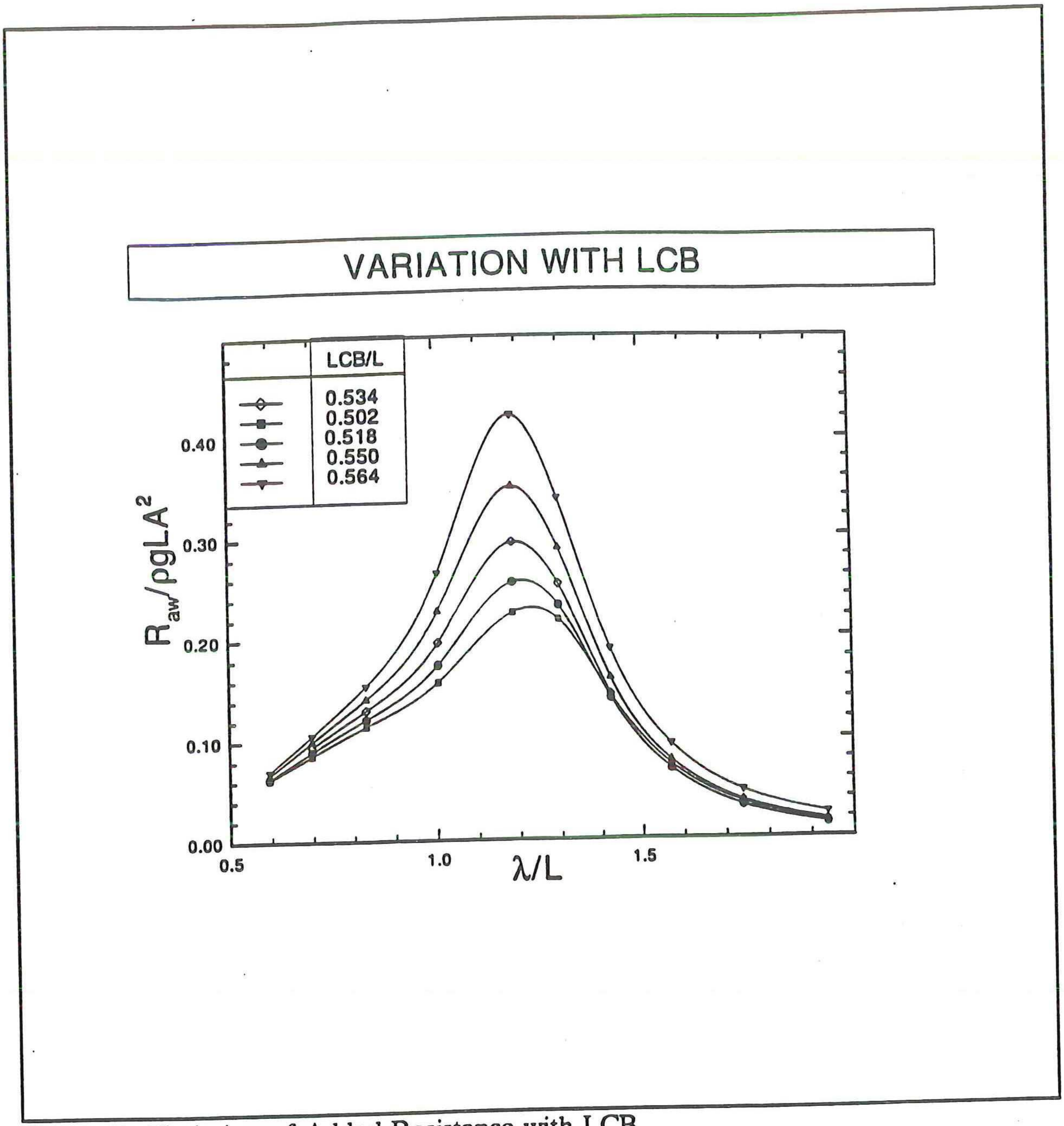

Figure 7 - Variation of Added Resistance with LCB

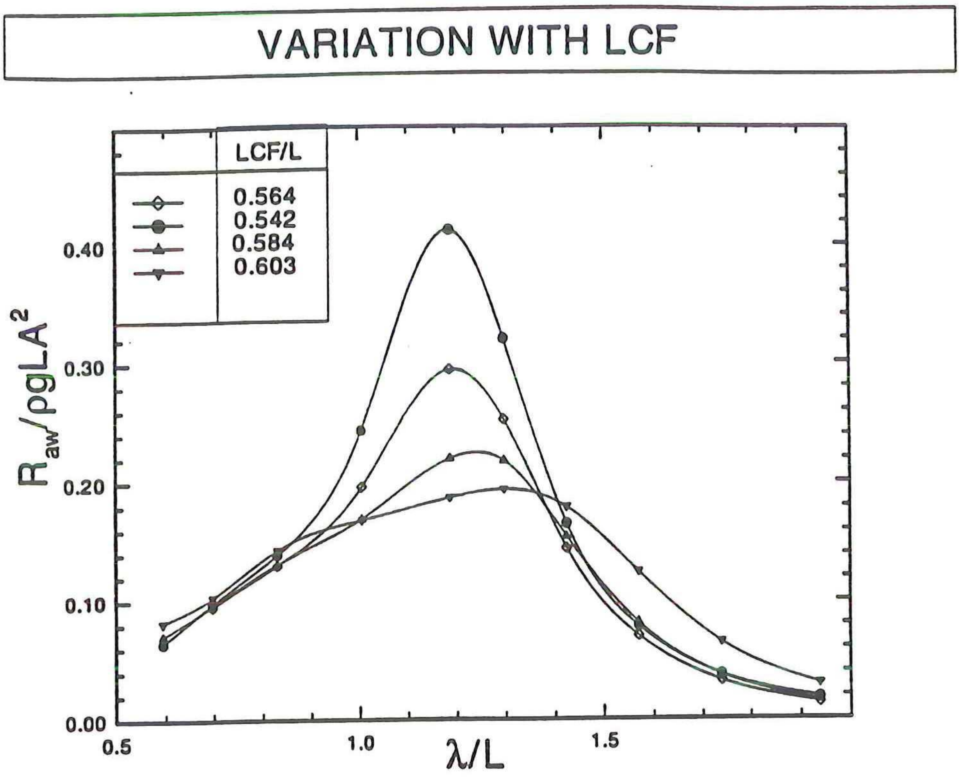

Figure 8 - Variation of Added Resistance with LCF

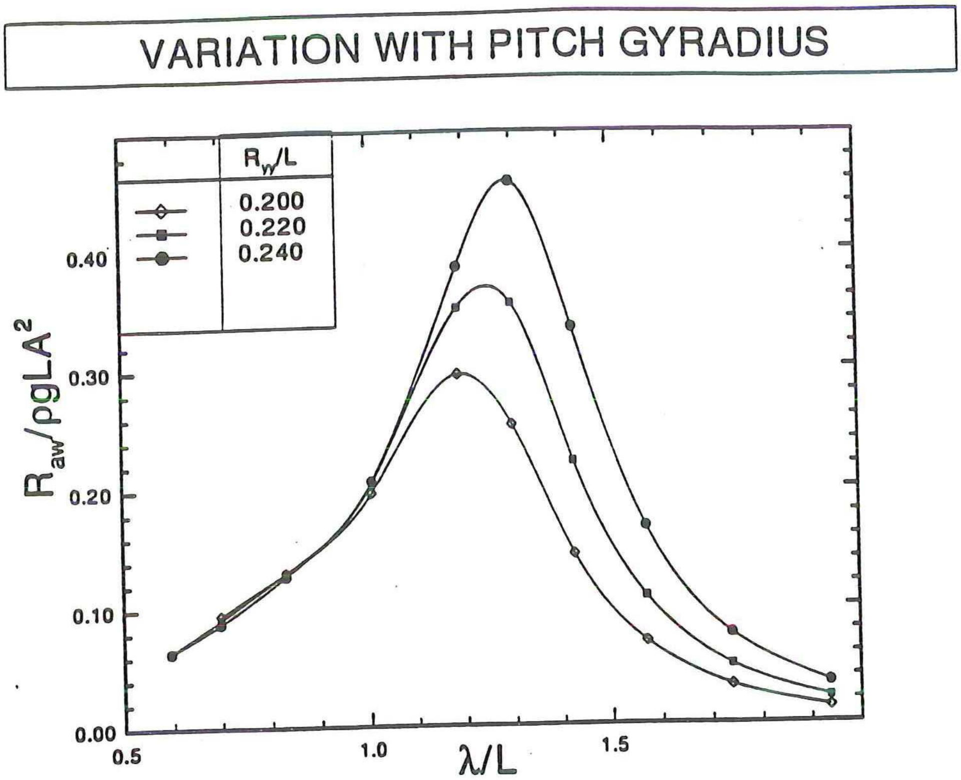

Figure 9 - Variation of Added Resistance with Gyradius

These sensitivities were then used as described next to produce an implementation of the added resistance estimator in the VPP.

At the same time that he produced the hull form and weight distribution sensitivities, Sclavounos also provided[10] sensitivity data for added resistance with forward speed, and as a function of heading relative to the waves. These were also incorporated by Teeters as described below.

At the outset of this discussion of adding seakeeping to the existing VPP, it should be noted that there exists within the present VPP resistance formulation some sort of accounting for added resistance in waves, albeit in an implicit form.

In support of this notion recall that:

* The target speeds produced by the VPP match sailing experience sufficiently well to be useful in tuning and monitoring performance, and

* Attempts to compare model test resistance data with VPP predictions for the same hulls have consistently shown that the VPP overpredicts calm water resistance.

Examples of this difference are shown in Figure 10 for a 12-Meter and Figure 11 for a cruiser/racer.

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[10]. Sclavounos, Paul, letter report dated 1 October 1992.

