THE EFFECTS OF SHIP LOAD VARIATIONS AND SEASTATE
ON HULL GIRDER DEFLECTION AND COMBAT SYSTEM
ALIGNMENT

by

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B.S. Naval Architecture and Marine Engineering
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Submitted to the Department of
OCEAN ENGINEERING
in Partial Fulfillment of the Requirements
for the Degree of

MASTER OF SCIENCE IN NAVAL ARCHITECTURE AND MARINE
ENGINEERING

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
September, 1990

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Chairman, Departmental Graduate Committee
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Stuart Hayden Mennitt

Submitted to the Department of Ocean Engineering on 17 August 1990 in partial fulfillment of the requirements for the Degree of Master of Science in Naval Architecture and Marine Engineering

ABSTRACT

This thesis computationally analyzes the effect of commonly occurring ship load variations and wave induced bending moments on hull girder flexure. The deflection of the hull is used to determine the impact on the alignment of the vessel’s combat system. Simple beam theory is applied for the structural portion of the analysis. Wave induced bending moments are determined by using a quasi-static approach with regular waves. Calculations and results are presented for the FFG7 class of U.S. Navy frigates.

It is shown that commonly occurring load conditions produced no significant problems with the alignment of the ship’s combat system. The effect of waves can be more significant. Deflections of up to 9 arc minutes are predicted between elements of the combat system in seastate 6. This is out of the elements’ alignment tolerance and could affect the operability of the system.

Thesis Supervisor: Professor Richard Celotto
Title: Associate Professor of Naval Construction and Engineering
ACKNOWLEDGEMENTS

I would like to thank Professor Celotto for his guidance through the course of this thesis. His encouragement and suggestions kept this project moving and focused. This thesis could not have been realized without his help.

I would like to thank Professor Tibbitts for his assistance. His extensive knowledge of naval engineering was extremely helpful.

I want to thank my friends at MIT for their generous assistance. Cliff Whitcomb and Norbert Doerry deserve special recognition for their help in working through often frustrating technical obstacles.

I owe my appreciation to my colleagues at David Taylor Research Center, Naval Sea Systems Command, Supervisor of Shipbuilding and Repair, Research, Analysis & Management Corporation, and George G. Sharp, Incorporated for their prompt response to my requests for information.

I would like to thank my family for their constant support and encouragement during this project. They will always be an inspiration.

Finally, I want to thank David Taylor Research Center for providing me with the opportunity to be at MIT. Without their sponsorship, none of this would have been possible.

Sincerely,

Stuart Mennitt
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1. **Introduction**

A warship's effectiveness in combat depends predominantly on the effectiveness of its combat system. The effectiveness of a weapon system depends on proper interaction of its constituent subsystems. Modern naval combat systems are comprised of many complex subsystems. These subsystems are integrated in a way that attempts to maximize the overall performance of the vessel.

Various integrated systems and subsystems comprise a modern warship's combat system. This integration requires a correct exchange of information between the different systems and subsystems in order that the combat system function properly as a whole. The successful exchange of information requires both the actual passing of accurate electronic data and the use of a common physical frame of spatial reference. The latter is made possible by the physical alignment of combat system components relative to a common reference system.

Initial combat system alignment is accomplished at the shipyard as part of new construction. Once the vessel is in the fleet, the US Navy requires that the combat system be aligned periodically. A complete combat system alignment can take over a week and requires a certain ship loading condition as well as nearly constant sea and air temperature. It is only practical for a warship to undergo a complete combat system alignment when it is in a shipyard for construction, conversion, repair, or overhaul!

Complete combat system alignments are typically done during selected restricted availabilities which occur every eighteen to twenty-four months. Selected restricted availabilities are limited overhauls that usually last less than six months. The initial alignment, performed at the builder's shipyard, is required to be carried out while the ship
is floating at a displacement of at least 90% for Builder's Sea Trials.\footnote{General Specifications for Ships of the United States Navy, S9AA0-AA-SPN-010/GEN-SPEC, Naval Sea Systems Command, 1989, Section 184.} Thereafter, alignment procedures are required to be performed when the ship is at a condition of at least 80% of its total load.\footnote{Combat System Alignment Manual (CSAM) for FFG7 Class, SW225-B6-CSA-010/OP2456 FFG7 CL, 2nd Revision, Naval Sea Systems Command, 15 August 1987, p. 1-8.} Thus, effects such as transition from drydock to afloat, changed configuration, and settling of ship structure are minimized. While the 90% Builder’s Sea Trial displacement and "total load" specifications are vague, they attempt to bring the ship close to a full load condition for alignment.

