Ferry Wake Wash Analysis in San Francisco Bay

S. Anil Kumar¹, Justus Heimann², Bruce L. Hutchison³, and Scott W. Fenical⁴

¹ Senior Analyst, The Glosten Associates, Inc., 1201 Western Avenue, Suite 200, Seattle, WA 98101, U.S.A.; (206) 624-7850; FAX (206) 682-9117; e-mail: sakumar@glosten.com
² CFD Specialist, FRIENDSHIP Systems GmbH, Benzstrasse 2, D-14482 Potsdam, Germany; +49 331 96766-0; FAX +49 331 96766-19; e-mail: heimann@friendship-systems.com
³ Senior Principal, The Glosten Associates, Inc., 1201 Western Avenue, Suite 200, Seattle, WA 98101, U.S.A.; (206) 624-7850; FAX (206) 682-9117; e-mail: blhutchison@glosten.com
⁴ Principal, Coast & Harbor Engineering, Inc., 155 Montgomery Street, Suite 608, San Francisco, CA 94104, U.S.A., (415) 773-2164; FAX (415) 276-3784; e-mail: scott@coastharboreng.com

Abstract

The present paper describes the analysis of ferry wake wash along a proposed route between San Francisco and a new ferry terminal at Hercules. The steady wave field generated by a candidate catamaran ferry was calculated for a range of vessel speeds and water depths, using established computational fluid dynamics (CFD) techniques. The matrix of cases analyzed span the range of vessel speeds (5 to 35 knots) and water depths (3 to 32 m) anticipated for ferry service along the proposed route. The cases analyzed span the sub-critical, trans-critical, and super-critical flow regimes, based on whether the depth-based Froude number is less than, equal to, or greater than one, respectively.

The free-wave spectra which fully characterize the ship-generated wave system in the far field are also calculated and presented, including for shallow-water cases. The calculated ferry wakes and the free-wave spectra enable the propagation and transformation of the wave system into the far field over varying bathymetry, so that the impact of ferry wakes on the shoreline may be studied.

The analysis is part of a broader “shoreline and biological response” approach to wake wash impact analysis. The approach contains site-specific elements, but the process may also be applied to evaluate wake wash impact of specific, yet-to-be-built ferries on other future routes.

Keywords:
Fast ferries, CFD, free-wave spectra, wake wash

Introduction

The San Francisco Bay Area Water Transit Authority (WTA) is overseeing the expansion of the public water transit system in the Bay area. The proposed expansion will add eight new routes to the existing six routes and as many as 31 new passenger ferries to the existing fleet over the next twenty years. The WTA identified certain potentially sensitive shoreline areas along the prospective new routes. Figure 1 shows existing and potential ferry service routes in the San Francisco Bay area, including a proposed route between San Francisco (labeled “Ferry Building”) and Hercules/Rodeo (labeled “Rodeo”).

The present paper describes the analysis of a candidate ferry’s wakes along the proposed route, specifically the computational fluid dynamics (CFD) analysis of the ferry’s wakes and the spectral characterization of the ferry wake system in water of any specified depth.
Figure 1. Map Showing Existing and Potential New Routes, Including the Proposed Route between San Francisco to Hercules/Rodeo, and also Potentially Sensitive Shoreline Areas (Adapted from [2])

Figure 2 shows a drawing of a 149-passenger catamaran ferry, the **Harbor Bay Express II (HBE II)**, which was identified as a candidate ferry for the proposed route. The catamaran ferry features an asymmetric demi-hull form with a planar inner side. The outer hull side features V-shaped sections with a hard chine and a tunnel stern. The vessel has a maximum speed of 28 knots and its principal particulars are: overall length of 72.3 ft, length between perpendiculars of 65.3 ft, design draft of 4 ft, overall beam of 23 ft, demi-hull beam (at the design draft) of 6.9 ft, demi-hull spacing of 8.7 ft.

Drawing courtesy of Hage Marine

**Figure 2. Drawing of the 149-Passenger Catamaran Ferry Harbor Bay Express II: Profile View (Top) and Plan View of the Starboard Side (Bottom)**
Computational Method

References [3, 4, 5, and 6] describe some of the problems associated with high-speed-ferry operations, particularly those due to wash waves, and present some guidelines for managing wake wash. Reference [7] includes a review of various methods to predict ship-generated waves in the far field and to evaluate ferry wake wash. The final draft of this paper will include a discussion on how the approach adopted here differs from and improves upon those described in [8, 9, 10, and 11].

