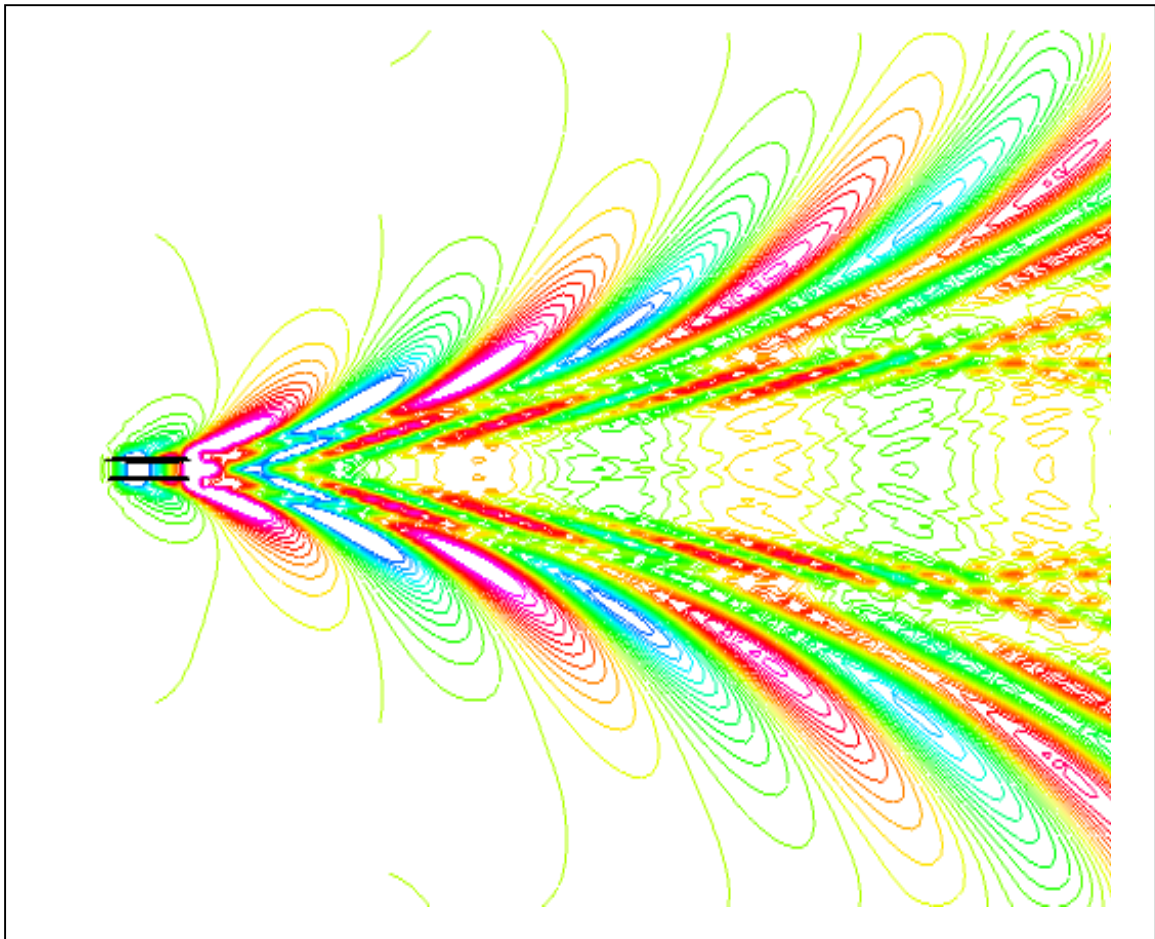


THE PREDICTION, MEASUREMENT AND ANALYSIS OF WAKE WASH FROM MARINE VESSELS¹



by
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ABSTRACTs

In the marine environment, wake wash from passing vessels can be detrimental to a shoreline environment, damage shoreline property and disturb or damage other marine operations. Slowdowns to prevent such impact can hamper or curtail high speed vessel operations that depend

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on speed for successful service. To prevent this failure, low wash vessel designs are needed and success must be assured before significant dollar investments are made. This paper describes:

- *The establishment of "no harm" wash criteria,*
- *The prediction of wash using Computational Fluid Dynamics for various speeds of high speed aluminum catamarans,*
- *The techniques of measurement and analysis of the wash from actual vessels, and*
- *Agreement between wash predictions and wash measurements.*

This paper documents a successful program which Washington State Ferries used to procure new, high speed passenger ferries which are environmentally friendly, for use on the Puget Sound.

INTRODUCTION

This paper introduces the problem of wake wash by briefly discussing the mechanics of wave generation by marine vessels. The method of prediction of wash by Computational Fluid Dynamics is described along with validation of predictions by full scale tests on the water. The techniques of wash measurement in full scale tests are shown as well as the methods used by the authors to analyze the data obtained. Using the analysis to perform optimizations of vessel design characteristics is introduced. Finally, comparisons of wash characteristics of several vessels are shown.

Pollution:

Not too many years ago, the word *pollution*, used in the marine world, meant refuse or other bio-undegradable material dumped over the side of a vessel. Today the word has an expanded meaning. It includes air pollution caused by particulate matter in exhaust gas, noise pollution caused by engine noise, and a host of environmentally unfriendly effects of vessel motion near beaches (particularly wetlands) and other vessels. As more and more fast ferries are traveling our waters and as we become more aware of the cumulative effects of these effects on our environment, we must deal with each of the pollution issues as design criteria in high speed vessel design, just as we deal with safety related issues and vessel performance.

Wake Wash or Wash?

Wake wash, or wash as it is more frequently called, is unique among these issues because the elements of design which affect wash are also directly related to vessel performance- resistance, stability, deadweight capacity, seakeeping etc. For those of us still tuned to the design spiral, we may think of wash as another spoke in the wheel.

First let's look at areas of the world where wake wash has had a significant impact on water transportation. For those of us in the Pacific Northwest, we don't have to look far. Rich Passage, that narrow one mile stretch between Bainbridge Island and Port Orchard, has been the focal point for wake wash problems and studies ever since ferries started traveling between Bremerton and Seattle. And we are not alone. The Parramatta River between Sydney and Parramatta

in Australia, The Thames River in England, The Solent and particularly the route between Southampton and The Isle of Wight in England, The Danish Coast, the harbor channels of Martha's Vineyard and Nantucket, The Mare Island Channel and the East Bay Estuary in San Francisco Bay have experienced scrutiny. These are just a few areas that have received particular attention in the last five years and there are many many more. The problem is there, it is significant, it is getting more significant and it will not go away. We need to deal with it.

How do we deal with it?

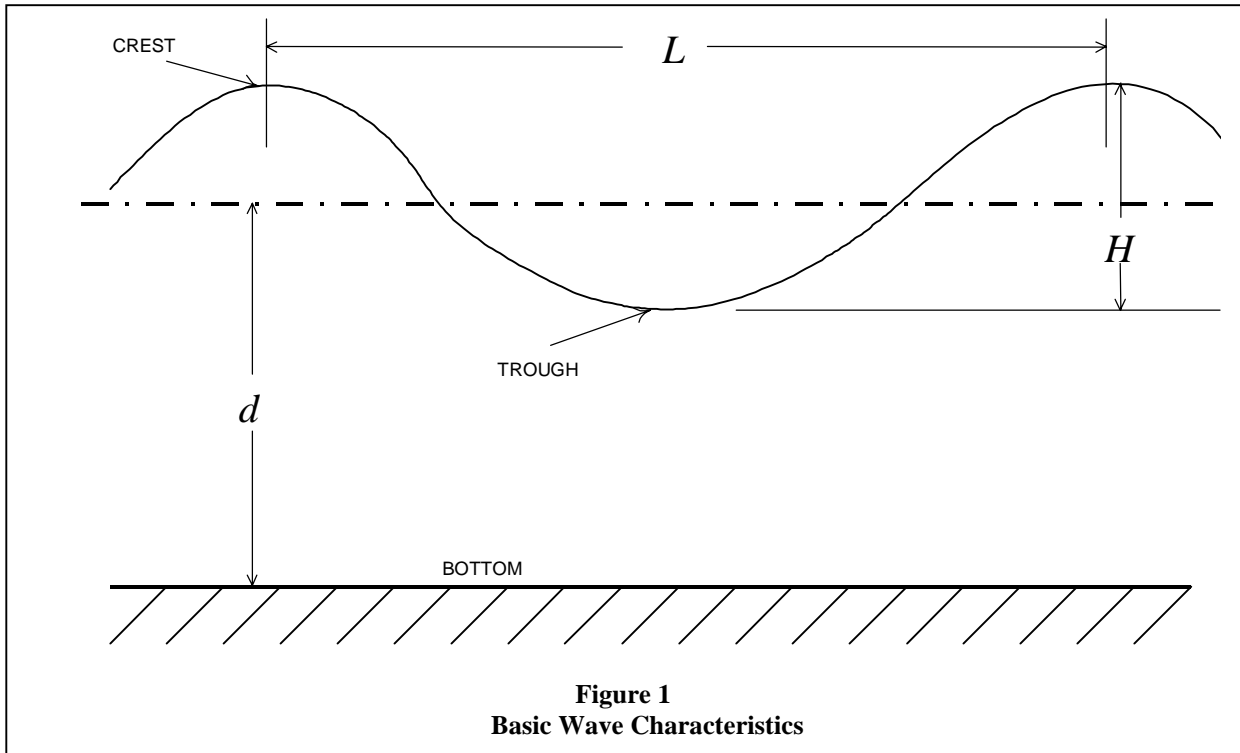
First we need to understand the mechanics of wash, then we need to establish some standards of measurement- what is acceptable under which conditions. Then we need to figure out how to design to meet these conditions and how we do this without compromising other design criteria unacceptably. We can do all of these things.