During the period of time between these alignments, there are many factors that contribute to alignment degradation. Combat system alignment errors can be categorized as being either static or dynamic in nature. Tables 1-1 and 1-2 summarize these errors and the causes behind them.

The static misalignment errors in Table 1-1 are the result of improper alignment procedures and are not inherent in the ship’s design. Some of the errors mentioned in Table 1-2 are the result of poor design or integration of a weapon or component. The result of the latter is that the element cannot dynamically compensate for the vessel’s motion in a seaway.

Of the remainder of the causes of errors in combat system alignment, three are common to all surface combatants:

- Structural distortion due to thermal effects

\begin{thebibliography}{99}
\end{thebibliography}
- Structural distortion due to wave induced stresses
- Structural distortion due to loads depletion

Table 1-1: Static Alignment Error Sources

<table>
<thead>
<tr>
<th>Error</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Step-type errors</td>
<td>a. Transition from drydock to afloat</td>
</tr>
<tr>
<td></td>
<td>b. Structural distortion due to heavy seas, storms, etc.</td>
</tr>
<tr>
<td></td>
<td>c. Structural distortion due to configuration change (e.g., modernization of sonar equipment)</td>
</tr>
<tr>
<td></td>
<td>d. Fuel and ammunition loadout.</td>
</tr>
<tr>
<td>2. Static misalignment</td>
<td>a. Roller path inclinations of system equipment</td>
</tr>
<tr>
<td></td>
<td>b. Dial and synchro zero adjustment</td>
</tr>
<tr>
<td></td>
<td>c. Improper alignment from offset centerline, tram settings, benchmarks, etc.</td>
</tr>
<tr>
<td>3. Slowly varying errors</td>
<td>a. Fuel and ammunition depletion</td>
</tr>
<tr>
<td></td>
<td>b. Settling of ship structure (new ship, overhaul, etc.)</td>
</tr>
<tr>
<td></td>
<td>c. Solar/thermal expansion</td>
</tr>
</tbody>
</table>

Table 1-2: Dynamic Alignment Error Sources

<table>
<thead>
<tr>
<th>Error</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Hull distortion</td>
<td>a. Wave induced bending</td>
</tr>
<tr>
<td></td>
<td>b. Ship maneuvering</td>
</tr>
<tr>
<td>2. Other</td>
<td>a. Uncompensated roller path changes due to gun movement</td>
</tr>
<tr>
<td></td>
<td>b. Inability of stable element to reflect ship motion</td>
</tr>
<tr>
<td></td>
<td>c. Inability of weapon system to respond to ship movement</td>
</tr>
<tr>
<td></td>
<td>d. Ship internal equipment movement and vibration</td>
</tr>
</tbody>
</table>

The three modes of hull structural distortion are shown in Figure 1-1. Thermal effects and wave stresses can produce all three components. Load variations can induce hull flexure in only the vertical bending and torsional modes. The stresses that a seaway puts in a ship’s hull are generally most severe in the vertical bending mode. For this
reason, the primary stresses resulting from a wave induced bending moment are considered the main design criteria for the hull structural strength of most vessels.\cite{Principles of Naval Architecture, 2nd Revision, The Society of Naval Architects and Marine Engineers, Jersey City, NJ, 1988, Vol. 1, Section 3.}

![Figure 1-1: Modes of Hull Flexure](image)

Hull flexure caused by changes in loading is also primarily in the vertical bending mode. It is possible in most vessels to obtain some torsional flexure by diagonally distributing loads. This would, however, be a very uncommon occurrence for a warship. Load items tend to be consumed evenly when distributed port and starboard.

Like hull flexure caused by wave action and variations in loading, flexure due to thermal differentials in the hull structure is most often in vertical bending. The flexure is due to a temperature differential between regions of the hull structure. This is most
common between the underwater portion of the hull and the above water portion. Figure 1-2 depicts a vessel that is undergoing flexure in vertical bending due to the temperature difference between the sea and the air. Uneven solar heating (port or starboard) would tend to flex the hull horizontally. Only a complex and unlikely combination of hull heating and cooling would result in a torsional flexure.