The commercial CFD program, \textit{SHIPFLOW™} (version 2.8) was used for predicting the wave and wake field of the candidate ferry. \textit{SHIPFLOW} is widely used in ship design for predicting the resistance and flow properties of ships and other marine structures. More information about the method is provided in [12]. The flow calculation within \textit{SHIPFLOW} is based on a zonal approach:

- a higher-order potential-flow panel method with linear or nonlinear free-surface boundary conditions is used to calculate the flow field in the outer, essentially inviscid flow field
- Momentum integral methods are used to calculate the laminar and turbulent boundary layers around the ship
- A Reynolds-averaged Navier-Stokes method with the k-\varepsilon turbulence model, finite-difference discretization, and a numerically generated body-fitted coordinate system is used to calculate the viscous flow at the stern and downstream of the ship

Alternatively, the entire flow field may be modeled as a potential-flow problem, as was done in the present study. \textit{SHIPFLOW} has been extensively applied to a wide variety of hull forms, including traditional monohulls and also catamaran and trimaran hull forms. Nonetheless, prior to undertaking a calculation of the waves and wake field of the HBE II, validation and verification analyses were carried out.

Validation Study

Numerous catamaran ferries are in service worldwide, and extensive data exist on most of these hull forms. The data are usually collected from physical tests of scaled models in a towing tank and include resistance, longitudinal wave cuts, sinkage and trim, and flow velocities in the propeller plane. However, the data are inevitably proprietary and difficult to obtain.

Data were obtained for a catamaran ferry which was extensively tested at a scale of 1:16.5 in a large European towing tank. The ferry (see Figure 3) has an overall length of about 240 ft, total beam of 59 ft (14.2 ft beam along water line for each demi-hull), draft of 7.95 ft, and a maximum speed of 40 knots. The towing-tank width was approximately 3.1 times the model length.

Potential-flow CFD calculations were performed for this ferry for a number of vessel speeds, ranging from 15 knots to 40 knots. Figure 3 shows a rendering of the ferry model and an illustrative plot of the calculated wave field and also the wave elevation contours around the ferry at a speed of 36 knots (corresponding to a length Froude number of 0.74) in calm water. The wave elevation contours are non-dimensionalized by ship length. The reference length used was the length along the load water line, of 210.2 ft.
Comparisons were made between the calculations and the experimental data. These are shown in Figure 4. The calculated total resistance differs from the model-tests data by between 1.0% at 22 knots and 9.9% at 40 knots. This is within the acceptable range of differences to be expected between CFD calculations and physical data. The sinkage and trim calculations accurately predict not only the trends in the data but also the magnitudes. Finally, Figure 4 shows a comparison between the calculated and measured wave cut at a distance of Y/L=0.515 from the sailing line. The validation suffers from the availability of limited wave cuts data, in that no time series of longitudinal wave cuts were available. Measurements were available of only the maximum crest height, minimum trough height and maximum peak-to-peak wave height in the longitudinal wave cut. The comparison between the calculations and the data are still reasonably good, thereby validating the CFD method for a catamaran ferry.
Ferry Wake Analysis for the *Harbor Bay Express II*

CFD calculations were then undertaken of the waves and wake field generated by the HBE II for a total of 28 combinations of vessel speed and water depth. The ferry proposed for the San Francisco–Hercules route is expected to have a service speed of 25 knots. Figure 5 shows the variation of undredged water depth with distance along the route and the cumulative probability of water depths along the proposed route.

![Figure 5. Undredged Water Depth (Left) and Cumulative Probability of Water Depth (Right) along the Proposed Route from San Francisco to Hercules](image)