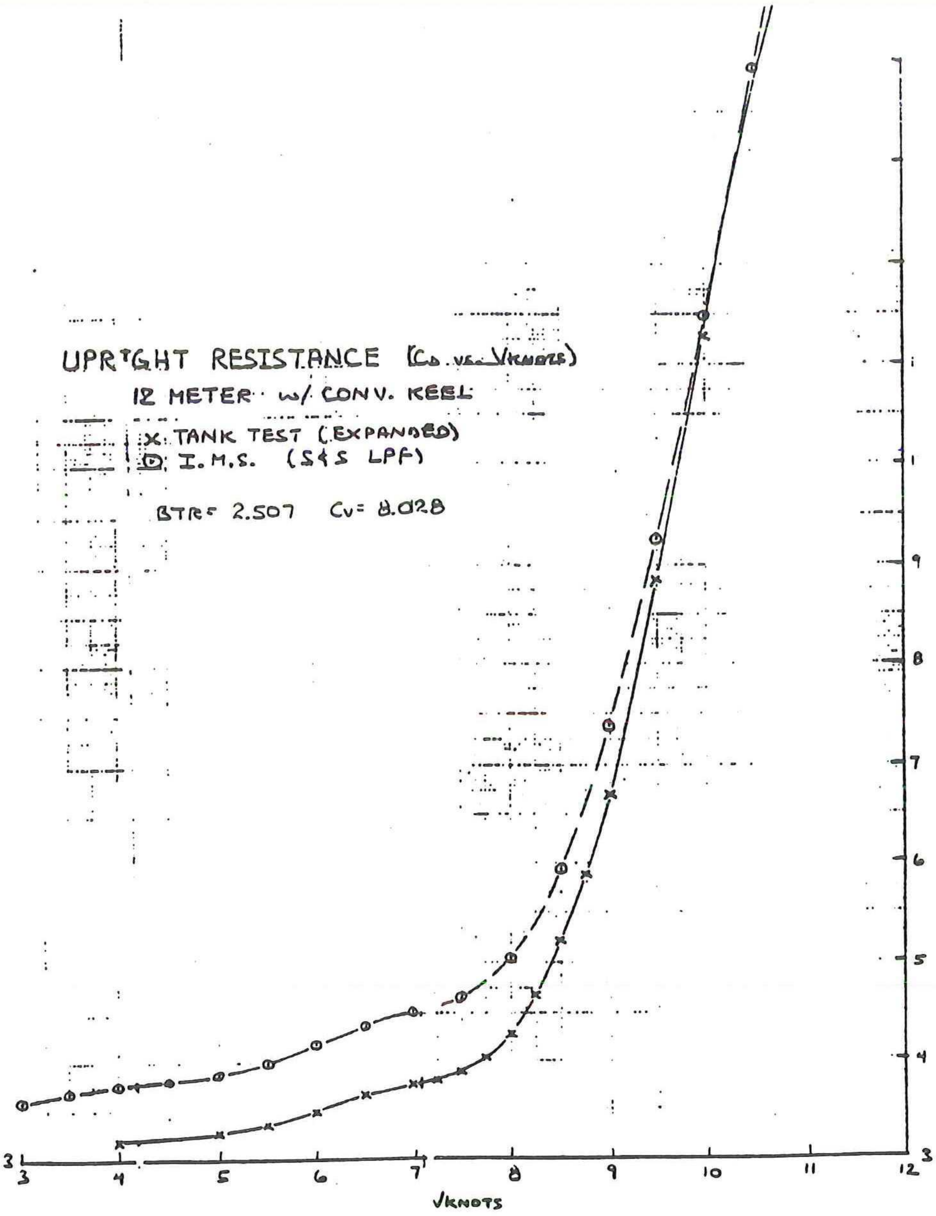

Figure 10 - Measured and Predicted Resistance for 12-Metre

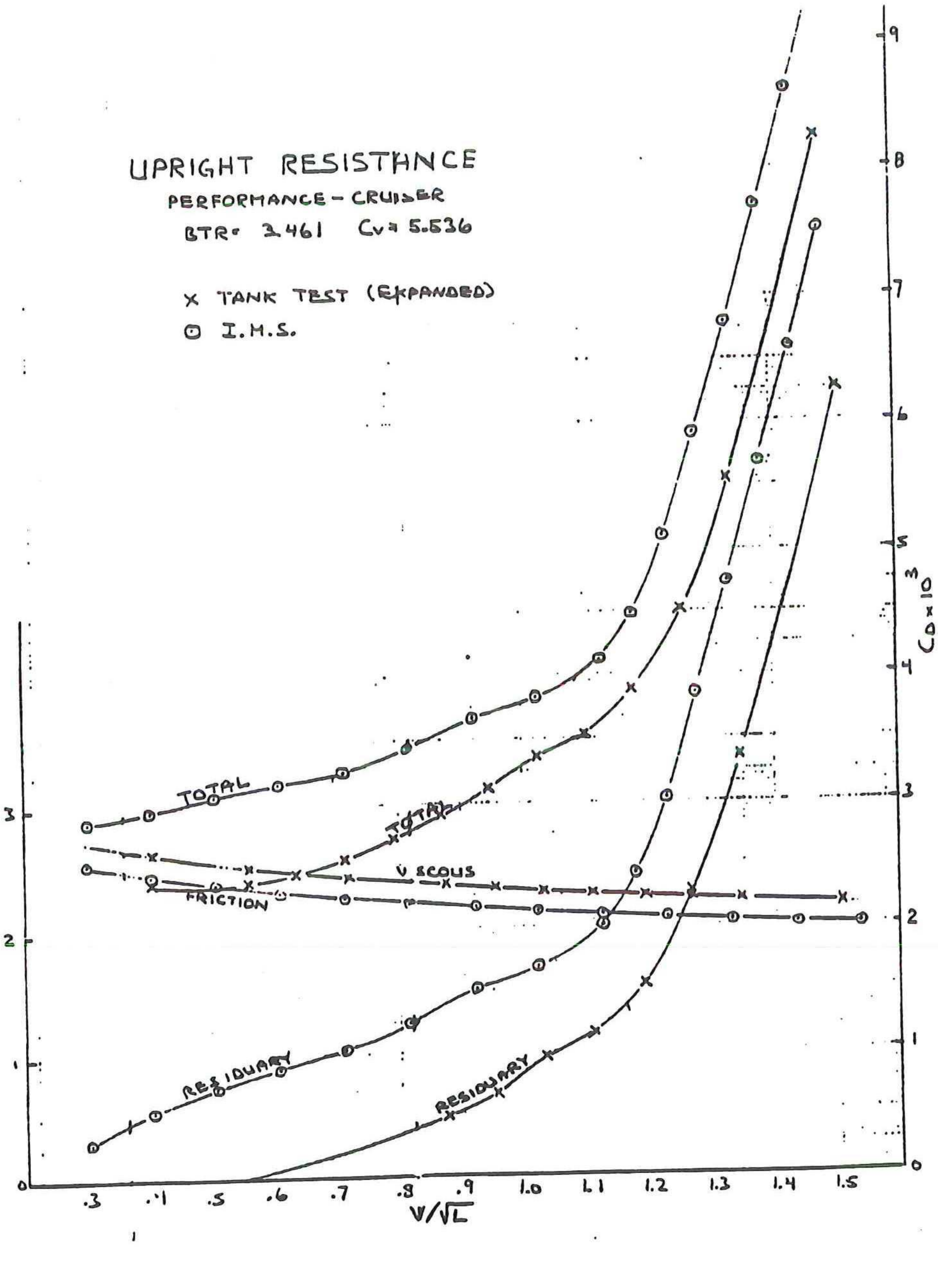

Figure 11 - Measured and Predicted Resistance for Cruiser/Racer

It should also be noted that one of the reasons that Phase I results were produced in the form of time allowance differences was known inadequacies in the VPP resistance formulation, and an expressed concern at that time that the imposition of a new component of resistance into the VPP directly would destroy the apparent utility of the target speeds in use. It was expected that these might be rectified by the time Phase II results were available by improvements in the VPP calm water resistance formulation, but this has proven to be an optimistic assumption.

Accordingly, the DELR2 code presented herein is structured to be used in a difference mode at the outset, but can also be used to predict a quantitative value of added resistance at such time as the calm water problems alluded to above are solved.

It is equally important to appreciate that the DELR2 code required as input information values of hull form parameters calculated in the heeled condition. This meant that implementation was paced by producing a version of the LPP which could compute heeled values, but this improvement was vital to improving the calm water formulation in any event.

In DELR2, Teeters has produced[11] a linearized implementation of the results calculated by Sclavounos. He has constructed a model for added resistance which utilizes 5 slope coefficients for the added resistance terms: pitch gyradius, length-beam ratio, displacement-length ratio, LCB, and LCF. The formulation is set up to use at the outset differences from a conceptual base boat, but can be used with the base boat values set to zero to predict the quantitative added resistance. In addition, Teeters has formulated fits for speed effects and heading effects.

Figures 12 through 16 show the computed values and linear fits as derived by Teeters for the five parameters.

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[11]. Teeters, James, " Implementation Study of Added Resistance for IMS Handicaps", ITC, September 1992.