Wash vs. the Perception of Wash:

There is a misconception in the public that wake wash is directly proportional to speed - the faster the boat is going, the more wake it is making and the more energy that it is putting into the water and the more that will wash up on the beach. When dealing with large displacement hulls (tankers, bulk carriers etc.) this is true in very nearly all cases. But when dealing with light weight high speed ferries, particularly multihulls, the opposite is true in many cases as we shall see. So when you see the sign under a bridge or in a channel that says "No Wake- Slow Down", you may need to take issue with the sign. First, there is no such thing as *NO* wake. If you drag a pencil through the water, you are creating a wake (and wash), you are imparting energy to the water and that energy is dissipated only by friction; a process that may take miles to complete.

THEORY OF WAVE FORMATION AND PROPAGATION

Most waves that we observe in the ocean are wind generated waves and wind generated waves are often



confused by several factors such as fluid motion beneath the wave surface and the confusion of several sets of wave patterns merging. However a simple wind generated wave is similar in format to a vessel generated wave that has traveled a distance from the vessel and an understanding of wind generated waves is important in understanding vessel generated waves and the intermingling of the two. These waves eventually assume a sinusoidal or simple harmonic form and can be analyzed with classic sinusoidal theory. The terms and measurable criteria are illustrated in Figure 1.

Most ocean waves that we observe will not fit the profile of the sinusoidal wave of Figure 1, but rather they will be a confusion of several wind-driven wave patterns. However, absent significant interference from other wave systems, a vessel generated wave that has traveled approximately one ship length from the point of generation will assume a form close enough to that of the sinusoidal wave, that we can use classic wave theory to quantify and characterize the wash generated by various hull forms and specific vessels. This wave theory is defined by the following basic characteristics, illustrated in Figure 1:

- L Wavelength - The length of the wave from one point to the same point on the next wave.
- H Wave Height - The height of the wave from crest to trough
- T Period - The time that it takes for two successive wave crests to pass a given point.

Later we will introduce the significance of water depth (d) when we discuss the effect of shallow water on critical speed.

The basic formulae for wave front propagation are the relationship of these elements. We introduce celerity C as the velocity of the wave front (phase velocity) and it is defined as $C = L/T$. This term is useful in distinguishing vessel speed (V_k) from wave front speed (C).

The relationship between celerity and wave length and water depth is given by:

$$C = \sqrt{\frac{gL}{2\pi} \tanh\left(\frac{2\pi d}{L}\right)}$$

The classification of deep water, transitional water, and shallow water is developed from the relative value of the function $\tanh\left(\frac{2\pi d}{L}\right)$:

Classification	d/L	$2\pi d/L$	$\tanh\left(\frac{2\pi d}{L}\right)$
Deep water	$> 1/2$	$> \pi$	~ 1
Transition water	$1/25$ to $1/2$	$1/4$ to π	$\tanh\left(\frac{2\pi d}{L}\right)$
Shallow water	$< 1/25$	$< 1/4$	$\sim 2\pi d/L$

As previously noted, the development of wave theory is based on the assumption that the waves assume a sinusoidal wave form after a certain distance of travel. Actual measurements show this to be true for wind generated waves.

The theory also holds true for vessel generated waves, providing that they have traveled a sufficient distance to allow gravity to do its work. Although we often note steeper and sharper waves closer to the line of travel of the vessel, if we get several vessel lengths away, the sinusoidal theory gives us a good basis for comparison of waves characteristics between various vessels.

Wave energy

The relative damage to the beach, to a passing vessel, or to a shore structure is a function of the amount of energy expended by the wave front upon impact. This function is not easily measured directly but we have the measurable quantities from which energy density per linear meter of wave front can be calculated⁶ The energy is the sum of the potential and kinetic energy and is given by:

$$E = E_{kinetic} + E_{Potential}$$

$$E = \frac{\gamma g H^2 L}{16} + \frac{\gamma g H^2 L}{16}$$

$$E = \frac{\gamma g H^2 L}{8}$$

where g is acceleration due to gravity and γ is the density of water.

Using the relationship for wavelength as a function of period for open ocean waves of $L = \frac{gT^2}{2\pi}$ then

$$E = \frac{\gamma g^2 H^2 T^2}{16\pi}$$

$$E = 1961 H^2 T^2$$

with energy density expressed in joules/meter of wave front when wave height is in meters and period is expressed in seconds.

Vessel Generated Waves:

With few exceptions (and those are unusual shapes), every vessel moving through the water generates at least two sets of waves, divergent waves which move out from the bow and transverse waves which move out from the stern. They are illustrated in Figure 2.

These patterns are easily observed when viewed from above in an airplane or standing on a bridge. In this

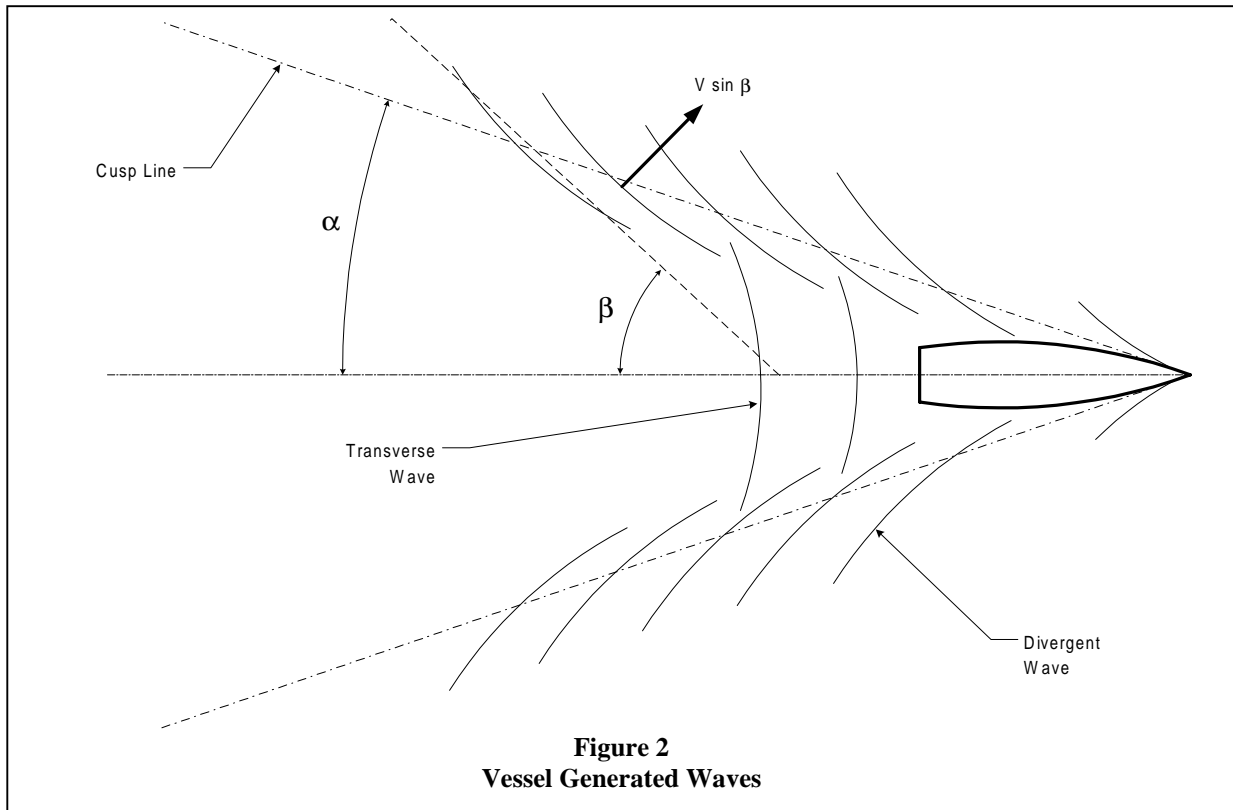


Figure 2
Vessel Generated Waves

⁶Assuming, of course, that the wave has maintained the sinusoidal profile.

aerial view of M/V INTINTOLI and AMD 360 at 18 Knots (Figure 3), the line of cusps and the angle, B, from