These three causes are of potential concern to the warship operator. For example, assume the vessel’s combat system is aligned with the ship near full load condition, in calm water, and in weather conditions that minimize temperature differences within the hull. The vessel then puts to sea. Fuel is used up, and ballast water is added. The ship encounters waves. The sun warms the hull above the waterline. The structure of the ship distorts as a result of these causes. The operator may assume his ship’s combat system is still in alignment. It is possible that, without the operator’s knowledge, one or more of these causes has distorted the shape of the vessel to the point of creating significant misalignment between elements of the combat system. If the ship returns to port and the alignment is checked under conditions of hull temperature, load, and seastate similar to when the system was initially aligned, everything would be within specifications. The problem with misalignment in the operational environment would remain undetected.
This thesis presents a study of the effects of ship load variation and seastate on hull girder deflection and combat system alignment. A goal is to assess the possibility that US Navy ships may be operating at sea with combat systems not in alignment. The author acknowledges the significance of hull deflections due to temperature variations. Thermal effects on a ship’s structure are relatively complex and require detailed finite element analysis for meaningful results. Such an undertaking is beyond the scope of this project. The effects of load variations and seastate on hull girder deflection are, however, within the scope of this study.

The study focuses on the FFG7 class of US Navy frigates. Due to the nature of the calculations, it is not realistic to work with a generic ship. Although one can conjecture on a theoretical basis as to the qualitative effects of shipboard load changes and seastate on combat system alignment, to determine the magnitude of the effects and ascertain whether or not any cause for concern exists requires studying a defined vessel. Specific information is required concerning hullform, scantlings, and lightship and loads weight distribution. It is expected that this study will be of interest to the operators of these vessels as well as to US Navy ship designers and combat system engineers.

Calculations are made at four load conditions: full load, 80% fuel load, 60% fuel load, and minimum operating condition. The still water condition is used to establish baseline deflection and alignment. Wave effects are analyzed at the full load condition using the quasi-static method. Regular trochoidal wave profiles of varying heights are used to represent seastates 2, 4, and 6.
2. **Description of the FFG7 Class Frigate**

The FFG7 class is the most modern frigate in the US Fleet. The first ship of the class was commissioned in December of 1977. A total of fifty-four have been built, with the final ship in the class, the FFG61, being commissioned in July of 1989.

Table 2-1\(^5\)[,\(^6\] contains some characteristics of the FFG7 class. FFG8 and later ships of the class, FFG36-61, are modified to incorporate the Light Airborne Multi-Purpose System Mk III (LAMPS III). The major components of this upgrade are the SH-60B helicopter and the Recovery Assist Secure and Traverse (RAST) system. The transom of these modified ships are angled aft to provide more space for the RAST equipment and the larger helicopters. The total displacement is higher due to both a higher lightship weight and additional loads. The hull scantlings on the LAMPS III frigates are increased slightly to provide the additional hull strength needed due to the higher displacement.\(^7\)

The FFG7’s primary mission is anti-submarine warfare (ASW). It also has secondary capabilities in anti-air (AAW) and anti-surface warfare (ASU). The combat system of the FFG7 class is described in Table 2-2\(^8\)[,\(^9\]. Also included in Table 2-2 are navigational and radio elements that are sensitive to alignment. Figure 2-1 contains

---


\(^6\)FFG61 Final Weight Estimate, July 1989, Gibbs & Cox, Inc.

\(^7\)FFG36-61 Longitudinal Strength and Inertia Sections Drawing, NAVSHIPS Drawing No. PF109-802-5414870.

\(^8\)Jane’s Fighting Ships 1988-89, pp. 762-3.