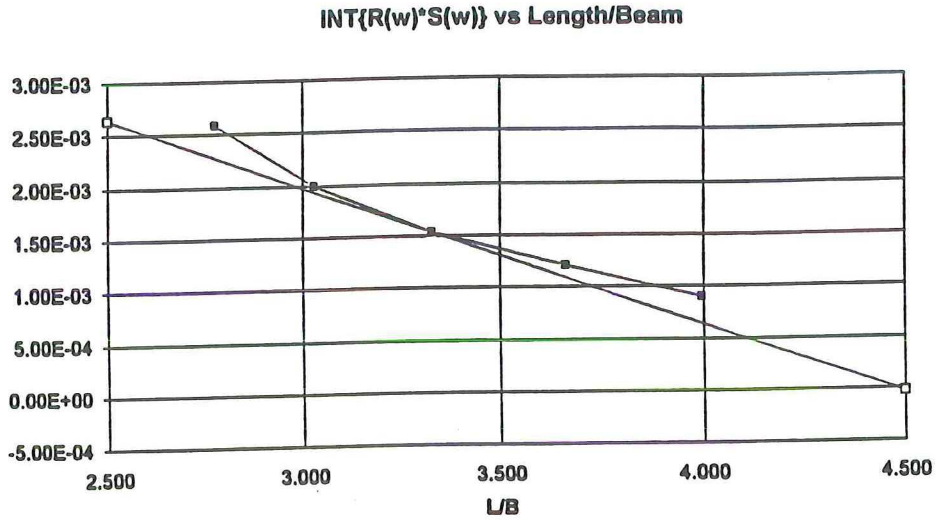


Figure 12 - Computed Values and Linear Fit for L/B

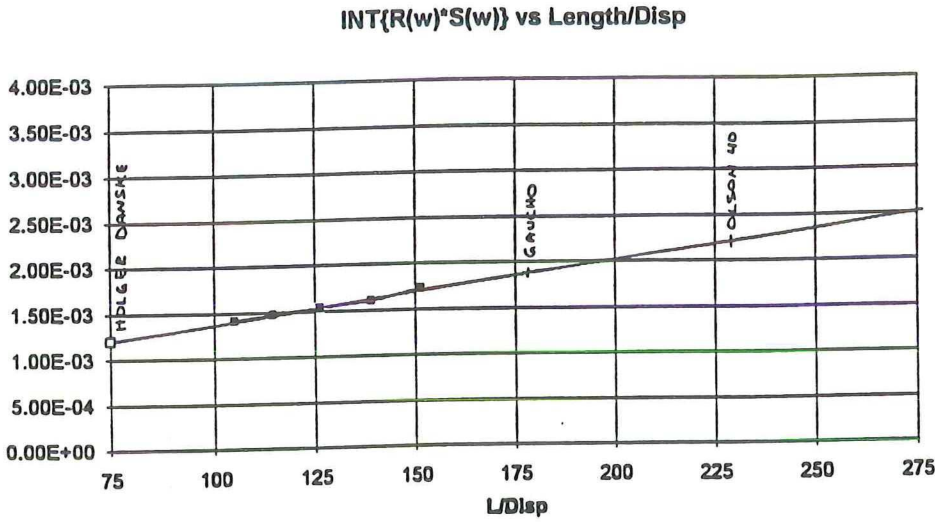


Figure 13 - Computed Values and Linear Fit for Length-Displacement Ratio

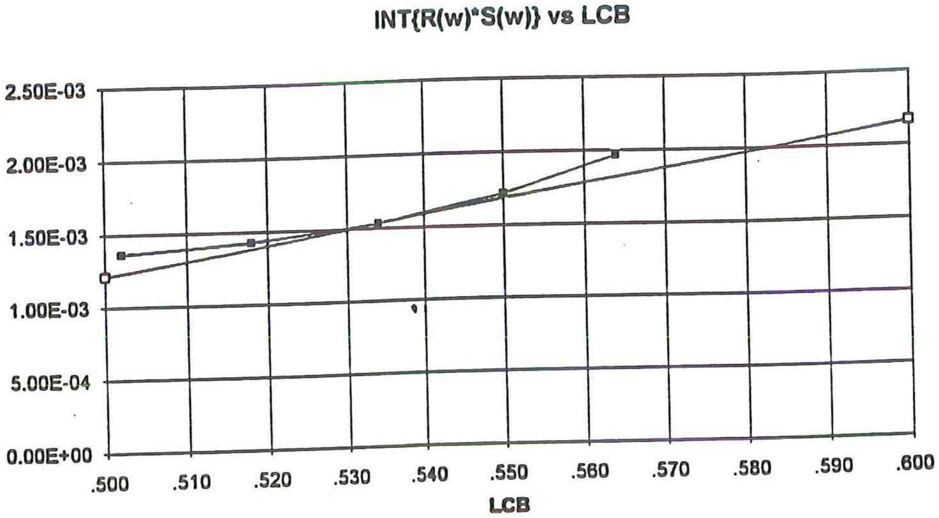


Figure 14 - Computed Values and Linear Fit for LCB

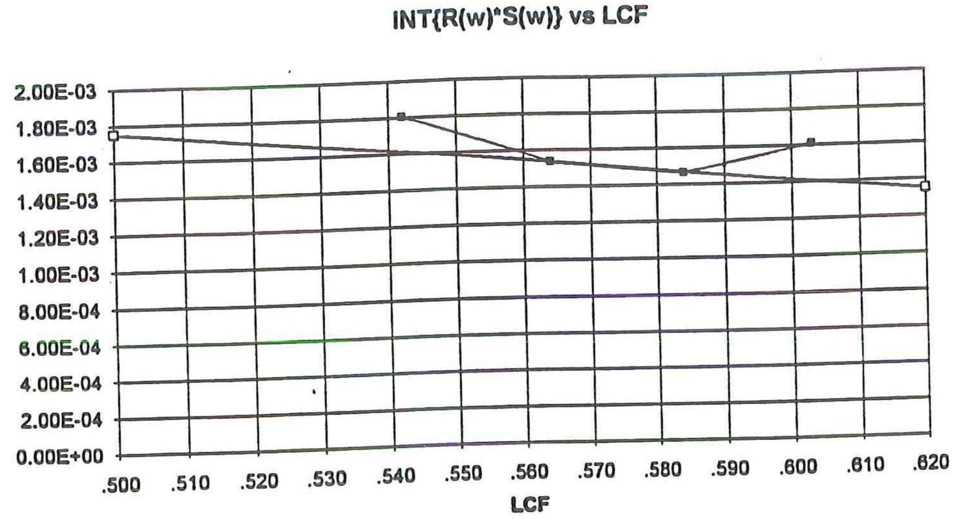


Figure 15 - Computed Values and Linear Fit for LCF

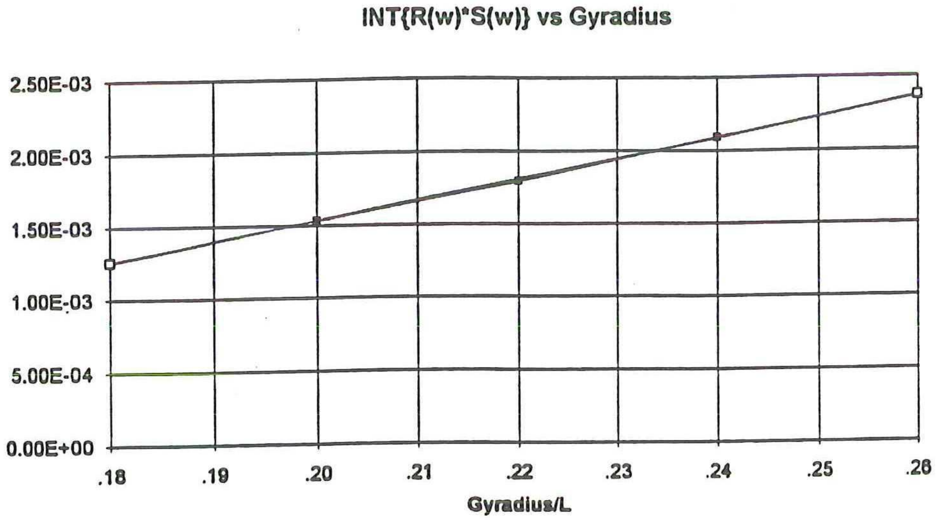
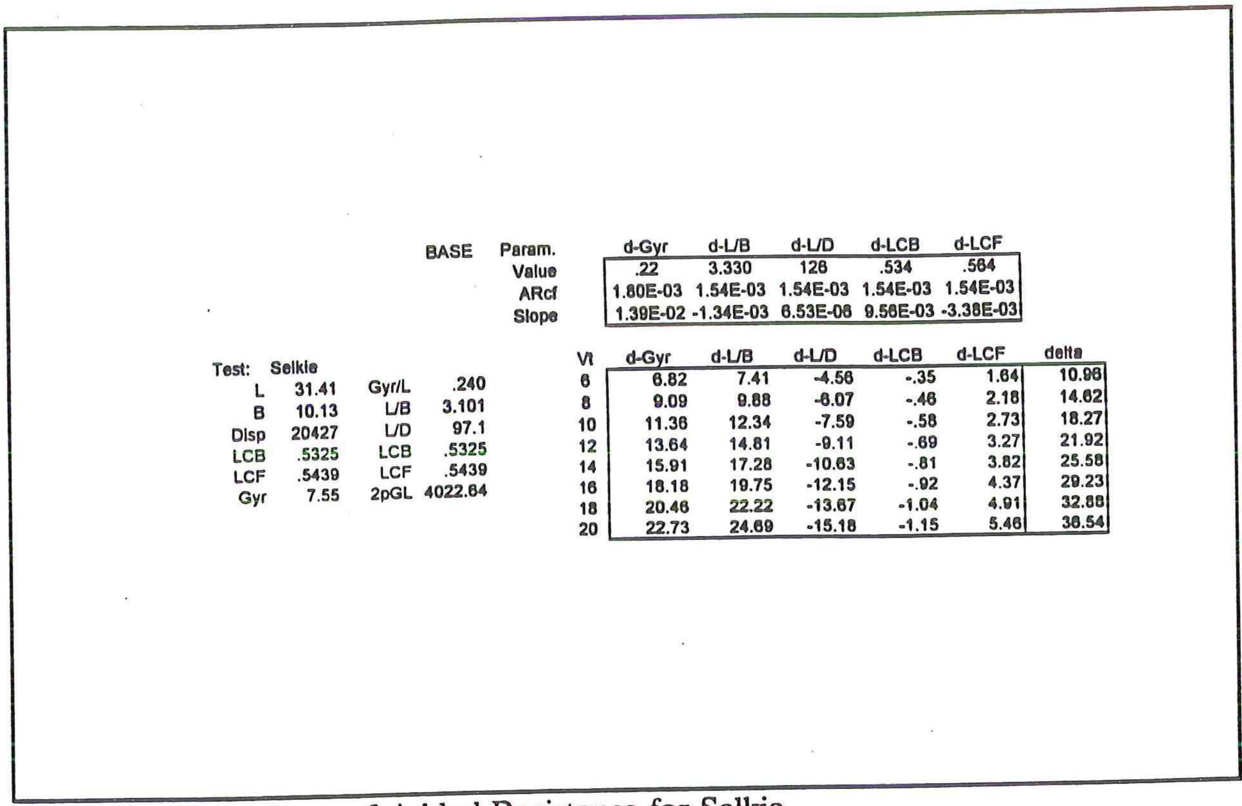


Figure 16 - Computed Values and Linear Fit for Gyradius

For a sample yacht: Selkie, Figure 17 shows a breakdown of the added resistance components relative to a base boat for a range of wind speeds. In this case, Selkie would be expected to have 18.27 pounds of added resistance more than the base boat in 10 knots of VTW, of which the largest components arise because of her assumed gyradius and her length-beam ratio, L/B.