Figure 3
Aerial View of M/V INTINTOLI at 18 Knots



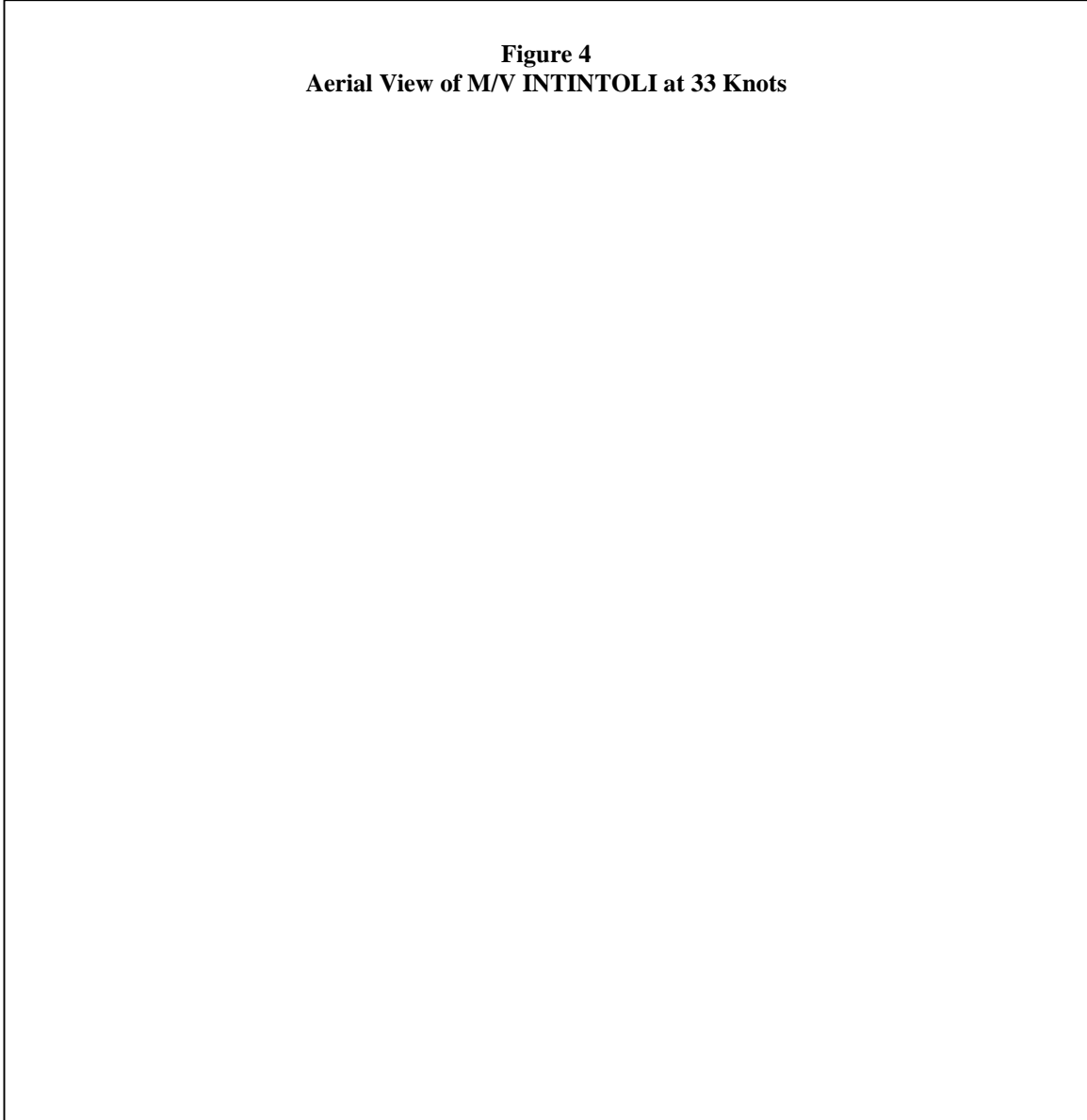
the interaction of the bow divergent wave and the transverse wave is clearly evident:

At higher speeds, the transverse stern wave (or Kelvin wave) appears to disappear to be replaced by a more prominent stern divergent wave as seen in this aerial view of M/V INTINTOLI at 33 Knots (Figure 4).

The generation of the divergent waves is a function of the hull form (Prismatic Coefficient), angle of entry, speed, and speed-length ratio $V/\sqrt{L_s}$ and is significant in the development of the height and energy of the wave train,

particularly at low or intermediate speeds. The transverse wave form is usually negligible in slow speed ships but increases with speed ships but increases with speed up to a length Froude Number of about 0.6. and at higher speeds the transverse wave disappears in the range of $0.6 \leq F_n \leq 1.0$ leaving a bow divergent wave and a stern divergent wave. In at least one case, the HSC craft SASSACUS, the authors have observed the disappearance of the bow divergent waves at Froude numbers greater than 1.0, leaving only the stern divergent wave as dominant.

Figure 4
Aerial View of M/V INTINTOLI at 33 Knots



The angle α in salt water develops to be 19.46° initially for all ships but the angle of obliquity β , varies with hull form and speed, being lower at higher speed length ratios and fine entry bows (4° - 10°) and higher for lower speed length ratios and fuller hull forms (20° - 30°).

The significance of the angle of obliquity (β), is that the direction of the movement of the energy front will be as shown in figure 2 and the wave length (L) and wave period (T) will be affected by the angle of wave generation. In general, the finer the bow entry, the smaller the angle β and thus the smaller the wavelength and period. This smaller wavelength results in a lower energy density for a vessel's wash.

The information needed to quantify and compare wave effect is contained in the few simple formulae developed. So

if we want to calculate, for comparative purposes, the amount of wave energy passing a given point, we need to measure the Wave height (H), the wave period (T) or the wave length (L) and from these we can calculate the wave energy density. Because of the difficulty of measuring the deep water wavelength (L) directly, the practice has been to measure and use the period (T).

VESSEL WAVE GENERATION IN DEEP AND SHALLOW WATER

Most often, the areas of shoreline that are of concern with the passage of high speed vessels, are those that line channels, canals, estuaries, or other water bodies where

water depth *under the keel of the vessel* is likely to be in ratio of half the vessel length or less. In these conditions, the wave pattern is influenced by the waves reflecting from the bottom. Vessel operators note that there is a change in the resistance curve in shallow water as evidenced by the fact that the hump speed will be lower in shallow water than in deep water. We measure this influence by using the Depth Froude number, defined as V_k / \sqrt{gd} .

As a general rule, depth Froude numbers in the range of 0.6-1.0 are likely to produce higher wave energy and wave height, and so they are to be avoided. In practical terms, when we plot out the wave energy for a given vessel, we may find that minimum wave energy is achieved at, for example “under 12 knots or over 28 knots” in deep water. The same vessel in shallow water may need to slow to under 8 or 10 knots in order to avoid the critical depth Froude number.

The slope at which the beach shoals will influence the point at which the waves may break and therefore expend energy before they roll up into beach front, pier structure, or other measuring point. Consequently, the quantity of energy that is acceptable will change with each geographic area and there can be no one energy or wave height value standard that will fit all conditions as environmentally acceptable.

Establishing Standards for Acceptable Wake Wash

The level for Rich Passage in Puget Sound was determined by a study involving coastal engineers measuring beach erosion, marine biologists measuring the effect on marine organisms, and naval architects measuring the wake wash parameters both visually (using an anchored pole and a stop watch) and graphically using submerged pressure sensors plotting data against a time line. This latter method has been perfected and is now the standard procedure used by the authors.

When a class of monohull vessels was introduced into service on Puget Sound on a route through Rich Passage in 1991, sharply increased complaints from shoreline residents caused Washington State Ferries to slow the vessels (and the catamaran TYEE) to a speed of 11- 12 knots through the sensitive area. After the slowdown, WSF retained Hartman & Associates, experts in shoreline impacts, to assess whether any damage had occurred and to determine at what speeds the vessels could operate without causing damage in the future. The consultants determined that in the six weeks of high speed operations, the vessels had caused no specific damage but that:

- At maximum speeds, the vessels contributed significantly to the energy impacting shorelines from all sources and, over time, could contribute to shoreline damage.
- At slowdown speeds (11-12 knots) the energy from the vessels’ wash was negligible when compared to waves from all other sources (weather, other vessels) and would not contribute significantly to shoreline erosion and other impacts.

This established the “no harm” level of wake wash. To quantify that level, WSF conducted wash measurements of the monohulls and TYEE at 11-12 knots in deep water (~ 60 meters) where there would be no bottom influence or beach shelving effects on the vessels’ wash to cause inconsistent data. The data was converted to a common distance off centerline of travel of 300 meters (~ 1000 feet) to establish a common frame of reference sufficiently far from the line of travel that the far field wash pattern had time to develop fully before measurement. The monohulls (SKAGIT and KALAMA) and TYEE had virtually the same wash pattern at this speed and the “no harm” level for Rich Passage in Puget Sound was established at

- Wash height of 28 cm (11”), peak-to-trough, measured 300 meters from centerline of vessel travel in deep water.
- Wash energy density of 2450 joules/meter (550 foot-pounds/foot) in the largest significant wave of the wave train as measured 300 meters from centerline of vessel travel in deep water.

Rich Passage in Puget Sound is only 730 meters wide at its narrowest point and its shoreline is occupied exclusively by private residences where most of the beaches have concrete or rock bulkheads. At the narrowest point, the beach shelving is relatively steep and the minimum depth is 25 meters at high tide. At other locations in the Passage, there are water depths as low as 15 meters at high tide.

WSF has found that vessels meeting the “no harm” wash level in Rich Passage also meet a satisfactory level in other areas in Puget Sound such as in Elliott Bay near Seattle where commercial and barge traffic often call for a “minimum wake” restriction.

In other locations, with different water depths, channel widths and shoreline conditions, a different standard than the one for Rich Passage may well be appropriate. In many cases the standard could be relaxed due to different conditions. The important point is that wash restrictions should be based on actual wash heights and energy densities and not on speed limits.

PREDICTION OF WAKE WASH:

The prediction of wake wash for a given hull design has become as critical in the design process as the prediction of speed, for many ferry contracts now carry severe penalties including default if the wake wash criteria is not met in trials.

There are many rules that can be followed to minimize wake wash and these are fairly well understood. Long skinny lightweight hulls with fine entrance, rounded bottoms, and smooth transition to the stern profile are likely to produce low wash characteristics as opposed to heavy, blunt bowed, broad

beamed, flat bottom vessels. However in the design process, the hull characteristics that produce low wash might not be those that produce good sea keeping, good space utilization, or high transport efficiency. Therefore, an accurate means of predicting wash characteristics is required.

Traditionally, model tests have provided a reasonably accurate *relative* profile of wash characteristics between two vessels. However model basins and model scaling introduce certain uncertainties to the process of predicting absolute characteristics. The edge and bottom effects of model basins of finite width and depth, for example cannot be easily or accurately accounted for in scaling. In recent years, the use of Computational Fluid Dynamics has provided a valuable and accurate tool for wake wash prediction and full scale tests, compared with CFD predictions, have given increased confidence to the use of this tool.