Table 2-1: FFG7 Class Dimensions

<table>
<thead>
<tr>
<th>Item</th>
<th>FFG7, 9-35</th>
<th>FFG8, 36-61</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASW</td>
<td>LAMPS I</td>
<td>LAMPS III</td>
</tr>
<tr>
<td>Helicopters</td>
<td>2 x SH-2F</td>
<td>2 x SH-60B</td>
</tr>
<tr>
<td>RAST</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>LBP</td>
<td>408'-0&quot;</td>
<td>408'-0&quot;</td>
</tr>
<tr>
<td>LOA</td>
<td>445'-0&quot;</td>
<td>453'-0&quot;</td>
</tr>
<tr>
<td>B-max</td>
<td>46'-11.5&quot;</td>
<td>46'-11.5&quot;</td>
</tr>
<tr>
<td>D-amidship</td>
<td>30'-0&quot;</td>
<td>30'-0&quot;</td>
</tr>
<tr>
<td>Disp.:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lightship</td>
<td>2750 ltons</td>
<td>3096 ltons</td>
</tr>
<tr>
<td>Full Load</td>
<td>3585 ltons</td>
<td>3987 ltons</td>
</tr>
<tr>
<td>Machinery:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Main Engines</td>
<td>2 LM2500 gas turbines,</td>
<td>2 LM2500 gas turbines,</td>
</tr>
<tr>
<td></td>
<td>41000 shp total</td>
<td>41000 shp total</td>
</tr>
<tr>
<td>Auxiliary</td>
<td>2 x 325hp auxiliary propulsion units</td>
<td>2 x 325hp auxiliary propulsion units</td>
</tr>
<tr>
<td>Generators</td>
<td>4 x 1000 Kw diesel generators</td>
<td>4 x 1000 Kw diesel generators</td>
</tr>
<tr>
<td>Speed, Sustained</td>
<td>29 knots</td>
<td>29 knots</td>
</tr>
<tr>
<td>Range</td>
<td>4500 nm @ 20 knots</td>
<td>4500 nm @ 20 knots</td>
</tr>
</tbody>
</table>

an outboard profile of the FFG7 class and shows the location of many of the items in Table 2-2. Figure 2-1 also specifies alignment tolerances which are described in Chapter 3.
### Table 2-2: FFG7 Class Combat System

<table>
<thead>
<tr>
<th>Primary Combat System Components</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Missiles:</strong></td>
<td></td>
</tr>
<tr>
<td>Mk 13 Launcher</td>
<td>Single arm launcher, 40 round rotary magazine, launches SM1-MR (medium range) AAW and Harpoon ASU missiles.</td>
</tr>
<tr>
<td><strong>Guns:</strong></td>
<td></td>
</tr>
<tr>
<td>Mk 75 76mm</td>
<td>Dual-purpose rapid fire 76mm gun capable of engaging both air and surface targets.</td>
</tr>
<tr>
<td>Mk 15 CIWS</td>
<td>Close in weapons system, point anti-missile defense, 20mm radar controlled gun.</td>
</tr>
<tr>
<td><strong>Torpedoes:</strong></td>
<td></td>
</tr>
<tr>
<td>2 Mk 32 Launchers</td>
<td>Two triple tube mounts firing Mk 46 lightweight ASW torpedoes.</td>
</tr>
<tr>
<td><strong>Countermeasures:</strong></td>
<td></td>
</tr>
<tr>
<td>4 Mk 36 SRBOC</td>
<td>Super rapid-blooming offboard chaff. Launches chaff canisters and infra-red decoys.</td>
</tr>
<tr>
<td>SLQ 32V(2)</td>
<td>ESM/ECM, threat radar warning receiver.</td>
</tr>
<tr>
<td>SLQ-25 NIXIE</td>
<td>Torpedo decoy/countermeasure system.</td>
</tr>
<tr>
<td><strong>Fire Control:</strong></td>
<td></td>
</tr>
<tr>
<td>Mk 92 Mod 2 FCS</td>
<td>Integrated missile and gun fire control.</td>
</tr>
<tr>
<td>2 Mk 24 TDT</td>
<td>Target designation transmitter, optical manual sight for Mk 75 gun.</td>
</tr>
<tr>
<td><strong>Radars:</strong></td>
<td></td>
</tr>
<tr>
<td>SPS 49</td>
<td>Long range two-dimensional (range and bearing) air search radar.</td>
</tr>
<tr>
<td>SPS 55</td>
<td>Surface search/navigation radar.</td>
</tr>
<tr>
<td>SPG 60 STIR</td>
<td>Separate target illumination radar, director for SM1-MR and Mk 75 gun in AAW mode.</td>
</tr>
<tr>
<td>Mk 92 CAS</td>
<td>Combined antenna system, search and track for Mk 92 FCS and director for Mk 75 gun in ASU mode.</td>
</tr>
<tr>
<td><strong>Sonars:</strong></td>
<td></td>
</tr>
<tr>
<td>SQS 56</td>
<td>Active/passive hull mounted sonar.</td>
</tr>
<tr>
<td>SQR 19 TACTAS</td>
<td>Passive towed array sonar.</td>
</tr>
<tr>
<td><strong>Helicopters:</strong></td>
<td></td>
</tr>
<tr>
<td>2 SH-2F or</td>
<td>LAMPS I</td>
</tr>
<tr>
<td>2 SH-60B</td>
<td>LAMPS III</td>
</tr>
<tr>
<td><strong>Other Alignment Sensitive Equipment</strong></td>
<td></td>
</tr>
<tr>
<td>URN-25 TACAN</td>
<td>Tactical air navigation system.</td>
</tr>
<tr>
<td>URD-4</td>
<td>Radio direction finding device.</td>
</tr>
<tr>
<td>WSN-2</td>
<td>Gyrocompass, primary.</td>
</tr>
<tr>
<td>Mk 27 GC</td>
<td>Gyrocompass, backup.</td>
</tr>
<tr>
<td>Pelorus Stand</td>
<td>Optical orientation determination apparatus.</td>
</tr>
<tr>
<td>SGSI</td>
<td>Stabilized glide slope indicator, for helicopter landing approach.</td>
</tr>
</tbody>
</table>
Figure 2-1: FFG7 Class Outboard Profile
Figure 2-2: FFG7 Class Combat System Block Diagram
3. **Alignment Requirements and Tolerance**