BASE Param.	d-Gyr	d-L/B	d-L/D	d-LCB	d-LCF
Value	.22	3.330	126	.534	.564
ARcf	1.80E-03	1.54E-03	1.54E-03	1.54E-03	1.54E-03
Slope	1.39E-02	-1.34E-03	6.53E-06	9.56E-03	-3.38E-03

Test:	Selkie		
L	31.41	Gyr/L	.240
B	10.13	L/B	3.101
Disp	20427	L/D	97.1
LCB	.5325	LCB	.5325
LCF	.5439	LCF	.5439
Gyr	7.55	2pGL	4022.64

Vt	d-Gyr	d-L/B	d-L/D	d-LCB	d-LCF	delta
6	6.82	7.41	-4.56	-.35	1.64	10.96
8	9.09	9.88	-6.07	-.46	2.18	14.62
10	11.36	12.34	-7.59	-.58	2.73	18.27
12	13.64	14.81	-9.11	-.69	3.27	21.92
14	15.91	17.28	-10.63	-.81	3.82	25.58
16	18.18	19.75	-12.15	-.92	4.37	29.23
18	20.46	22.22	-13.67	-1.04	4.91	32.88
20	22.73	24.69	-15.18	-1.15	5.46	36.54

Figure 17 - Breakdown of Added Resistance for Selkie

In contrast, a yacht like Gaucho might be expected to have less added resistance than the base boat, assuming a low gyradius, and a low length-beam ratio when heeled. Her example is shown in Figure 18 for a hypothetical set of lines, where it is indicated that she might have 10.16 pounds less added resistance that the base boat in 10 knots VTW.

BASE Param.	d-Gyr	d-L/B	d-L/D	d-LCB	d-LCF
Value	.22	3.330	126	.534	.564
ARcf	1.80E-03	1.54E-03	1.54E-03	1.54E-03	1.54E-03
Slope	1.39E-02	-1.34E-03	6.53E-06	9.56E-03	-3.38E-03

Test:	Gaucho
L	37.85
B	10
Disp	19382
LCB	.5818
LCF	.6015
Gyr	7.57

Gyr/L	.200
L/B	3.785
L/D	179.1
LCB	.5818
LCF	.6015
2pGL	4847.4

Vt	d-Gyr	d-L/B	d-L/D	d-LCB	d-LCF	delta
6	-8.07	-17.71	10.07	13.29	-3.68	-6.10
8	-10.76	-23.61	13.43	17.72	-4.91	-8.13
10	-13.45	-29.52	16.79	22.15	-6.14	-10.16
12	-16.14	-35.42	20.15	26.58	-7.36	-12.19
14	-18.83	-41.32	23.50	31.01	-8.59	-14.22
16	-21.51	-47.23	26.86	35.44	-9.82	-16.25
18	-24.20	-53.13	30.22	39.87	-11.04	-18.29
20	-26.89	-59.03	33.58	44.30	-12.27	-20.32

Figure 18 - Breakdown of Added Resistance for Gaucho

The corrections shown above are for the case of head seas, and a nominal speed. Teeters then has produced correction factors to apply to these figures to allow for the actual boat speed and heading from the VPP solution.

In order to provide for these features, Sclavounos provided additional calculations as a function of wave heading for three Froude Numbers, Figures 19 - 21, and for different Froude Numbers at fixed headings, Figures 22 - 25.