WASH PREDICTION BY COMPUTATIONAL FLUID DYNAMICS (CFD)

Introduction

Evaluations were made of the wake wash for five candidate catamaran designs, two at two different displacements, for the Washington State Ferries (WSF) High Speed Passenger Only Ferry procurement. The method of evaluation was based on Computational Fluid Dynamics (CFD) using a non-linear free surface module, FSWAVE, coupled to a three-dimensional panel method, VSAERO. As part of the evaluation process, there was a validation phase using full scale sea trials data measured on three existing ferry designs. This validation phase gave confidence in the predictions for wake wash for those designs where data was non-existent.

FSWAVE Background

FSWAVE is a computer program which computes the non-linear characteristics of a free surface disturbed by an arbitrary hull configuration. This hull configuration can be either completely submerged or surface piercing. Multiple hulls may also be modeled. The program is written as a “plug in” module which couples with the VSAERO panel code. The only additional inputs required by VSAERO when coupled with FSWAVE are the panel grid over the portion of the undisturbed free surface to be modeled and several additional parameters, such as the Froude Number, Water Depth, etc. The use of the program is described in a separate document which is itself a supplement to the VSAERO User’s manual. This document is meant to describe the features of the FSWAVE program and to provide a brief summary of the theory which supports it. A more complete description of this theory can be found in the report by Michael Hughes and Volker Bertram: *A Higher Order Panel*

Method for 3-D Free Surface Flows, Institute fur Schiffbau Report No. 558, Hamburg, Germany.

FSWAVE uses desingularized panels above the free water surface combined with normal VSAERO panels on the body surface to predict the steady flow past submerged or floating vehicles. The procedure can be used to predict the wave forms produced by and the wave resistance of ships traveling through calm water with a constant forward speed. Provisions are made for predicting the change in the draft and trim of the ship resulting from its forward velocity, to model the flow past a transom stern, to model the flow past a ship traveling in shallow water, and to model the flow past lifting surfaces near a free surface. The program satisfies the nonlinear boundary condition on the free water surface. This is done by iteratively computing the linearized solution about the flow resulting from the previous iteration. The first iteration solves for the flow linearized about uniform flow. The basic features of FSWAVE are summarized in the following list:

- Source and dipole panels on ship surface.
- Desingularized source panels above free surface.
- Nonlinear free surface boundary condition satisfied by iterative procedure.
- Ship equilibrium condition (dynamic sinkage and trim) also satisfied during iterative process.
- Open and Radiation conditions are fulfilled using “staggered grids.”
- Bottom effect in shallow water can be modeled by images.
- Fully separated transom sterns can be modeled.
- Lifting flows can be modeled.

Physical Model

Consider a ship moving with constant speed U in a channel of constant depth and width. Both depth and width may be infinite and are, in fact, assumed to be so in most cases. For inviscid and irrotational flow, this problem is equivalent to a ship being fixed in an inflow of constant speed.

For the considered ideal fluid, continuity gives Laplace’s equation which holds in the entire fluid domain. A unique description of the problem requires further conditions on all boundaries of the modeled fluid domain:

- Hull condition: Water does not penetrate the ship’s surface.
- Transom stern condition: For ships with a transom stern, we assume that the flow separates and the transom stern is dry. Atmospheric pressure is then enforced at the edge of the transom stern.
- Kinematic condition: Water does not penetrate the water surface.

- Dynamic condition: There is atmospheric pressure at the water surface.
- Radiation condition: Waves created by the ship do not propagate ahead⁷.
- Decay condition: Far away from the ship, the flow is undisturbed.
- Open-boundary condition: Waves generated by the ship pass through unreflected by any artificial boundary of the computational domain.
- Equilibrium: The ship is in equilibrium, i.e. trim and sinkage are changed such that the dynamic vertical force and the trim moment are counter-acted.
- Bottom condition (shallow-water case): No water flows through the sea bottom.
- Side-wall condition (channel case): No water flows through the side walls,
- The decay condition replaces the bottom and side-wall conditions if bottom and side-wall are at infinity, i.e. in the usual infinite fluid domain case.

General Outline

The problem is solved using boundary elements (panels on the ship hull and channel walls, desingularized panels above the free surface). In VSAERO, the condition of no flow through the hull (and side walls if present) is satisfied automatically using the boundary integral formulation approach to a panel method based on Green's Theorem (see VSAERO User's Manual Section 2.1). In FSWAVE, however, the free surface does not form one of the boundaries of the integral equations, but rather the velocity and its derivatives are computed at the control points on the free surface and the appropriate boundary condition is satisfied directly at these points. VSAERO/FSWAVE can be thought of as a combined Green's Theorem/Velocity method approach to a panel method, where Green's Theorem is applied to solid bodies (i.e. the ship and side walls) and a velocity method is used on the free surface. This combined method requires that the ship hull configurations (and side walls if present) form a set of closed bodies.

The wave resistance problem features two special

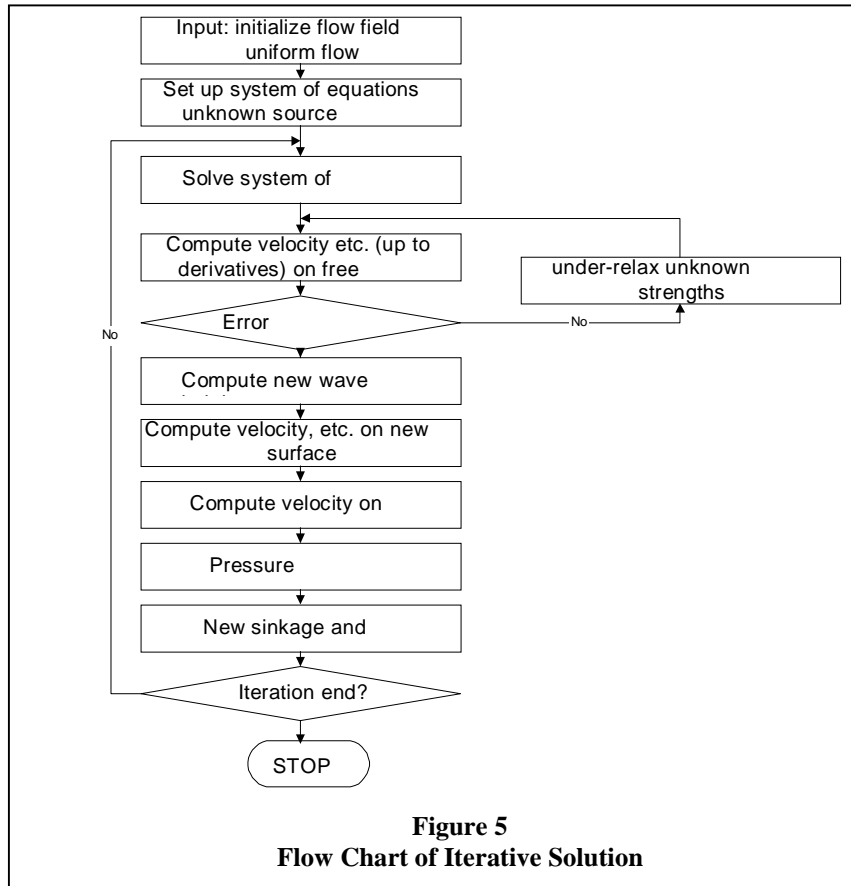


Figure 5
Flow Chart of Iterative Solution

⁷This condition is not valid for transcritical depth Froude numbers when the flow becomes unsteady and soliton waves are pulsed ahead!

problems requiring an iterative solution approach:

1. A nonlinear boundary condition appears on the free surface.

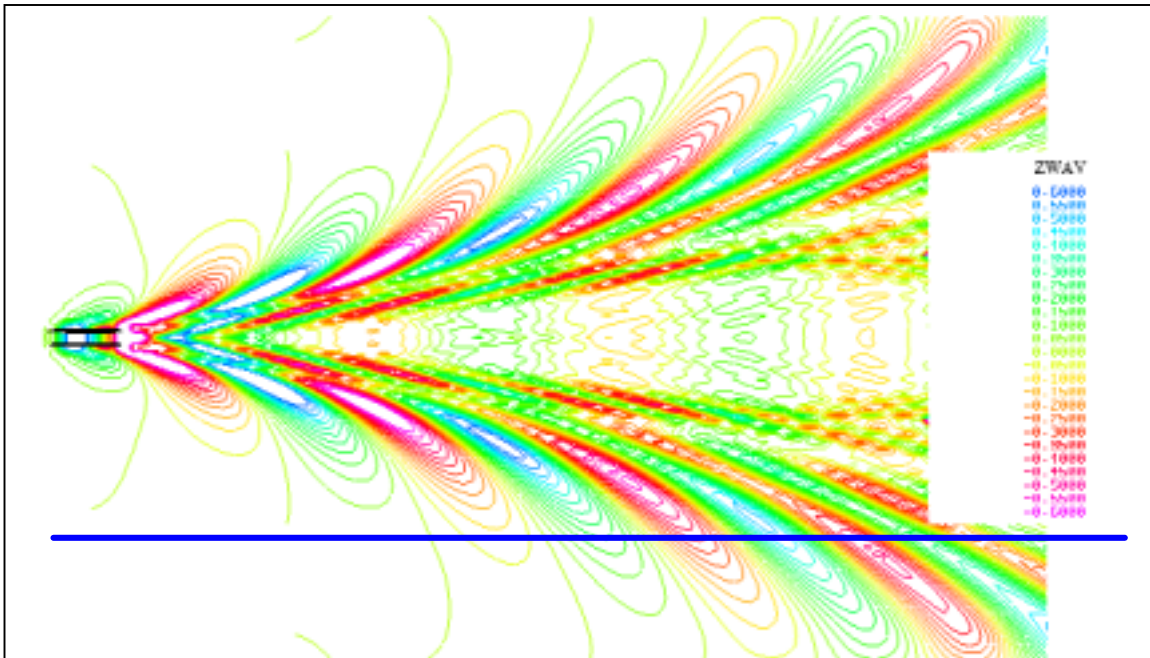


Figure 6
Wash Pattern Of An AMD 350 Catamaran At 30 Knots

AMD 350 Wake Wash Trials
 April 17, 1996

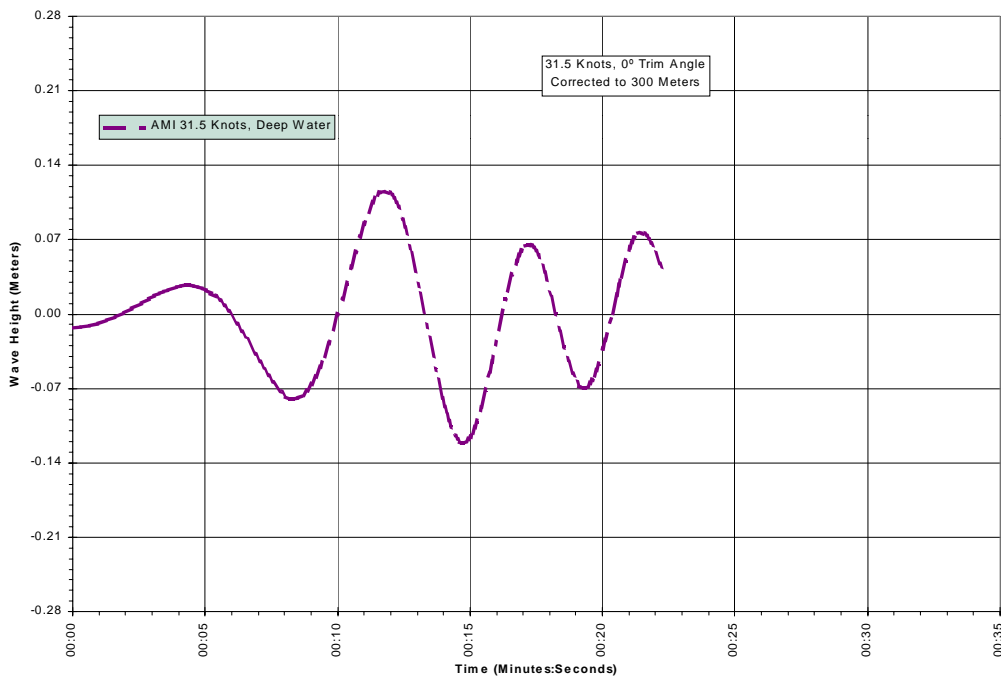


Figure 7
Wash Prediction for AMD 350 Catamaran

2. The boundaries of water (waves) and ship (trim and sinkage) are not known *a priori*.
 The iteration starts with approximating

- the unknown wave elevation by a flat surface,
- the unknown potential by the potential of uniform parallel flow,

- the unknown position of the ship by the position of the ship at rest.

In each iterative step, wave elevation, potential, and position are updated yielding successively better approximations for the solution of the nonlinear problem, see Figure 5.

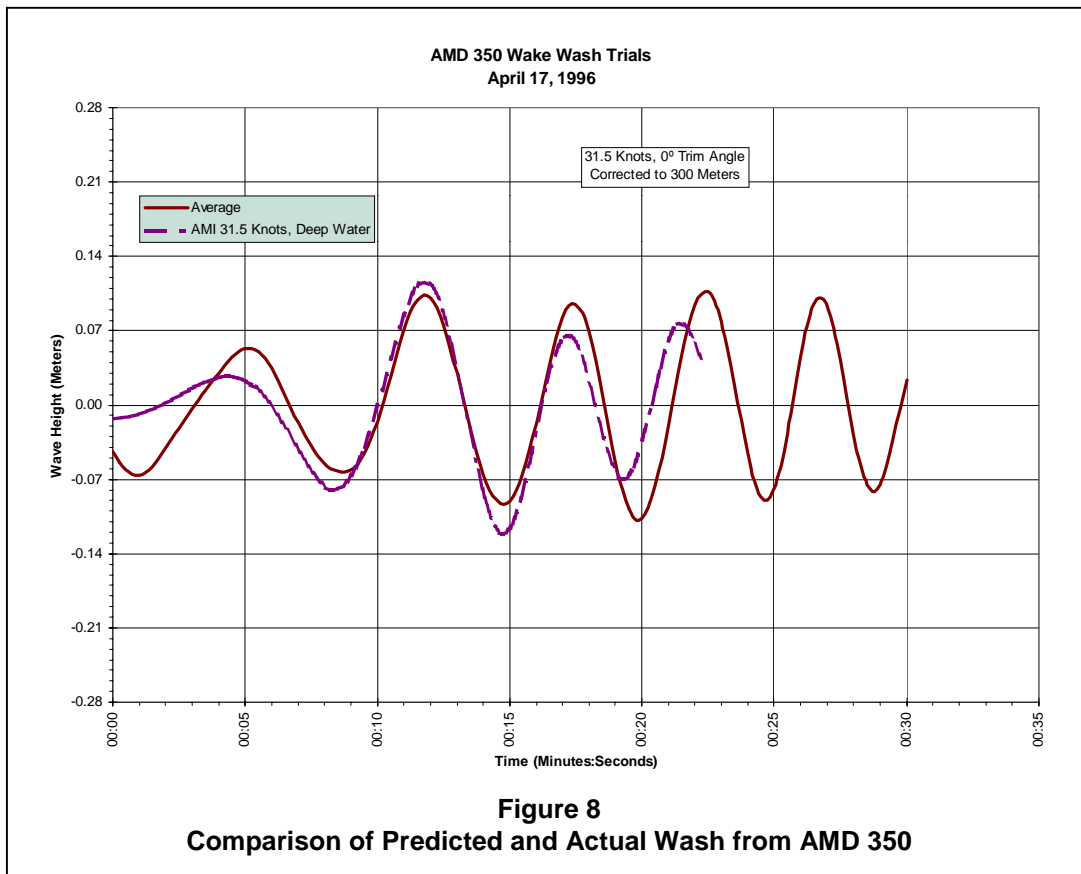
The graphical results of a run depicting the wash pattern of an AMD 350 catamaran at 30 knots is shown below in Figure 6. The graphics are normally presented in color so that a rough approximation of the wave peaks and troughs are shown by the colors in the graphics similar to the representation of stress in Finite Element Stress Analysis.

The post-processed data from VSAERO can be refined and presented in as much detail as might be required. For example, a longitudinal slice can be taken as shown by the line in Figure 6 and the data on that line can be presented graphically as a chart of wash height vs. time of the wave passing a given point, simulating the conditions of actual measurement in an on-the-water full scale wash trial. Such a

Bremerton run as a passenger only ferry. Extensive wake profile measurements were taken using the methods described in Section V. The vessel was ballasted to approximate full load conditions, and runs were made at distances approximately 90, 150 and 300 meters from the measuring probes.

The initial VSAERO/FSWAVE prediction of wave height at the 150 meter distance was considerably lower than that measured. The run was made at the static trim condition specified for the TYEE. After a thorough investigation, it was determined that vessel trim has a large effect on the predicted wave height. As a result, the trim of the TYEE under full load operations was measured with a digital inclinometer. The CFD prediction for the TYEE wake wash was re-run at the measured trim angle (1.27° bow up) and good agreement between theory and experiment at the 150 meter distance was obtained both in wave height and period.

Subsequently, additional validation between CFD



graph is presented in Figure 7 below:

Validation

The validation effort was first centered on the vessel, M/V TYEE. This vessel currently operates on the Seattle to

predictions was obtained during testing of a candidate vessel presented by Advanced Multihull Designs, the AMD 350, tested in Fremantle, Western Australia. WSF engineering staff used linear theory,

$$\frac{H_2}{H_1} = \sqrt[3]{\frac{d_1}{d_2}}$$

to replot the averaged measured wave profiles to the 300

meter distance. AMI's predicted wave profile at 150 meters was corrected in a similar way to 300 meters. The comparison with the average of the AMD 350 data is shown in Figure 8. Agreement is excellent both in wave height and period.