To achieve the performance of which a combat system is capable, each subsystem must be physically aligned to required tolerances. Alignment tolerances are based on individual equipment criteria and represent the minimum acceptable standards of alignment. At the same time, alignment tolerances must be realistic, considering both that which is achievable in an industrial environment as well as maintainable in an operational environment. Only when this alignment is maintained can the combat system be expected to satisfy tactical requirements.

Each component that is sensitive to alignment must be aligned to a common reference to ensure a proper exchange of data between the various systems and subsystems. All missile launchers, gun bores, radar antennas, fire control directors, gyrocompasses, and other directional pointing equipment must be able to achieve a parallel condition with each other. These pointing lines must be able to remain parallel within acceptable tolerances. Combat system alignment refers to establishing this parallelism.

Combat system alignment is based on the concepts of parallel lines and planes and reference frames. The lines which are of interest are referred to as pointing lines. The pointing line may be a centerline of a torpedo tube, a propagation axis of a radar antenna, or a bore axis of a gun. The planes of interest are usually those in which the individual combat system components rotate. A reference frame is a combination of a fixed
reference point, reference plane, and reference direction. A reference frame is used as a coordinate system to measure individual component planes and pointing lines.\[10\]

During new vessel construction the ship base plane (SBP) is the first reference plane to be established. The SBP is a horizontal plane that includes the ship’s baseline. The centerline reference plane (CRP) is a vertical perpendicular to the SBP and includes the ship’s centerline. The master reference plane (MRP) is a plane above the baseline that is parallel to the SBP. The MRP is defined early in the ship’s construction by a master level block (MLB). The MLB is typically represented by a heavy machinery foundation or combination of foundations. In the FFG7 class the MLB is located in Auxiliary Machinery Room 1 (AMR 1). As the name implies, the MLB serves as a physical reference for further construction alignment. After construction, the MLB is only used in case of major damage or structural changes. The weapon control reference plane (WCRP) is then established. During new construction the WCRP is aligned parallel to the MLB (and thus to the MRP and SBP).

The WCRP serves as a reference plane for all combat system alignment requirements throughout the life of the ship. Equipment that rotates in a vertical axis does so about its roller path. For each of these components, the plane in space perpendicular to its vertical axis of rotation is called the roller path plane for that component. The roller path plane (RPP) of the Mk 75 76mm gun mount is the WCRP for the FFG7 class. Figure 2-1 shows the relative location of the Mk 75 gun relative to the other components of the FFG7 class combat system.


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Reference marks are required in addition to reference planes. The main reference marks used are either on the ship’s centerline or parallel to the centerline with a horizontal offset. Like the reference planes, the reference marks are established during new construction and are not altered under normal conditions.

The RPP’s of all equipment in the combat system are aligned to the WCRP. This is usually done during initial construction by machining the roller paths and or their foundations. After machining, the parallelism between RPPs is checked. Any angle between two RPPs is referred to as the roller path inclination (RPI). The machining of each roller path must meet a specified RPI tolerance. Depending on the particular piece of equipment, it may be possible to later adjust the RPP with shims, leveling rings, or adjusting screws. If this second adjustment is possible, there will be a second set of RPI tolerances referred to as operational RPI tolerances. Both the foundation machining and operational RPI tolerances for the FFG7 class combat system are shown in Table 3-1[11].