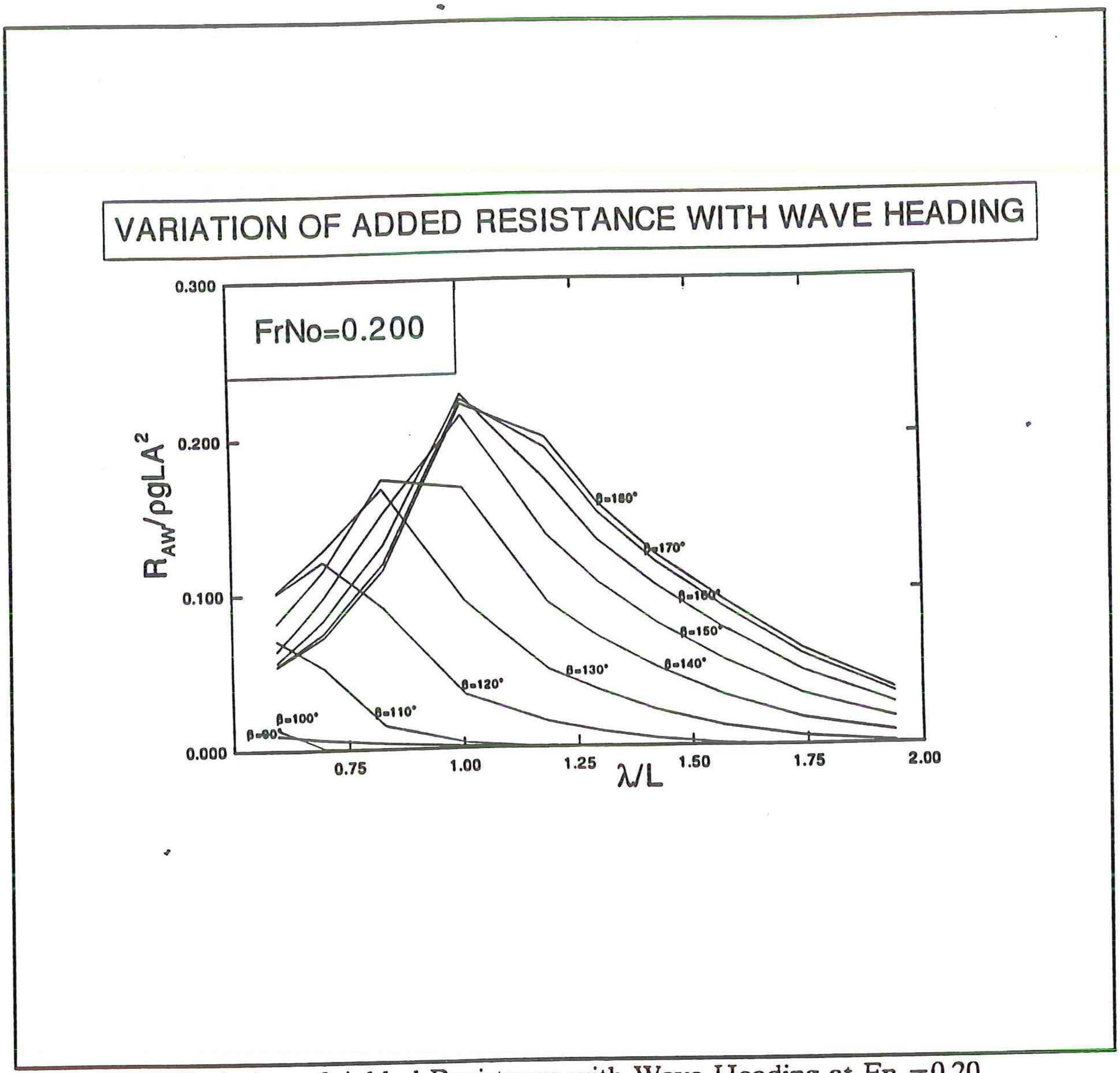


Figure 19 - Variation of Added Resistance with Wave Heading at Fn =0.20

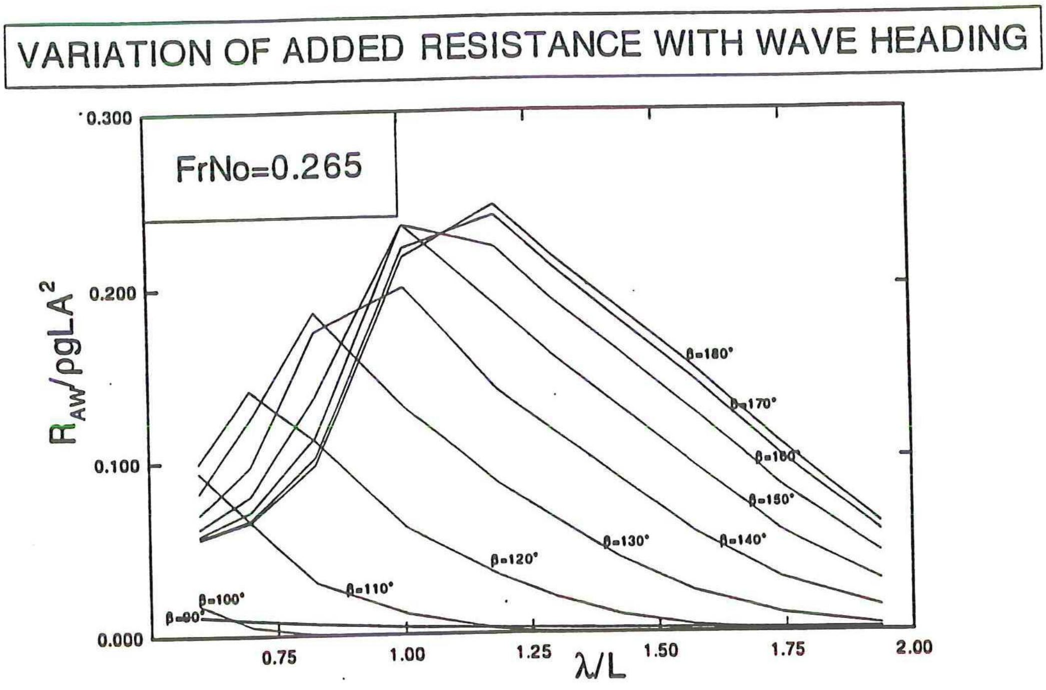


Figure 20 - Variation of Added Resistance with Wave Heading for Fn =0.265

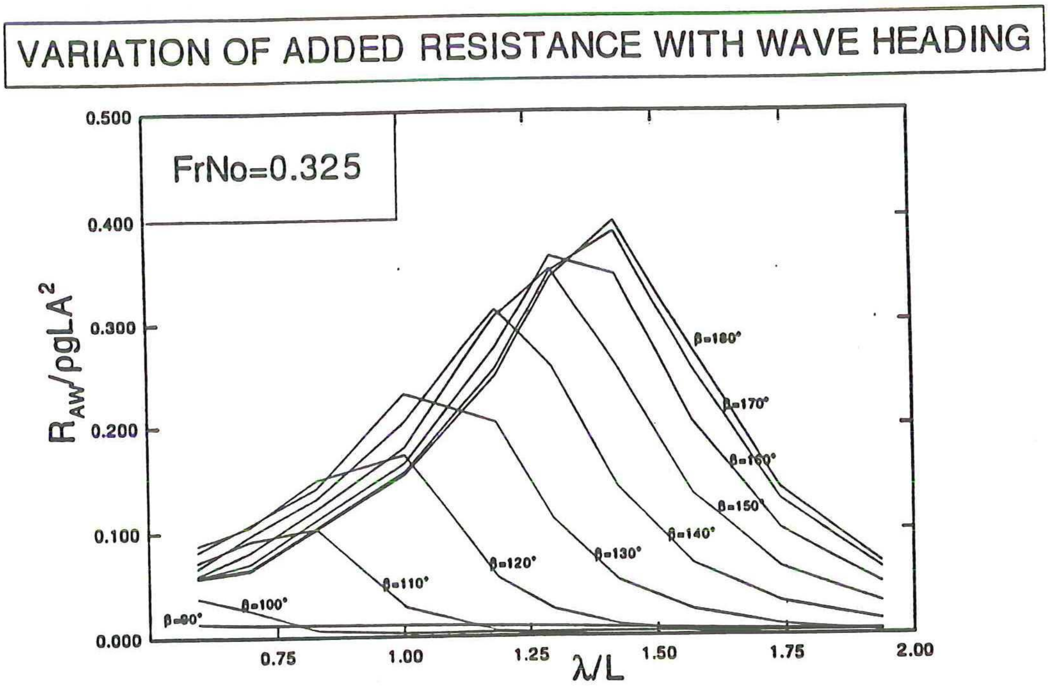


Figure 21 - Variation of Added Resistance with Wave heading for Fn =0.325

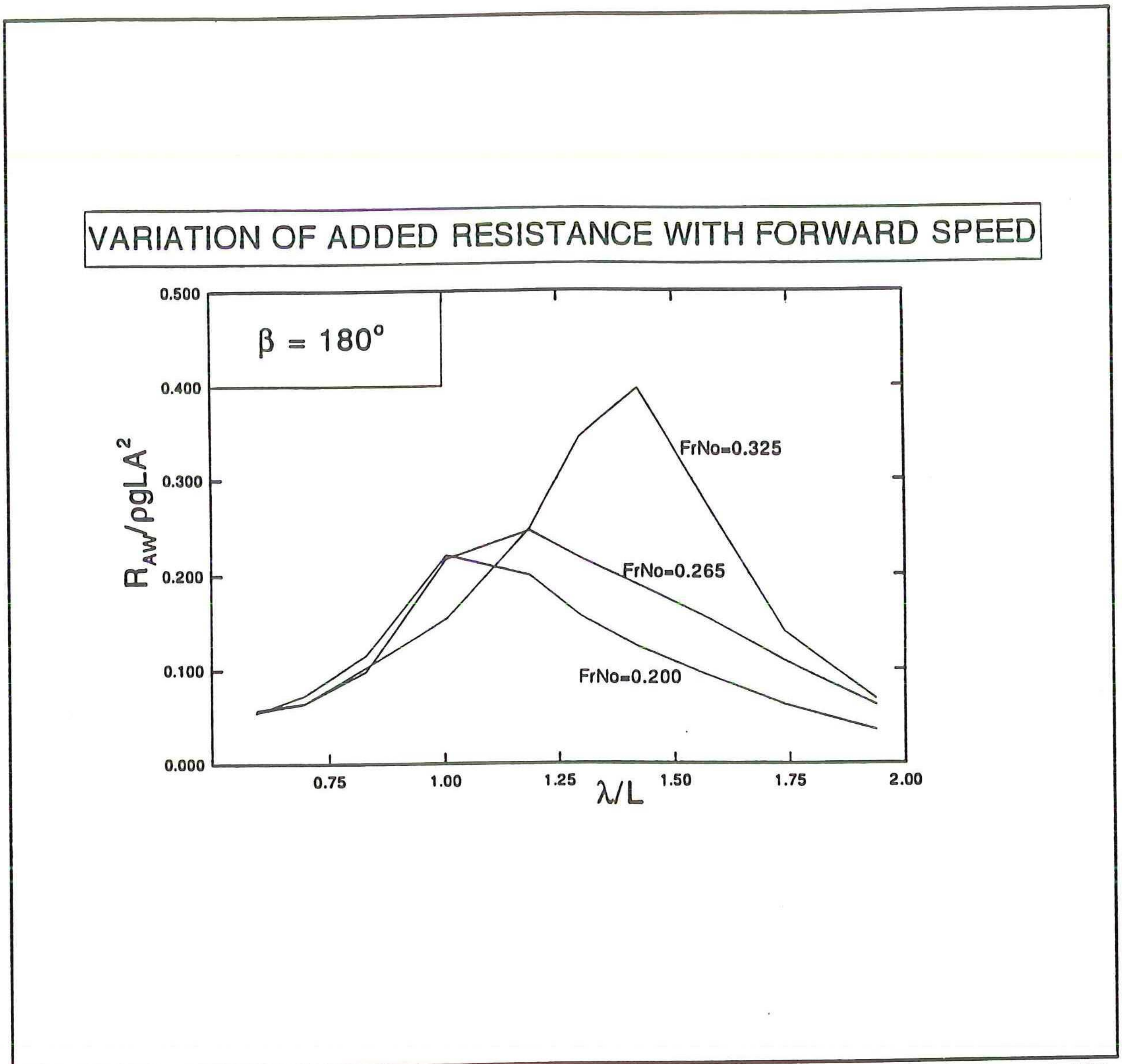


Figure 22 - Variation of Added Resistance with Forward Speed for Heading of 180-degrees

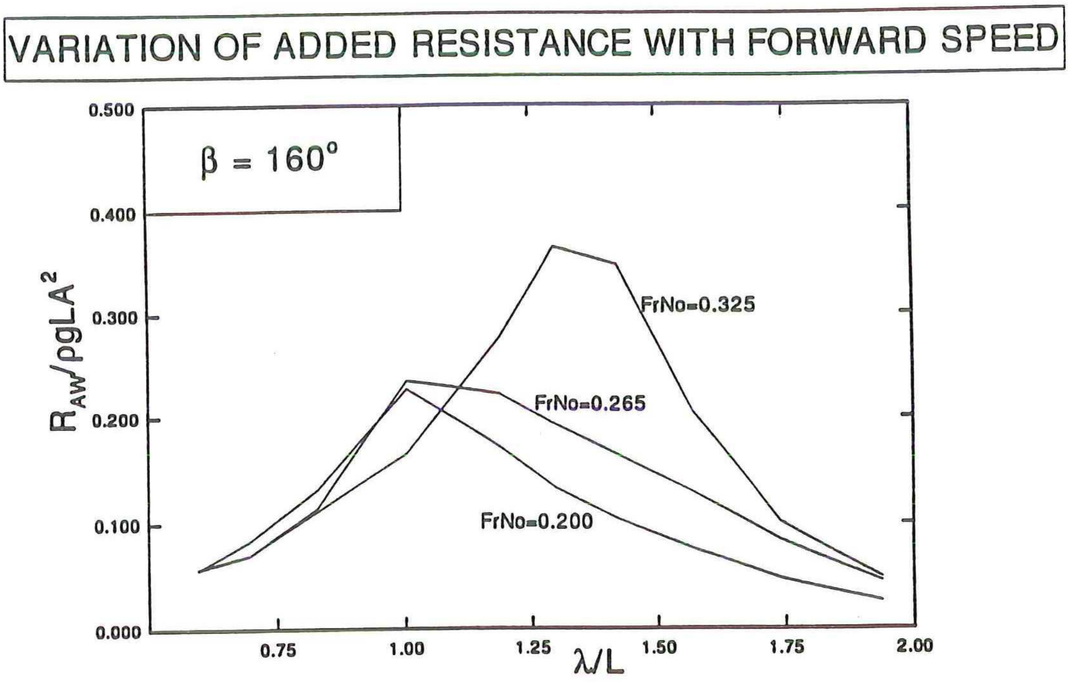


Figure 23 - Variation of Added Resistance with Forward Speed for Heading of 160-degrees

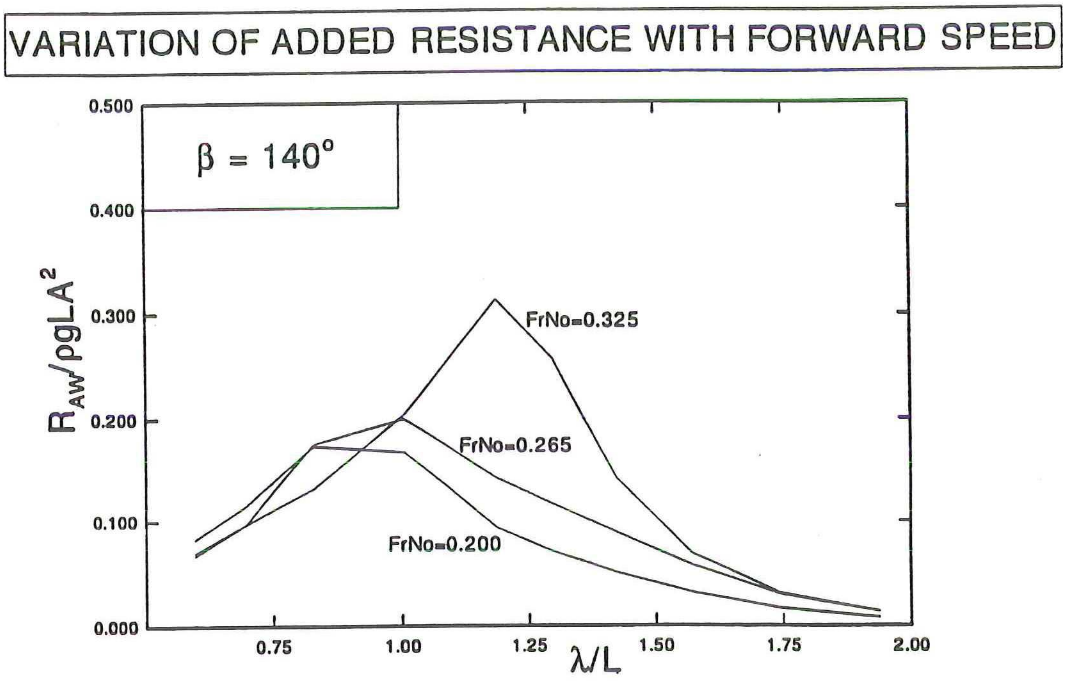


Figure 24 - Variation of Added Resistance with Forward Speed for Heading of 140-degrees