**Table 1. Matrix of Vessel Speed and Water Depth Combinations Analyzed Using CFD**

<table>
<thead>
<tr>
<th>Case</th>
<th>Speed (knots)</th>
<th>Length Froude No.</th>
<th>Depth (m)</th>
<th>Depth Froude No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>25</td>
<td>0.921</td>
<td>3</td>
<td>2.371</td>
</tr>
<tr>
<td>2</td>
<td>25</td>
<td>0.921</td>
<td>5</td>
<td>1.837</td>
</tr>
<tr>
<td>3</td>
<td>25</td>
<td>0.921</td>
<td>7</td>
<td>1.552</td>
</tr>
<tr>
<td>4</td>
<td>25</td>
<td>0.921</td>
<td>9</td>
<td>1.369</td>
</tr>
<tr>
<td>5</td>
<td>25</td>
<td>0.921</td>
<td>12</td>
<td>1.186</td>
</tr>
<tr>
<td>7</td>
<td>25</td>
<td>0.921</td>
<td>18</td>
<td>0.908</td>
</tr>
<tr>
<td>9</td>
<td>25</td>
<td>0.921</td>
<td>24</td>
<td>0.838</td>
</tr>
<tr>
<td>11</td>
<td>25</td>
<td>0.921</td>
<td>30</td>
<td>0.750</td>
</tr>
<tr>
<td>12</td>
<td>35</td>
<td>1.289</td>
<td>5</td>
<td>2.571</td>
</tr>
<tr>
<td>13</td>
<td>35</td>
<td>1.289</td>
<td>12</td>
<td>1.660</td>
</tr>
<tr>
<td>15</td>
<td>35</td>
<td>1.289</td>
<td>21</td>
<td>1.255</td>
</tr>
<tr>
<td>17</td>
<td>35</td>
<td>1.289</td>
<td>33</td>
<td>1.001</td>
</tr>
<tr>
<td>18</td>
<td>20</td>
<td>0.736</td>
<td>3</td>
<td>1.897</td>
</tr>
<tr>
<td>20</td>
<td>20</td>
<td>0.736</td>
<td>7</td>
<td>1.242</td>
</tr>
<tr>
<td>22</td>
<td>20</td>
<td>0.736</td>
<td>12</td>
<td>0.948</td>
</tr>
<tr>
<td>24</td>
<td>20</td>
<td>0.736</td>
<td>18</td>
<td>0.774</td>
</tr>
<tr>
<td>25</td>
<td>15</td>
<td>0.552</td>
<td>3</td>
<td>1.423</td>
</tr>
<tr>
<td>26</td>
<td>15</td>
<td>0.552</td>
<td>5</td>
<td>1.102</td>
</tr>
<tr>
<td>27</td>
<td>15</td>
<td>0.552</td>
<td>7</td>
<td>0.931</td>
</tr>
<tr>
<td>28</td>
<td>15</td>
<td>0.552</td>
<td>24</td>
<td>0.503</td>
</tr>
<tr>
<td>29</td>
<td>15</td>
<td>0.552</td>
<td>12</td>
<td>0.711</td>
</tr>
<tr>
<td>30</td>
<td>10</td>
<td>0.368</td>
<td>3</td>
<td>0.948</td>
</tr>
<tr>
<td>31</td>
<td>10</td>
<td>0.368</td>
<td>5</td>
<td>0.735</td>
</tr>
<tr>
<td>32</td>
<td>5</td>
<td>0.184</td>
<td>3</td>
<td>0.474</td>
</tr>
<tr>
<td>35</td>
<td>30</td>
<td>1.105</td>
<td>5</td>
<td>2.204</td>
</tr>
<tr>
<td>37</td>
<td>30</td>
<td>1.105</td>
<td>12</td>
<td>1.423</td>
</tr>
<tr>
<td>39</td>
<td>30</td>
<td>1.105</td>
<td>21</td>
<td>1.078</td>
</tr>
<tr>
<td>41</td>
<td>30</td>
<td>1.105</td>
<td>33</td>
<td>0.858</td>
</tr>
</tbody>
</table>

Key:  
Super-critical  
Trans-critical  
Sub-critical
guided by the Kelvin angle realized at the aft end of the domain.

Figure 6 shows a perspective view of the wave field for Cases 1, 7 and 11, corresponding to a vessel speed of 25 knots and depth Froude numbers of 2.371, 0.968, and 0.750 respectively. The wave field plots display the classic flow patterns associated with super-critical, trans-critical and sub-critical ship flows respectively.

Figure 6. Perspective View of Calculated Ferry Wave Field for Different Flow Regimes.
Vessel Speed = 25knots (Fr=0.921):
Fh=2.371 (Top), 0.968 (Center) and 0.750 (Bottom)

The number of panels in the calculation ranged from 10,200 to 12,700 and computer run times ranged from 70 minutes to 9.5 hours on an Intel Pentium® personal computer having a 3.4 GHz processor and 2GB of random access memory. Longitudinal and transverse wave cuts
were evaluated at a number of locations, from 0.2 L to 6.0 L off the sailing line (for longitudinal wave cuts) and from 0.2 L to 13 L downstream of the transom (for transverse wave cuts).