The next alignment procedure is to perform train and elevation adjustments. The purpose is to ensure that all relevant elements of the combat system aim at the same point in space. Two methods are used for train and elevation alignment. One is train and elevation zero alignment. Each element of the combat system is brought to zero train (parallel to the CRP) and zero elevation (parallel to its RPP). This is accurately done using boresight telescopes and theodolites. A theodolite is an optical device similar to a surveyor’s transit used to verify horizontal and vertical angles with precision. When zero train and elevation is reached, the controlling mechanism for each item being aligned is set to reflect the zero train and elevation condition.

### Table 3-1: FFG7 Roller Path Inclination Tolerances

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Foundation machining</th>
<th>Operational roller path inclination</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tolerance</td>
<td>Reference</td>
</tr>
<tr>
<td>Master Level Block</td>
<td>±0.5°</td>
<td>SCBP</td>
</tr>
<tr>
<td>SPS-49</td>
<td>±10°</td>
<td>MLB</td>
</tr>
<tr>
<td>SPS-55</td>
<td>±20°</td>
<td>MLB</td>
</tr>
<tr>
<td>AS-3316/SLQ-32</td>
<td>±90°</td>
<td>MLB</td>
</tr>
<tr>
<td>CW-1186/SLQ-32</td>
<td>±30°</td>
<td>MLB</td>
</tr>
<tr>
<td>Mk 36 Launcher</td>
<td>±2°</td>
<td>MLB</td>
</tr>
<tr>
<td>CIWS</td>
<td>±20°</td>
<td>MLB</td>
</tr>
<tr>
<td>SQS-56 Transducer</td>
<td>±10°</td>
<td>MLB</td>
</tr>
<tr>
<td>SVTT 32</td>
<td>±30°</td>
<td>MLB</td>
</tr>
<tr>
<td>CAS</td>
<td>±20°</td>
<td>MLB</td>
</tr>
<tr>
<td>STIR</td>
<td>±5°</td>
<td>MLB</td>
</tr>
<tr>
<td>Mk 13 Launcher</td>
<td>±3°</td>
<td>MLB</td>
</tr>
<tr>
<td>Mk 75 Gun (WCRP)</td>
<td>±3°</td>
<td>MLB</td>
</tr>
<tr>
<td>TDT 24</td>
<td>±20°</td>
<td>MLB</td>
</tr>
<tr>
<td>URN-25</td>
<td>±60°</td>
<td>MLB</td>
</tr>
<tr>
<td>URD-4</td>
<td>±60°</td>
<td>MLB</td>
</tr>
<tr>
<td>WSN-2</td>
<td>±20°</td>
<td>MLB</td>
</tr>
<tr>
<td>Mk 27</td>
<td>±20°</td>
<td>MLB</td>
</tr>
<tr>
<td>Pelorus Stand</td>
<td>±20°</td>
<td>MLB</td>
</tr>
<tr>
<td>SGSI</td>
<td>±60°</td>
<td>MLB</td>
</tr>
</tbody>
</table>
Table 3-2: FFG7 Train and Elevation Alignment Tolerances