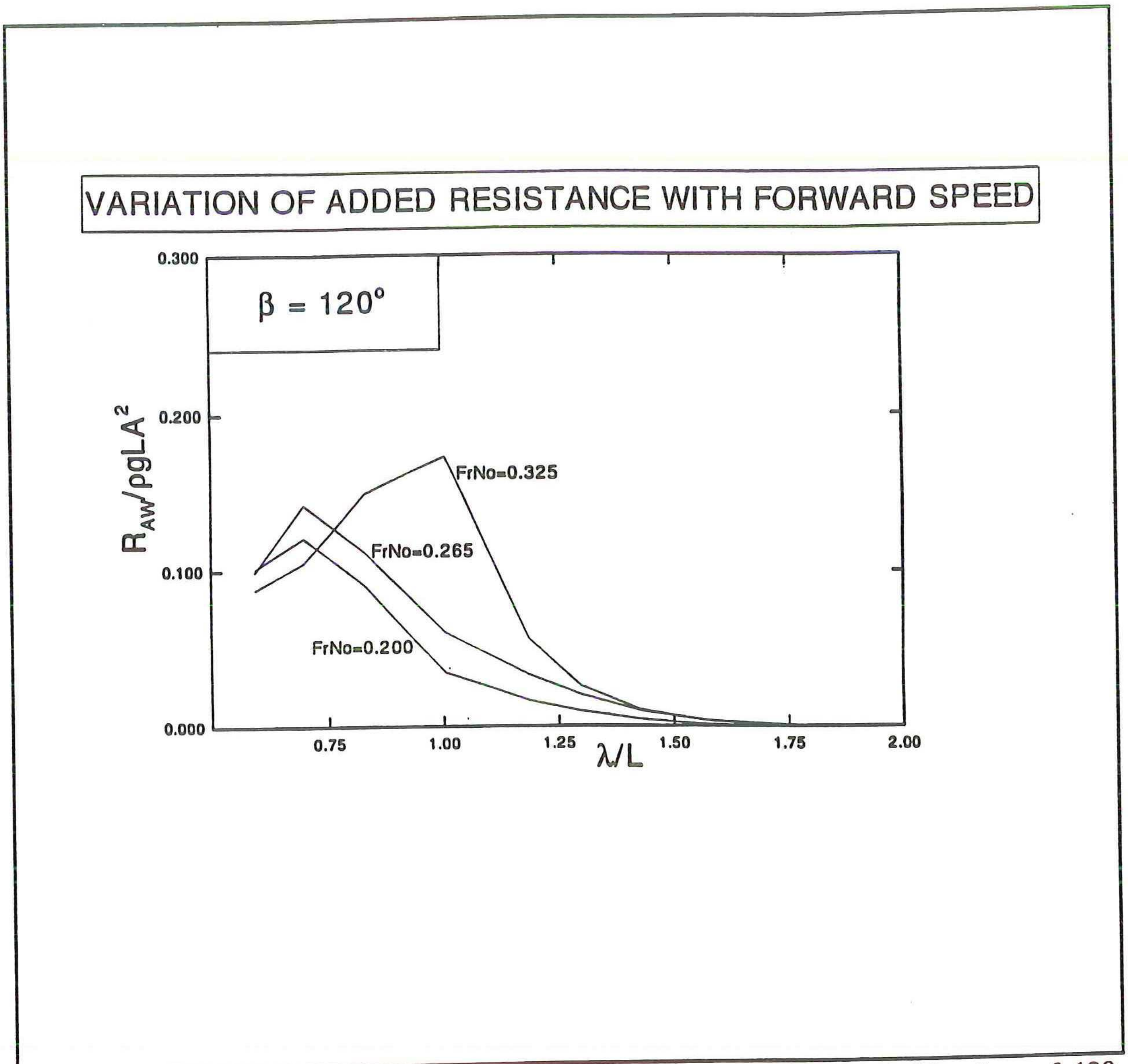
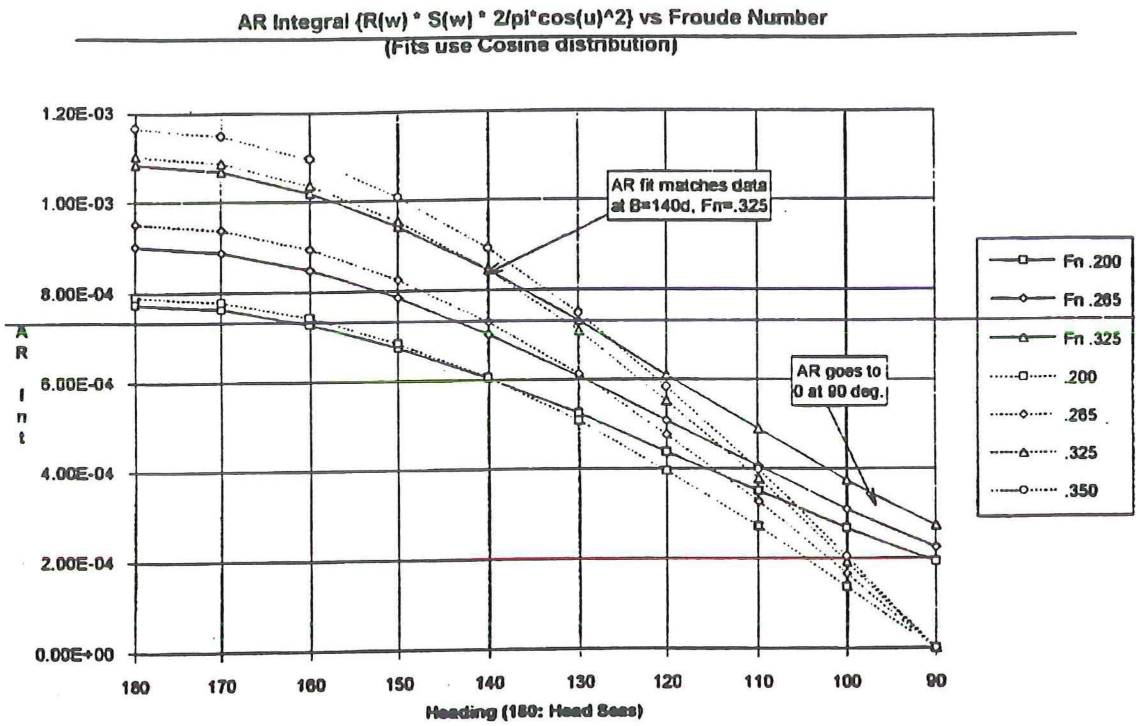


Figure 25 - Variation of Added Resistance with Forward Speed for Heading of 120-degrees

Teeters then fitted these predictions with correction factors to account for speed and heading relative to principle wave direction, Figure 26, and wave spreading.

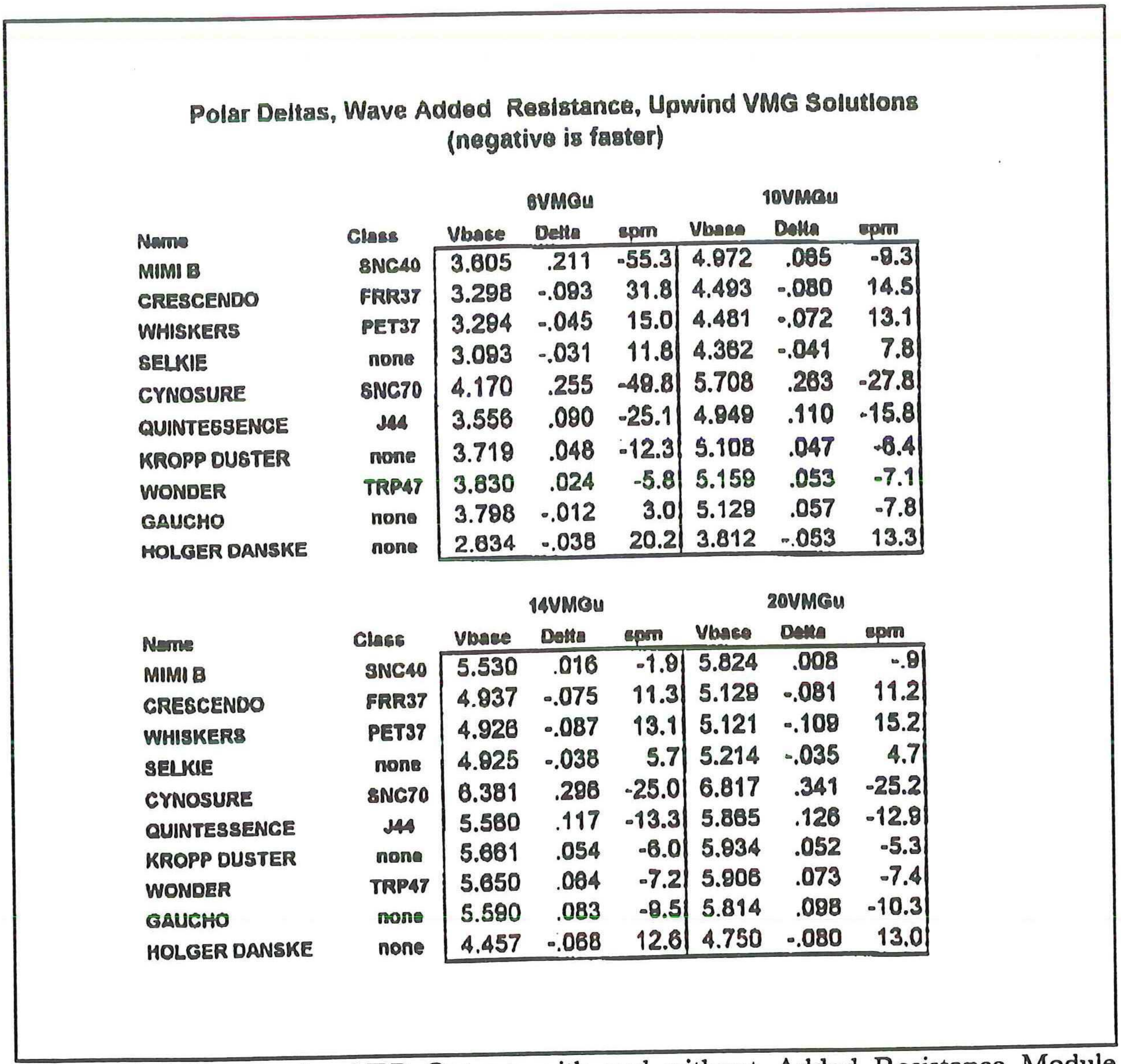

AR Integral {R(w) * S(w) * 2/pi*cos(u)^2} vs Froude Number
(Fits use Cosine distribution)

AR fit matches data at B=140d, Fn=.325

AR goes to 0 at 90 deg.

Figure 26 - Correction Factors for Speed and Heading Effects on Added Resistance

Finally, a comparison of VPP outputs for a small test fleet before and after added resistance effects as computed by DELR2 is shown in Figure 27.