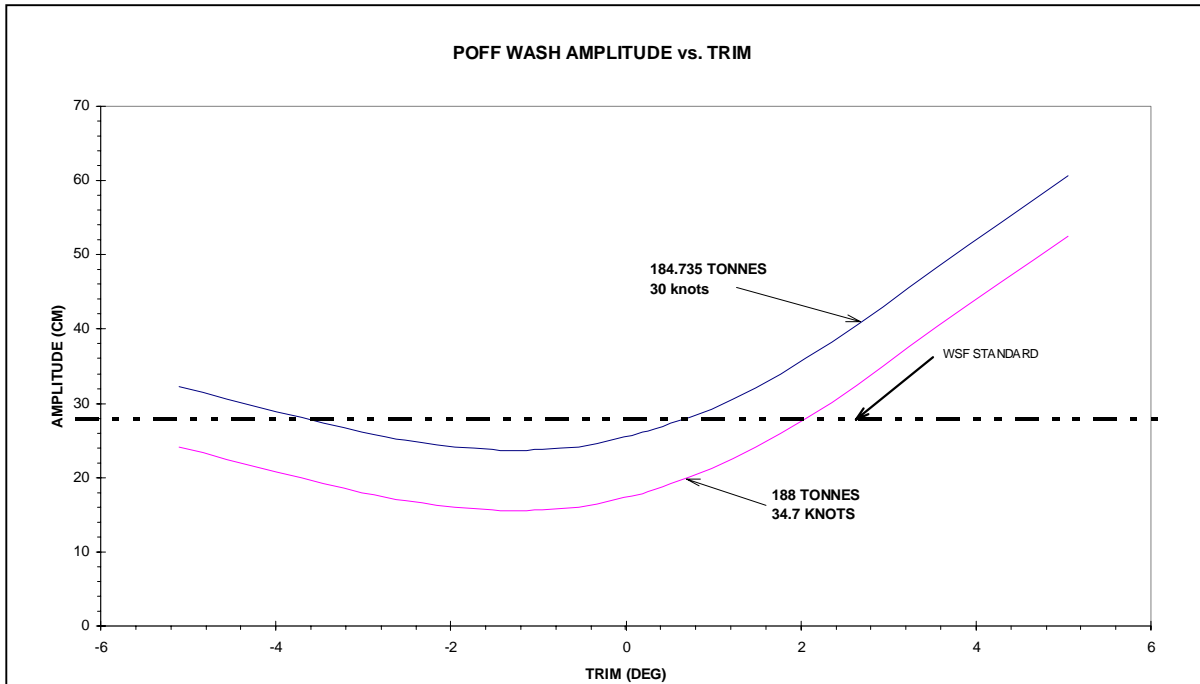


Figure 9
Variation of Wash Height with Changes of Displacement and Trim

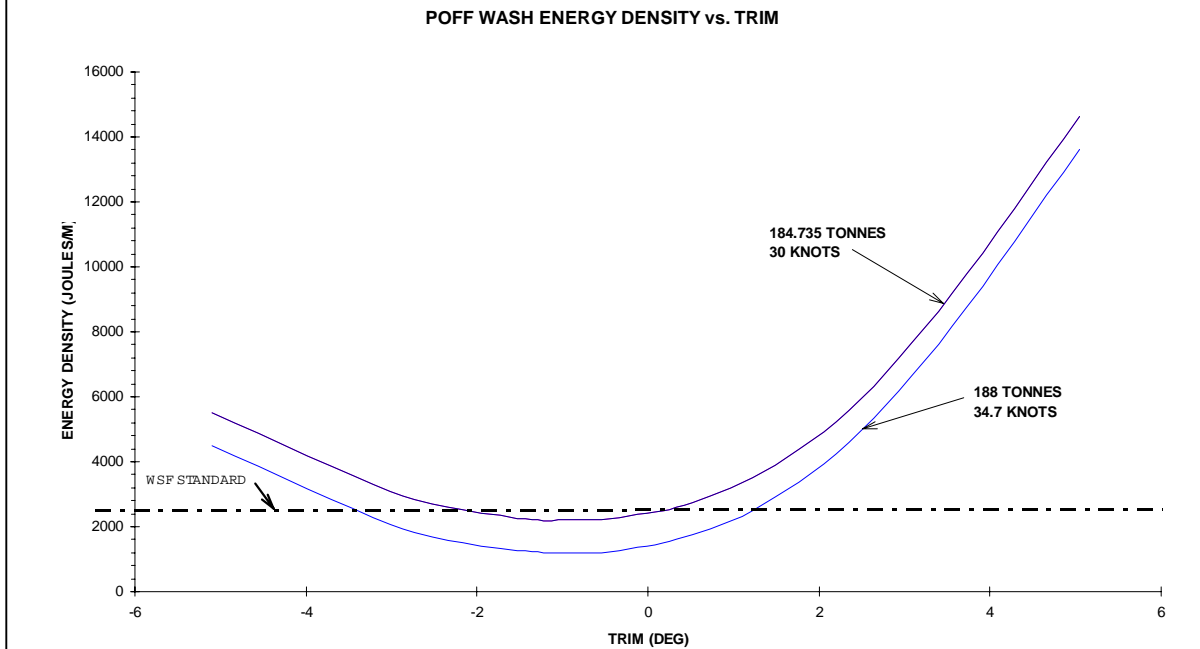


Figure 10
Variation of Wash Energy Density with Changes of Displacement and Trim

Wake Wash Prediction for Optimization

Discovery of the sensitivity of wash to vessel trim led the authors to make further investigations using CFD to test for points of optimization of hull separation in catamarans and of vessel dynamic trim. As an example, the following graphs present the optimization of dynamic trim for minimum wake wash. Figure 9 shows that, for wash height on the AMD 350 hull, the optimum trim occurs at about 1° down by the bow:

Results are similar for energy density as seen in Figure 10 below and it should be noted that a change in dynamic trim of as little as 1° can double the wash energy of a given

vessel at a given speed. This conclusion led WSF to specify trim tabs and a trim measurement system aboard the vessel contracted for in our current construction program in order to have an operational means of optimizing vessel trim to minimize wash.

WASH MEASUREMENT AND ANALYSIS

Wave heights and periods of vessel wash are measured using a submerged instrument package that