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Construction tolerance</th>
<th>Operational tolerance(^1)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Train(^2)</td>
<td>Elevation(^3)</td>
</tr>
<tr>
<td>Master Level Block</td>
<td>±0.5'</td>
<td>N/A</td>
</tr>
<tr>
<td>SPS-49</td>
<td>±30'(^1)</td>
<td>N/A</td>
</tr>
<tr>
<td>SPS-55</td>
<td>±30'</td>
<td>N/A</td>
</tr>
<tr>
<td>AS-3316/SLQ-32</td>
<td>±30°(^6)</td>
<td>N/A</td>
</tr>
<tr>
<td>CW-1186/SLQ-32</td>
<td>±30'</td>
<td>N/A</td>
</tr>
<tr>
<td>Mk 36 Launcher</td>
<td>±2°</td>
<td>N/A</td>
</tr>
<tr>
<td>CIWS</td>
<td>±20'</td>
<td>N/A</td>
</tr>
<tr>
<td>SQS-56 Transducer</td>
<td>±5'</td>
<td>N/A</td>
</tr>
<tr>
<td>SVTT 32</td>
<td>±60'</td>
<td>N/A</td>
</tr>
<tr>
<td>CAS</td>
<td>±1'</td>
<td>N/A</td>
</tr>
<tr>
<td>STIR</td>
<td>±1'</td>
<td>±1'</td>
</tr>
<tr>
<td>Mk 13 Launcher</td>
<td>±5'</td>
<td>±3'</td>
</tr>
<tr>
<td>Mk 75 Gun(WCRP)</td>
<td>±2'</td>
<td>±2'</td>
</tr>
<tr>
<td>TDT 24</td>
<td>±30'</td>
<td>±30'</td>
</tr>
<tr>
<td>URN-25</td>
<td>±60'</td>
<td>N/A</td>
</tr>
<tr>
<td>URD-4</td>
<td>±60'</td>
<td>N/A</td>
</tr>
<tr>
<td>WSN-2</td>
<td>±1°(^7)</td>
<td>N/A</td>
</tr>
<tr>
<td>Mk 27</td>
<td>±2°(^7)</td>
<td>N/A</td>
</tr>
<tr>
<td>Pelorus Stand</td>
<td>±12°</td>
<td>N/A</td>
</tr>
<tr>
<td>SGSI</td>
<td>±60°</td>
<td>N/A</td>
</tr>
</tbody>
</table>

NOTES:
1. Operational tolerances are achieved by various shipboard alignment procedures including horizon checks, star checks.
2. Referenced to the CRP.
3. Referenced to the RPP.
4. Referenced to the CAS.
5. Limit for roll and pitch is ±2' operational, and ±1' for optical alignment.
6. This tolerance becomes ±12° for ships equipped with the enhanced Band 1 antennas.
7. Construction train for these units represents the azimuth alignment tolerance to be met during optical alignment.
8. Operational train tolerance for these units include system alignment errors, heading accuracy, and alignment changes caused by ship's flexure due to mechanical, thermal, and dynamic loading (dockside only)
9. Tolerance for benchmarks is ±5°.
10. Tolerance for tram checks is ±3°.
The alternate method is a train and elevation space alignment. Boresight telescopes are used to bring the point lines of the combat system components to bear on a star. The range of the star ensures a negligible parallax error. Table 3-2\textsuperscript{[12]} contains a summary of the FFG7 class train and elevation tolerances.

\textsuperscript{[12]} \textit{Combat System Alignment Manual (CSAM) for FFG7 Class}, p. 2-3.
4. Hull Deflections Due to Changes in Loading

The calculation of hull deflection relies on the application of simple beam theory, which is commonly used in the analysis of ship hull girder primary stress and deflection. The hull is treated as a simply supported beam that has a distributed load applied. "Simply supported" implies that there are no concentrated moments applied to the hull girder. To be in static equilibrium the sum of the loads in any direction equals zero. This relates to the hydrostatic principle of a floating body's buoyancy being equal to its weight. The shear and moment is zero at the ends of the hull girder.\[13],[14]

Many validations of the application of simple beam theory to ship hull bending behavior prediction have been documented.\[15]\n
The following steps are taken in calculating hull deflections caused by both load variations and seastate:

1. Develop the longitudinal weight distribution of the ship in a baseline load condition.

2. Determine the still water longitudinal buoyancy distribution for the ship in the baseline condition.

3. Calculate the longitudinal shear distribution by integrating the load distribution (load=buoyancy-weight).

4. Calculate the longitudinal moment distribution by integrating the shear distribution.

\[13\] Principles of Naval Architecture, p. 235.
\[15\] Principles of Naval Architecture, p. 235.
5. Calculate the hull deflection by performing a double integration of the moment and structural inertia distributions. The hull material modulus of elasticity must be included.

6. Repeat steps 1-5 using a new load condition or incorporating wave conditions in step 2.

The first step is to develop the longitudinal weight distribution of the ship in a baseline load condition. Due to minor changes during construction and outfitting, the weights vary slightly between ships in a class. It is appropriate to choose one ship for purposes of weight data. A detailed final weight report was available for FFG61. This weight report for the FFG61 is used throughout this study for all weight information.