Polar Deltas, Wave Added Resistance, Upwind VMG Solutions
(negative is faster)

		6VMGu			10VMGu		
Name	Class	Vbase	Delta	spm	Vbase	Delta	spm
MIMI B	SNC40	3.605	.211	-55.3	4.972	.065	-9.3
CRESCENDO	FRR37	3.298	-.093	31.8	4.493	-.080	14.5
WHISKERS	PET37	3.294	-.045	15.0	4.481	-.072	13.1
SELKIE	none	3.093	-.031	11.8	4.362	-.041	7.8
CYNOSURE	SNC70	4.170	.255	-49.8	5.708	.263	-27.8
QUINTESSENCE	J44	3.556	.090	-25.1	4.949	.110	-15.8
KROPP DUSTER	none	3.719	.048	-12.3	5.108	.047	-8.4
WONDER	TRP47	3.830	.024	-5.8	5.159	.053	-7.1
GAUCHO	none	3.798	-.012	3.0	5.129	.057	-7.8
HOLGER DANSKE	none	2.634	-.038	20.2	3.812	-.053	13.3

		14VMGu			20VMGu		
Name	Class	Vbase	Delta	spm	Vbase	Delta	spm
MIMI B	SNC40	5.530	.016	-1.9	5.824	.008	-.9
CRESCENDO	FRR37	4.937	-.075	11.3	5.129	-.081	11.2
WHISKERS	PET37	4.926	-.087	13.1	5.121	-.109	15.2
SELKIE	none	4.925	-.038	5.7	5.214	-.035	4.7
CYNOSURE	SNC70	6.381	.296	-25.0	6.817	.341	-25.2
QUINTESSENCE	J44	5.560	.117	-13.3	5.865	.126	-12.9
KROPP DUSTER	none	5.661	.054	-6.0	5.934	.052	-5.3
WONDER	TRP47	5.650	.064	-7.2	5.906	.073	-7.4
GAUCHO	none	5.590	.083	-9.5	5.814	.098	-10.3
HOLGER DANSKE	none	4.457	-.068	12.6	4.750	-.080	13.0

Figure 27 - Comparative VPP Outputs with and without Added Resistance Module DELR2

It should be noted that these results are based upon a standard gyradius determined as a function of overall length, and that differences between yachts should be expected to vary when individual gyradii are introduced.

RESEARCH ON WAVE SPECTRA

The research in this area was conducted primarily by Richard C. McCurdy.

At the outset of the project, it was clear that we understood little about race course waves. Accordingly, a buoy capable of measuring actual waves was purchased and transported to many venues of actual races to increase our knowledge on this part of the problem, Figure 28.

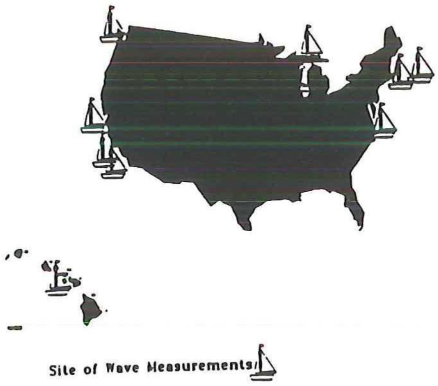


Figure 28 - Locations of Race Course Wave Measurements

A summary of the wave observations is given in Figure 29.

Location	Number of Observations		Average Wind, knots
Wind less than 8 knots			
Block Island	7		3.0
Catalina	4		5.0
Waukegan	4		5.5
Chesapeake	6		2.7
Puget Sound	12		4.9
		Group Average	4.2 knots
Wind 8 - 16 knots			
Long Beach	4		10.0
Catalina	5		8.6
San Francisco	6		12.1
LIS, Noroton	2		11.5
Puget Sound	7		11.1
		Group Average	10.7 knots
Wind greater than 16 knots			
Puget Sound	2		16
San Francisco	1		17
		Group Average	16.5 knots

Figure 29 - Summary of Wave Observations

Based upon an analysis of these observations, a number of general lessons were drawn:

* Racing rarely takes place in significantly large waves,

* The wave size measured is only mildly correlated with the observed wind speed when considered in terms of classical deep open ocean wave spectra, and

* Typical race course waves do not exhibit the sharply peaked spectra of fully developed sea spectra.

None of these lessons is surprising in hindsight because we tend to race in protected waters and to encounter diurnal wind patterns.

However, this part of the research proved to be particularly critical because of the lack of published data on this important aspect of added resistance in waves.

In order to construct a model for use in the VPP, the wave records were averaged in three bins: winds less than 8 knots(VTW avg = 4.8), winds 8-16 knots (VTW avg = 11), and winds greater than 16 knots(VTW avg= 17), to broadly represent light, medium , and heavy winds respectively as shown in Figure 30.

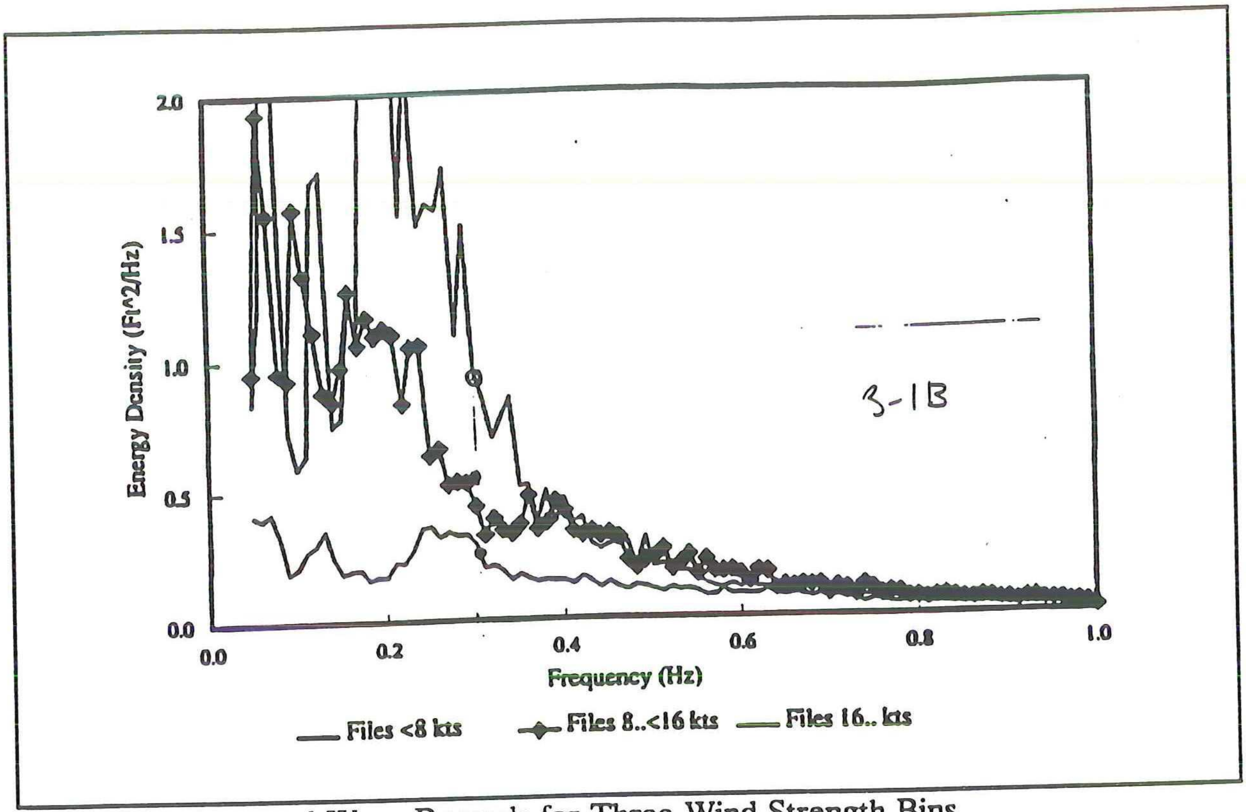


Figure 30 - Averaged Wave Records for Three Wind Strength Bins

From these faired spectra, a fit was selected to represent energy at various frequencies as a function of wind speed, in this case based upon the observed wind speed as taken by a race committee. The fit of the model is compared to the data in Figure 31.

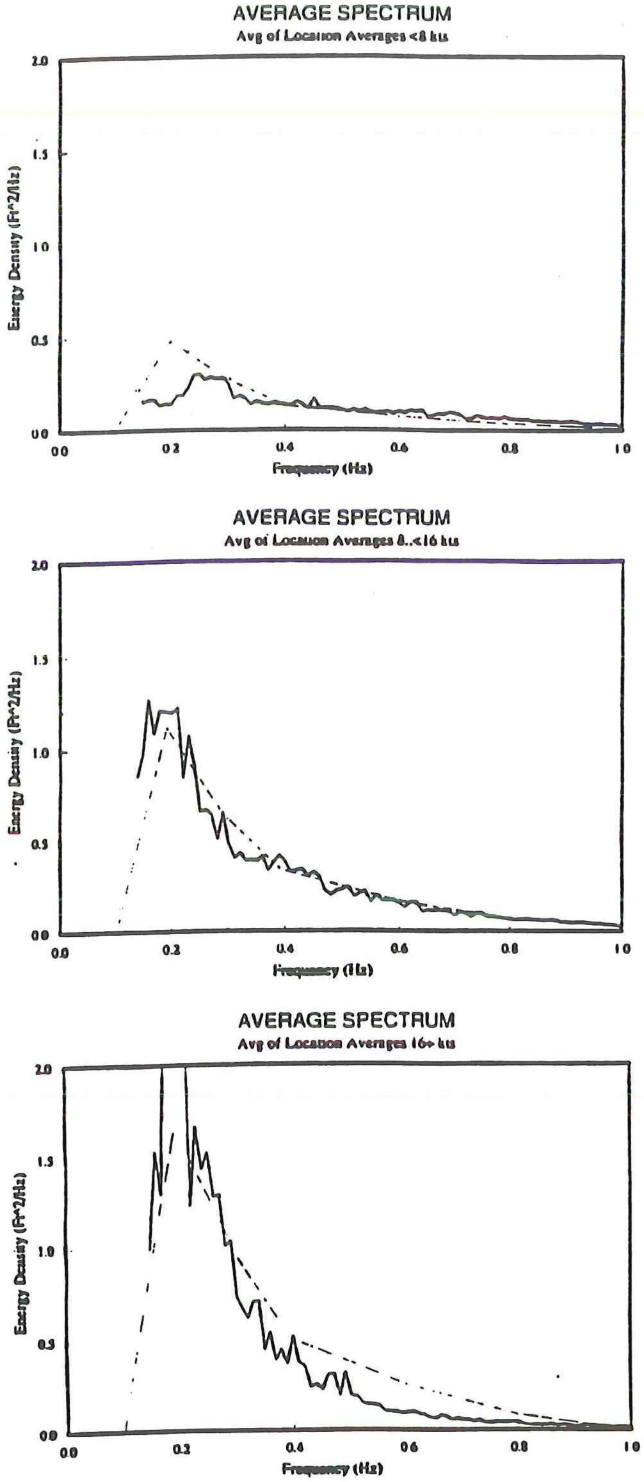


Figure 31 - Comparison of Wave Spectra Fit to Measured Data

Presumably, as more wave observations are made over a broader group of venues, this model may be refined or replaced. For this purpose, the Project wave buoy is available to other researchers who wish to undertake such additional measurements.