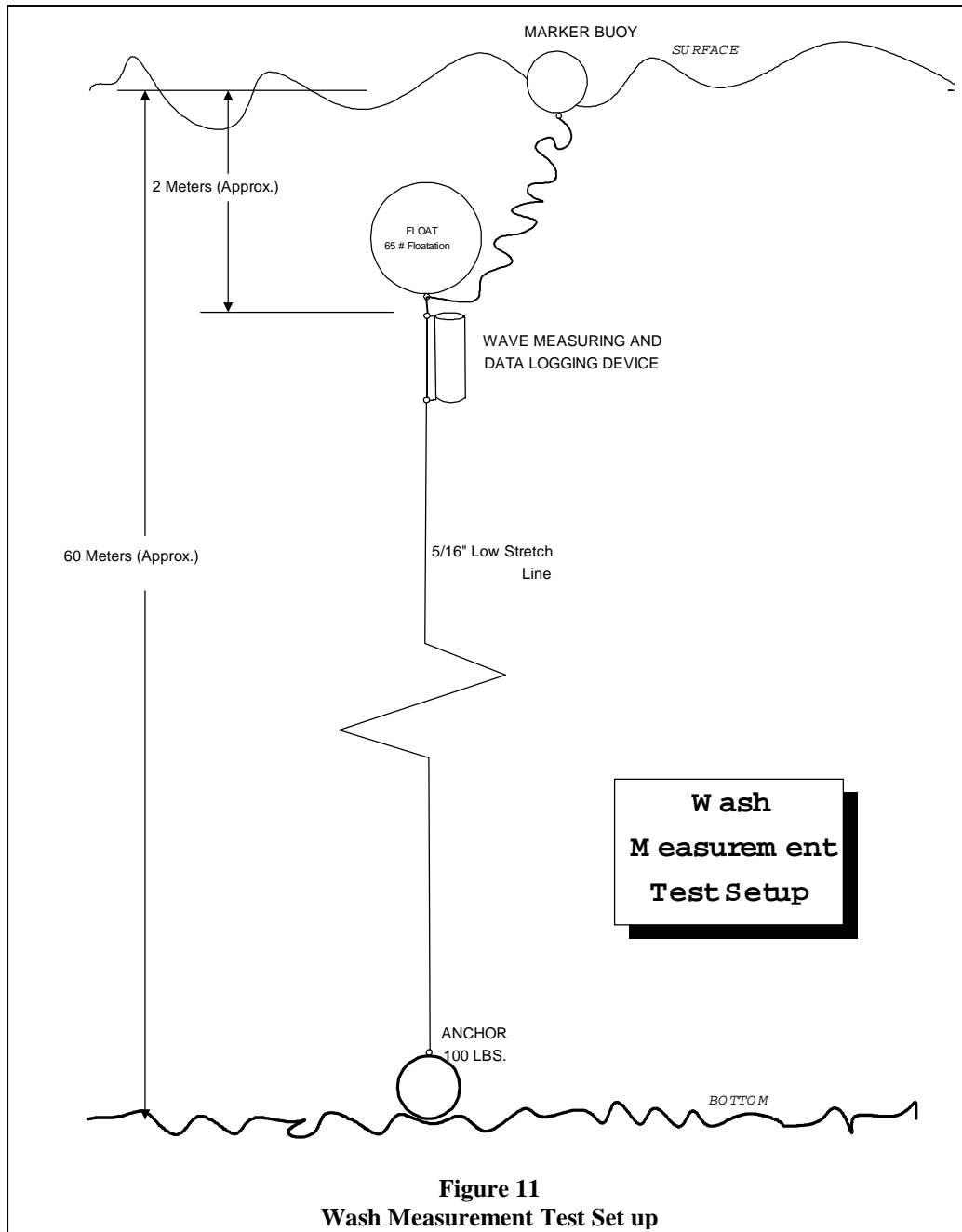


Figure 11
Wash Measurement Test Set up

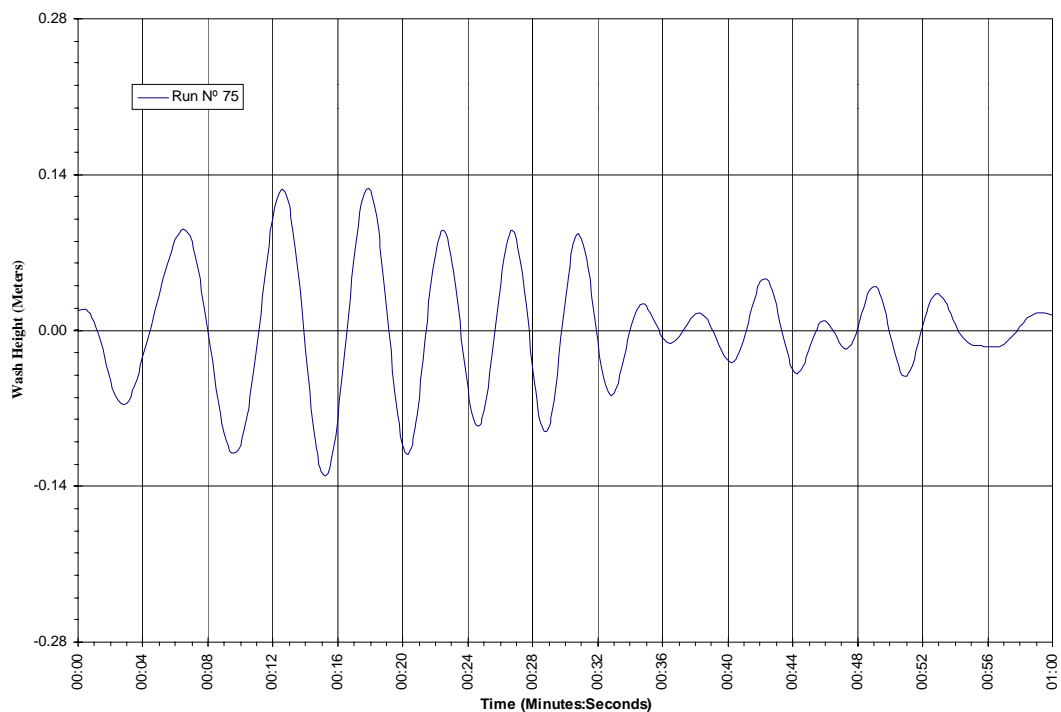


Figure 12
Wash from M/V CHINOOK at 34 Knots
M/V CHINOOK Wake Wash Trials April 16, 1998

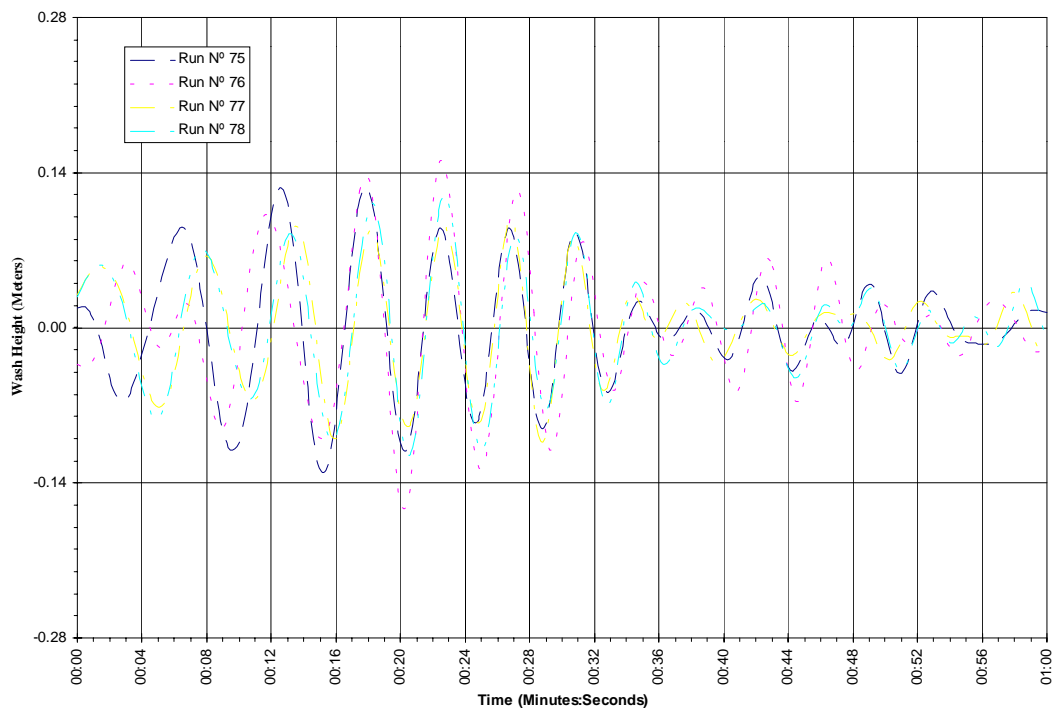


Figure 13
Overlay of Multiple Runs, M/V CHINOOK at 34 Knots

MV CHINOOK Wake Wash Trials April 16, 1998

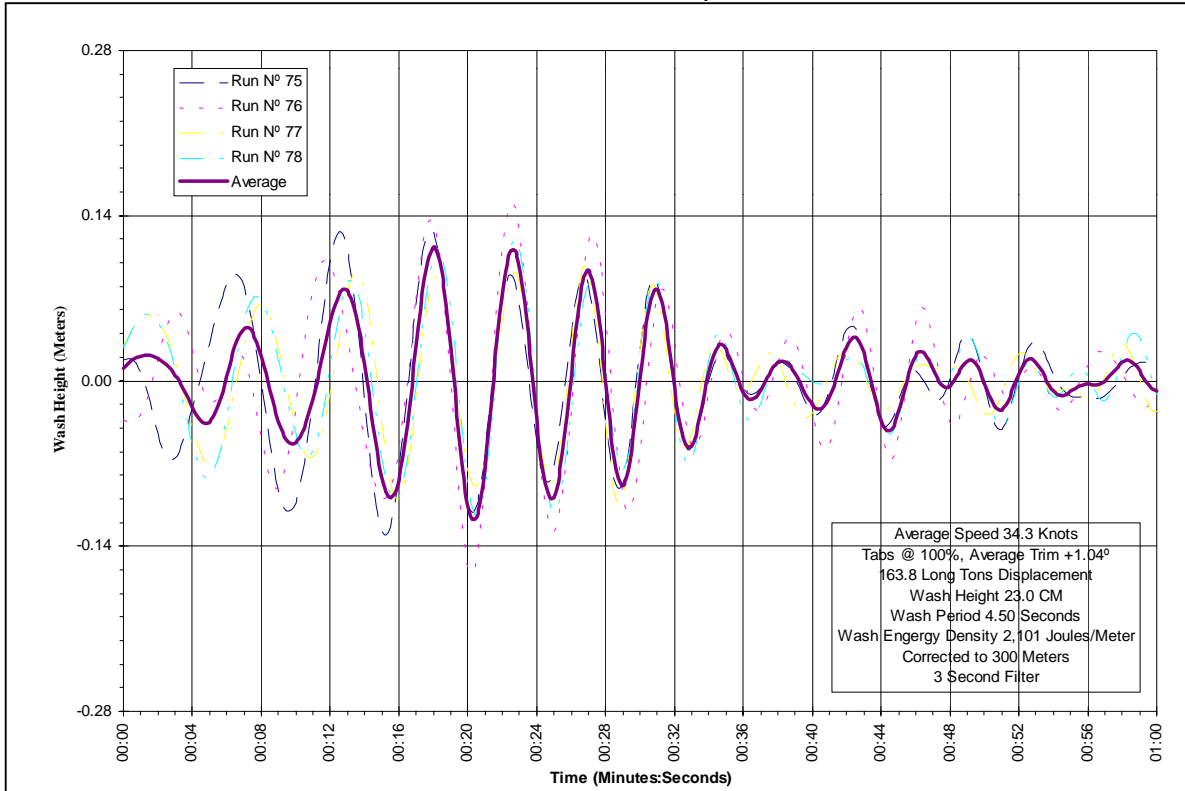
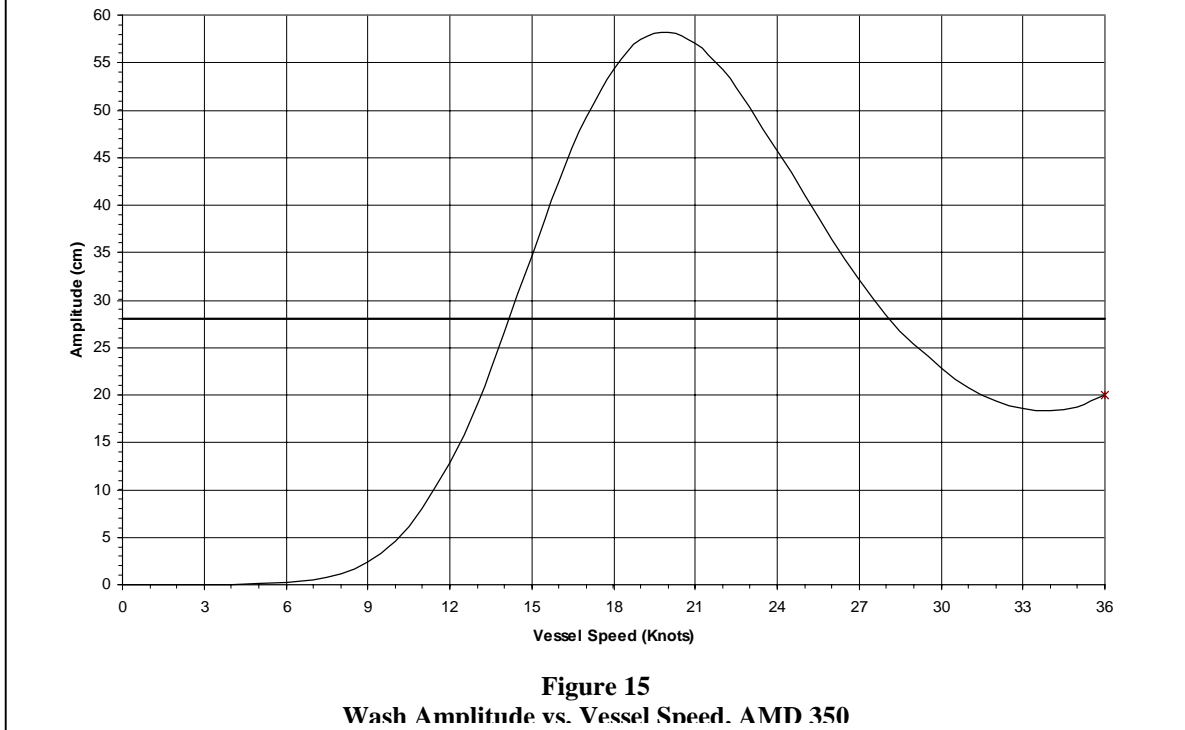


Figure 14
Computed Average of AMD 350 Wake Wash Trials, MV CHINOOK at 34 Knots
April 17, 1996



measures pressure 4 times per second and records data to an ASCII file in CMOS memory in the package. The instrument package is anchored to the bottom, typically in 200 feet of water to avoid all shallow water and critical depth effects, and suspended from a buoy that is held 6 to 10 feet below the surface of the water by a taut line to the anchor. A marker buoy on the surface is used for location and recovery. This test setup is depicted in Figure 11.