Representative results of longitudinal wave cuts are presented below. For the off-track locations shown in Figure 7, Figure 8 presents some longitudinal wave cuts at 25 knots (corresponding to Cases 1, 7 and 11).

The steady wave system of the catamaran as described by the longitudinal and transverse wave cuts are used to determine the free-wave spectra. This is described in the next sub-section.

Field wake wash measurements were conducted near the proposed new ferry terminal in accordance with an appropriate wake measurement protocol [1]. The tests incorporated numerous runs with the ferry past a set of two wave gages, one near the sailing line and one in the far field. The data were processed and analyzed and found to be of high quality and conclusive for use on this study as well as future studies. A comparison of the calculated and measured longitudinal wave cuts (Figure 9) shows that CFD correctly captures the trends in the data. However, CFD over-predicts the calculated wave heights. This is partly because the data were obtained for a lighter loading condition and partly, but is consistent with potential-flow CFD generally over-predicting wave heights. The over-prediction means that the calculated wash waves and the wash impacts would be conservative.
Free-Wave Spectra

The free-wave spectrum fully characterizes the Kelvin wave system of a ship in the far field. The advantage of obtaining free-wave spectra is that they may be used to calculate wave elevations in the far field. The free-wave spectrum may be obtained from wave elevation measurements that are sufficiently far away from the nonlinear local wave system near the hull (typically at off-track distances of $Y/L \sim 0.5$ or greater). Reference [13], while not actually used in the present study, is a seminal paper that describes a widely used procedure for determining the free-wave spectrum. However, it is limited to the case of infinitely deep water.

For the evaluation of free-wave spectra in waters of finite-depth, in the present study, a different method following the formulation described in [14] was implemented. A description of the wave pattern analysis method is presented in [15].

The spectral analysis for each of the 28 cases was conducted both for a set of longitudinal and a set of transverse wave cuts. Illustrative free wave spectra (cosine and sine components, $F$ and $G$ respectively) are presented in Figure 10.

Lastly, the variance or spectral energy density spectrum as a function of frequency (or wave propagation direction) was obtained for the ship wave system from the free-wave spectra components. These were provided as input into a numerical method for performing wave
propagation and transformation modeling over varying bathymetry, so that the impact of the ferry wakes on the shoreline could be studied. Figure 11 presents a snapshot from the ferry wake transformation and propagation modeling over the large areas of San Pablo Bay.

Figure 11. Snapshot from a Modeling of Ferry Wake Transformation and Propagation in San Francisco Bay (Adapted from Reference [1])

Subsequently, shoreline/mudflat sediment transport analysis may be performed to determine potential impacts of the ferry’s wash waves, as presented in [1].

Conclusions

The present paper describes the analysis of ferry wake wash impact along a proposed route between San Francisco and a new terminal at Hercules. The steady wave field generated by a candidate catamaran ferry was calculated for a range of vessel speeds and water depths, using established computational fluid dynamics (CFD) techniques. The free-wave spectra which fully characterize the ship-generated wave system in the far field are also calculated and presented, including for shallow water cases. The calculated ferry wakes and the free-wave spectra enable the propagation and transformation of the wave system into the far field over varying bathymetry, so that the impact of ferry wakes on the shoreline may be studied.

The analysis is part of a broader “shoreline and biological response” approach to wake wash impact analysis. The approach contains site-specific elements, but the process may also be applied to evaluate wake wash impact of specific, yet-to-be-built ferries on other future routes. The approach may be applied to mitigate wake wash problems in the following ways:

- establishing a rational basis for limiting vessel wave height/period/energy
- establishing ferry routes and speeds and other operational criteria
- assisting in vessel traffic control, vessel mooring and berthing at ferry terminals, and harbor maintenance
- suggesting hull design improvements so as to meet site-specific, route-based operational criteria in the following ways:
  - operational recommendations:
    - to help establish ferry routes and speeds
    - to help establish a rational basis for limiting vessel waves
    - to assist in vessel traffic control, vessel mooring and berthing at ferry terminals, and harbor maintenance
engineering recommendations:
  – for hull optimization in designing, so as to meet any site-specific, route-based regulations

References