EXPERIENCE WITH IMPLEMENTATION

Of course the final research has not been implemented at this time; the comments which follow are intended to infer what we might from related experiences.

The Phase I results were produced in the form of a handicapping change to reflect the effects of weight concentration only. These results as represented by the computer code modules DELR and SPM were installed in an experimental version of the IMS VPP at USSA in summer 1991, and the results of a test fleet made available to the IMS Committee and the ITC at the fall 1991 meetings in Newport. When a test fleet was run for a large variation in the value of pitch moment of inertia, the handicap changes seemed to experienced observers to emulate typical differences observed while racing[12].

Because of the apparent promise of the Phase I results and a demand to use the research results even while continuing development of the measuring machine, the Flag Officers of the Cruising Club of America requested that a surrogate method be devised for the 1992 Bermuda Race which would use then existing results to handicap the Race, and to make the opportunity available for experimenting with handicapping for pitching moment in accordance with the purpose of the Race related to contributing to the encouraging the development of cruising yachts.

A system was devised and tried which was based upon the following approach:

* Since measurement data did not exist on weight distribution per se, a means of inferring the relative attention paid to added resistance in waves using certificate data was developed,

* This measure of probability that a yacht had been optimized for performance in waves was assumed to correlate with a low pitch moment of inertia,

---

[12]. Note that for such apparent agreement, it was necessary to reason that the boats which appeared to be stripped out had indeed achieved weight concentration thereby. This leap of faith was based upon calculations of what sort of weight concentration should be possible for a typical yacht, and was not based upon measured weight concentration properties of the test fleet.

* The assumed value of pitch moment of inertia was then used in conjunction with the results of the Phase I research to calculate experimental certificates for the fleet.

Such a system has obvious shortcomings, but the application to the Race did not determine the winner, and seemed to give broad, but not complete, satisfaction to the sailors. Not surprisingly, a small but vocal group of those most adversely affected were quick to remind the public of the weakness of the assumptions involved in such a surrogate method as if this was not appreciated by the developers.

In fact the surrogate method was sufficiently appealing to the IMS Owners Committee of USSA, that it was adopted by USSA as a proscription effective 1 June 1992, and we now have had the benefit of a most of a season of racing under this implementation.

The greatest weakness in any implementation at this time is the lack of knowledge regarding gyradius values for actual yachts. This comes about because of the difficulty in devising a measuring machine for this property, and will likely limit introduction of pitching moment effects for some time unless improvements can be made in identifying boats which are likely to have had special attention to weight concentration.

IMPLICATIONS OF RESULTS

The research is sufficiently mature to allow for immediate implementation into the VPP. That does not mean that implementation will be straightforward for the reasons described below.

It is highly probable based upon the validation of the prediction tools, that the method could immediately improve the handicapping of weight distribution differences. However, a data base of realistic values of gyradius and the availability of measured values of weight distribution for the existing fleet are not in hand, and may not be for some time.

The use of a nominal gyradius, even without a surrogate method, will already start to handicap the fleet in the sense that the short-ended yachts have lower gyradius to sailing length ratios then more traditional yachts having long overhangs.

Of greater concern, is the problem that implementation will involve applying corrections to an already contaminated speed prediction as described in an earlier section. Until such time as the calm water resistance prediction tool can be improved to the extent that it agrees with measured resistances of hulls, some risk exists that implementing the added resistance results might not improve handicaps. This risk is considered to be small, and should be mitigated by careful study of the results on a test fleet before implementation.

RECOMMENDATIONS

Based upon the results of the project:

1. The DELR2 added resistance module is available to insert into the IMS VPP. This should be accomplished as soon as possible, commensurate with checking against a test fleet, and with the following provisions:

- Use the "base" boat option so that differences in added resistance are computed until the revised calm water resistance formulation is available which correlates better with experimental data.

- Use a surrogate method of representing gyradius until a measuring machine capability exists. For the immediate future, consider a linear decline in Gyradius from 0.24 LOA for older yachts to 0.20 for new yachts.

2. Continue to pursue the evaluation of the Mark IIB Machine.

- Phase 1 should consist of a program to evaluate and refine the mechanism and software to improve practicability,

- Phase 2 should be undertaken to characterize the uncertainty level of the various measurements for comparison with the error budget and selection of the final measurement procedure. This step is required to determine whether longitudinal inclining is needed, for example

- Phase 3 should consist of gathering field experience in the hands of practicing measurers. At the same time, code to perform the machine output signal processing by national authorities should be developed.

When the machine is ready for introduction, its adoption should be encouraged by invoking a yearly decline in the value of gyradius for yachts not measured

APPENDIX A

Listing of Computer Code Module DELR2

```
'**********************************************************
'****************   READ HEELED GEOMETRY FILE   **************
'**********************************************************


path$ = data.path$ + "FILESPHI\"
NA2$ = LEFT$(NA$, INSTR(NA$, ".")) + "phi"
OPEN path$ + NA2$ FOR INPUT AS #3
Nphi = 6
REDIM PHI.(Nphi), LSMh.(Nphi), LDR.(Nphi), LBR.(Nphi), LCB.(Nphi), LCF.(Nphi)

FOR i = 1 TO 15
      INPUT #3, HEEL, LSMh, temp, temp, temp
      INPUT #3, WSAu, WSAc, BTRu, BTRc
      INPUT #3, Bu, Bc, BWL, AMS1u
      INPUT #3, temp, temp, temp, temp
      INPUT #3, temp, temp, temp, temp
      INPUT #3, temp, temp, DISP, temp
      INPUT #3, WPAu, xLCFu, WPAc, xLCFc
      IF i = 3 OR (5 <= i AND i <= 9) THEN
            iphi = iphi + 1
            PHI.(iphi) = HEEL
            LSMh.(iphi) = LSMh
            LDR.(iphi) = LSMh ^ 3 / (DISP / 64!)
            LBR.(iphi) = LSMh / Bc
            LCF.(iphi) = xLCFu / LSMh
      END IF
NEXT i
INPUT #3, LOA, xLCB
FOR i = 1 TO Nphi
      LCB.(i) = xLCB / LSMh.(i)
NEXT i
CLOSE #3

'**********************************************************
'*****************       WAVE RESISTANCE DATA    *************
'**********************************************************
'
' Base Boat Values
      DATA  .325,   .22,  3.33,   126,  .534,  .564
      READ B.frn, B.gyr, B.lbr, B.ldr, B.lcb, B.lcf
' Added Resistance Slopes
      DATA .00191, .0139, -.00134, .00000653,.00956, -.00338
      READ S.frn., S.gyr, S.lbr, S.ldr, S.lcb, S.lcf
' Added Resistance Knobs
      DATA  1.000, 1.000, 1.000, 1.000, 1.000, 1.000
      READ F.frn., F.gyr, F.lbr, F.ldr, F.lcb, F.lcf
```

```
'************************************************************
'************************    ERFX   *************************
'************************************************************
SUB ERFX (ER) STATIC
        .
        .
        .
'*C WAVE ADDED RESISTANCE IF SAILING CLOSER THAN BEAM REACHING
Waveres = 0
IF GAM < 95! THEN CALL Wave.Res(VTW, VS, PHI, GAM, Waveres)

'*C TOTAL FORE & AFT HYDRO DRAG.
FRW = DRESID + DPROP + DFRIC + DI + DRU + DH + DC + Waveres
        .
        .
        .
END SUB
```

```
'
'   SUB Wave.Res (R1, VS, PHI, Waveres)
'
'     Input:
'          R1          Square root of L
'          VS          Boat speed, knots
'          PHI         Heel angle, degrees
'     Output:
'          Waveres     Wave added resistance delta, pounds
'
'   Jim Teeters, Sparkman & Stephens, October 1992
'
SUB Wave.Res (VTW, VS, PHI, BTW, Waveres)

' Heeled Geometry Arrays
SHARED Nphi, PHI.(), LSMh.(), LDR.(), LBR.(), LCB.(), LCF.(), LOA
SHARED DEGRAD, rho
SHARED B.frn., B.gyr, B.lbr, B.ldr, B.lcb, B.lcf
SHARED S.frn., S.gyr, S.lbr, S.ldr, S.lcb, S.lcf
SHARED F.frn., F.gyr, F.lbr, F.ldr, F.lcb, F.lcf

' Interpolate Geometry at Current Heel Angle
CALL Lin.intrp(PHI, Nphi, PHI.(), LSMh.(), LSMh)
CALL Lin.intrp(PHI, Nphi, PHI.(), LDR.(), LDR)
CALL Lin.intrp(PHI, Nphi, PHI.(), LBR.(), LBR)
CALL Lin.intrp(PHI, Nphi, PHI.(), LCB.(), LCB)
CALL Lin.intrp(PHI, Nphi, PHI.(), LCF.(), LCF)
GYR = B.gyr

FRN = VS * 1.6889 / SQR(32.17 * LSMh)

' Factor Representing Cosine Spreading Function Effect
F.spread = .55

' Factor for Boat Heading Relative to Wave Principal Direction
F.head = COS(BTW / DEGRAD) / COS(40 / DEGRAD)

' Dimensionalization
F.dim = 2! * 1.9905 * 32.17 * LSMh

' Deltas from Base boat
D.frn = F.frn * (FRN - B.frn) * S.frn
D.gyr = F.gyr * (GYR - B.gyr) * S.gyr
D.lbr = F.lbr * (LBR - B.lbr) * S.lbr
D.ldr = F.ldr * (LDR - B.ldr) * S.ldr
D.lcb = F.lcb * (LCB - B.lcb) * S.lcb
D.lcf = F.lcf * (LCF - B.lcf) * S.lcf

' Total Delta
D.war = D.frn + D.gyr + D.lbr + D.ldr + D.lcb + D.lcf

' Wave Added Resistance
Waveres = VTW * F.dim * F.spread * F.head * D.war

END SUB
```