To gather data, the test vessel passes the deployed instruments at a convenient distance at various specified speeds. The actual distance is measured using a navigational sextant as a stadimeter with the known height of the vessel from waterline to housetop enabling an accurate solution for distance. Wash measurement runs are conducted at a range of speeds from about 10 knots to maximum with the vessel ballasted to simulate the fully loaded condition in both displacement and trim. A series of runs are also conducted with all ballast pumped (no passengers) to determine the sensitivity of the vessel's wash to varying displacement due to passenger load.

After data download, custom software converts the pressure readings to wave heights as a function of time, enabling plots to be made of wave patterns passing over the buoy. The software first determines the depth of the buoy below the average water depth and then applies pressure attenuation factors to the specific pressure readings prior to converting the pressures to wave heights.

All data that is consistent and repeatable is analyzed. Each run's data is normalized to a distance off centerline of travel of 300 meters (~1000 feet) and wave height is plotted as a function of time. From this plot the predominant wave in each wash wave train can be determined and its trough-to-peak height and period is determined

In the usual data gathering trial, at least six runs at each speed and displacement are measured. The goal is to obtain at least four runs that are consistent with each other. Factors that can cause a run to be inconsistent are rudder movements just as the vessel passes the buoy and "porpoising". Runs inconsistent with the majority are discarded.

Overlapping plots are then developed for the consistent runs so that the predominant waves overlap in close alignment.

A data series is then computed that is the average of the data for each time instant. From this average curve, the height, period and energy density of the wash for the given speed and vessel loading are taken.

Plots are then developed of wash amplitude vs. speed, wash period vs. speed and wash energy density vs. speed.

Results of Recent Measurements

The summary graphs in Figures 16 and 17 give height and energy density profiles for several recent vessels measured by the authors.

M/V BRAVEST is one of two New York Fast Ferries designed by Nigel Gee specifically to achieve low wash. In comparison with other vessels tested by WSF in the last 7

years, the height and energy density of BRAVEST's wash is lower than any other vessel with a service speed of 25 knots or more and a passenger capacity of 250 or more.

M/V SASSACUS, a 45 knot ferry not designed specifically for low wash, nevertheless has a surprisingly low wash for vessel speeds between 30 and 38 knots. The length Froude number for this vessel is 1.0 at 39 knots and, though the authors observed and measured a sharp increase in wash height above that speed, there was no corresponding sharp jump in wash energy density because the dominant wave became the stern divergent wave with a period of only 2.5 seconds as opposed to the bow divergent waves whose period was 4.5 to 5.0 seconds.

M/V CHINOOK is an AMD 385 recently constructed for Washington State Ferries and is the result of our program to obtain a vessel with a service speed in excess of 30 knots, a passenger capacity of 350 and a wash profile sufficiently low to prevent slowdowns in Rich Passage in Puget Sound. At 34 knots, the vessel successfully met the criteria.

CONCLUSIONS

The development of the methods described here for the prediction, measurement and analysis of wake wash has enabled Washington State Ferries to

- Define the measurable characteristics of wash that are germane to wash severity and impact.
- Establish achievable standards for wash in sensitive shoreline locations.
- Use the CFD prediction and analysis methods developed to predict wash for not-yet-built vessels and as optimization tools to improve wash of candidate vessels.
- Use on-the-water measurement and analysis to verify wash for operational candidate vessels and to validate CFD predictions.

These capabilities have made it possible to confidently proceed with capital acquisitions in the knowledge that the resulting vessel(s) will be environmentally responsible and may be operated as anticipated without shutdowns.

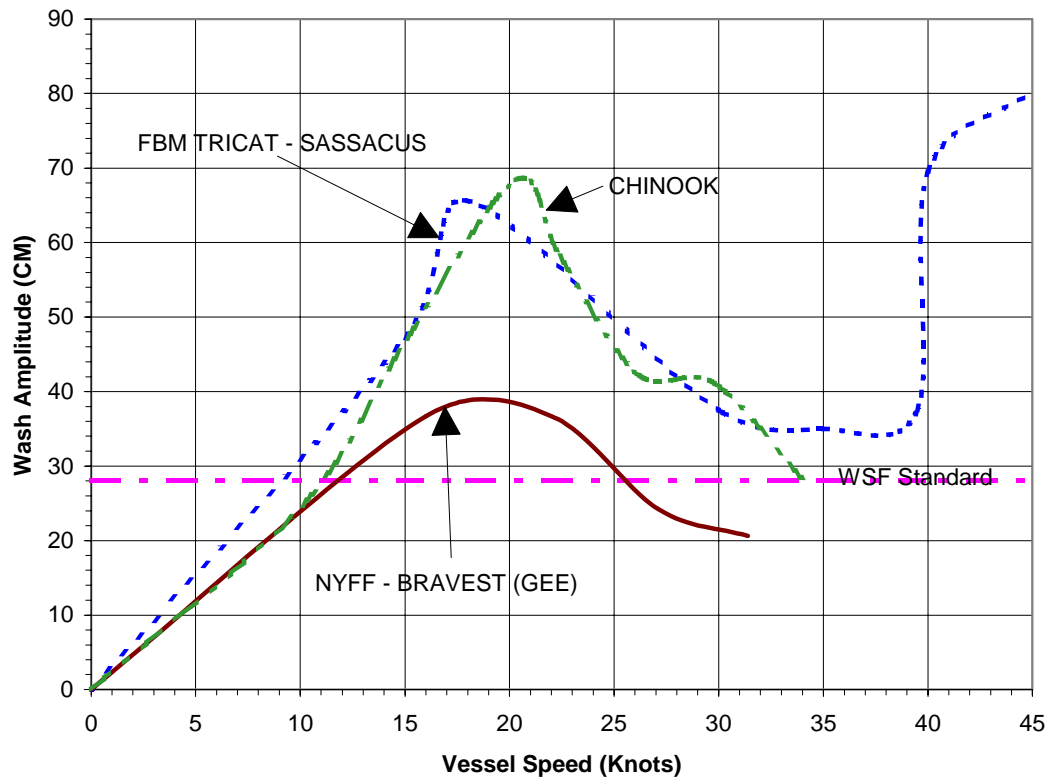


Figure 16
Wash Amplitude vs. Vessel Speed for Three Vessels

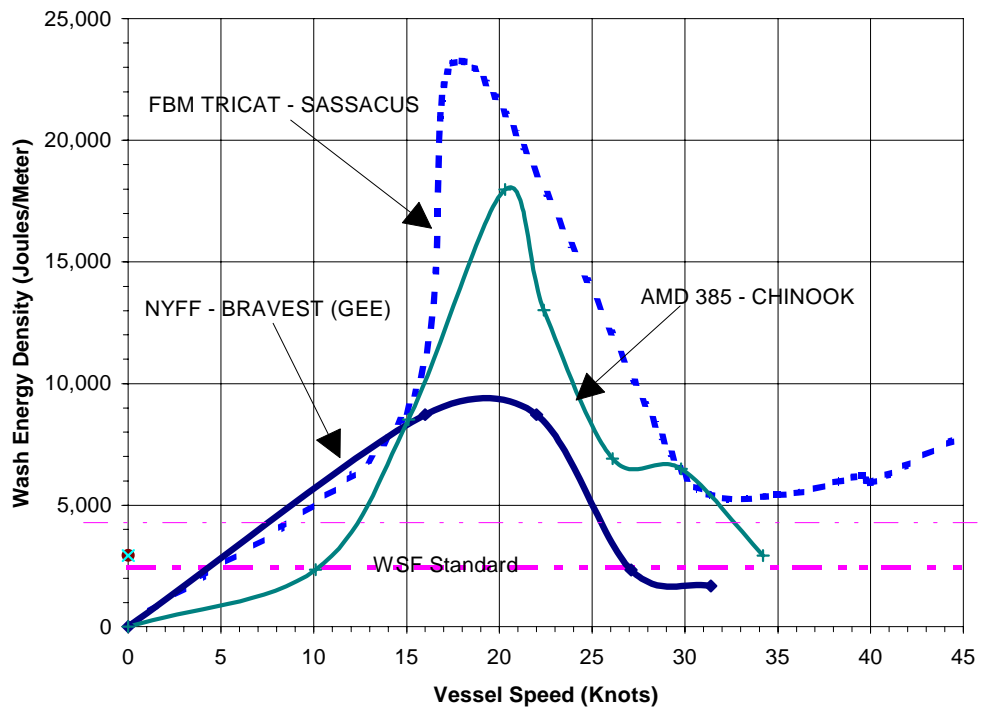


Figure 17
Wash Energy Density vs. Vessel Speed for Three Vessels