The longitudinal strength drawings for FFG36-61 are also used. As mentioned in Chapter 2, these ships (FFG36-61) are of greater displacement than FFG7-35. FFG36-61 also have heavier scantlings near the keel and shear strake from stations 9 through 13. The longitudinal strength drawings present a graphical representation of the longitudinal weight distribution for FFG36-61 in the full load condition. The weight is described by values in units of long tons (ltons) per foot between each of stations 0 through 20. The weight of the ship forward of the forward perpendicular and aft of the aft perpendicular is also included. The weight values are assumed constant between stations.

The full load displacement mentioned on the more generic FFG36-61 strength drawing is slightly lower than the full load displacement in the FFG61 weight report (3914 ltons vs. 3987 ltons). To reconcile this slight discrepancy, the strength drawing full load weight distribution values are scaled proportionally so that the full load total weight is that of the FFG61. The final step is to convert the ltons per foot values to ltons. This
is done by multiplying the tons per foot values by the appropriate station spacing. The result is used as input to the Ship Hull Characteristics Program (SHCP). Appendix A contains spreadsheets that show both the full load longitudinal weight distribution and the weight distribution for conditions less than full load.

The next three steps are the computation of longitudinal buoyancy, shear, and moment distribution. The Ship Hull Characteristics Program (SHCP) is used for these steps. SHCP is the US Navy’s standard hydrostatics program. The primary input is a numerical description of the hullform using a set of hull offsets. SHCP contains subprograms that perform such naval architectural calculations as trim lines, longitudinal strength, floodable length, and intact stability.\(^{16}\)

The longitudinal strength module of SHCP is used to derive the longitudinal moment distribution in all load and seastate variations studied. Figure 4-1 is a body plan generated by SHCP using the offsets for FFG36-61. Figure 4-2 presents an isometric view of the hull as modelled.

The longitudinal strength module of SHCP calculates a longitudinal hydrostatic buoyancy distribution using the longitudinal weight distribution and the hull offsets. SHCP calculates the longitudinal center of gravity (LCG) and displacement from the given weight distribution. The program next calculates the draft and trim corresponding to this LCG and displacement. SHCP determines the buoyancy for each section of the hull between stations. The net load on each section is the difference between the buoyancy and the weight. SHCP integrates the load longitudinally to determine the shear

at each station. The shear is then integrated to determine the bending moment at each station.

The SHCP longitudinal strength module output consists of a file containing an input summary and values for buoyancy, shear, and moment organized by station. SHCP also provides graphical representations of these data. Appendix B contains the SHCP output files showing the shear and bending moment values for each condition. The
Figure 4-2: SHCP Isometric View of FFG36-61
graphic SHCP output is also included in Appendix B. The moment values at each station are used in the remainder of the calculations.

Simple beam theory is now applied to derive the hull deflection. The differential equation for the elastic curve of a beam is

\[
\frac{d^2y}{dx^2} = \frac{M(x)}{EI(x)}
\]  

(1)

where:

- \( x \) = length along the beam's axis
- \( y \) = deflection perpendicular to the axis
- \( M(x) \) = moment along the axis
- \( I(x) \) = area moment of inertia of beam section
- \( E \) = modulus of elasticity of beam material

Integrating this equation twice gives an expression for the deflection at any point along the \( x \)-axis of the beam:

\[
\frac{dy}{dx} = \frac{1}{E} \int_0^d \frac{M(x)}{I(x)} \, dx + a
\]

(2)

\[
y(d) = \frac{1}{E} \int_0^d \int_0^d \frac{M(x)}{I(x)} \, dx \, dx + ad + b
\]

(3)

where:

- \( d \) = distance along \( x \)-axis

The hull girder can be assumed to flex relative to a straight line between the forward and aft ends. The deflections at these points are zero.

\[
y(0,L) = 0
\]

(4)
Applying these boundary conditions allows one to solve for the constants of integration:

\[
a = -\frac{1}{EL} \int_0^L \int_0^L \frac{M(x)}{I(x)} \, dx \, dx
\]

(5)

\[b = 0\]

(6)

The final equation for the deflection of a beam of length L simply supported at each end is:

\[
y(d) = \frac{d}{E} \int_M^d \int_0^L \frac{M(x)}{I(x)} \, dx \, dx - \frac{d}{LE} \int_0^L \int_0^L \frac{M(x)}{I(x)} \, dx \, dx
\]

(7)

The integrations are performed using the trapezoidal rule approximation on a station-by-station basis. Between each station the appropriate values for the bending moment and moment of inertia are used. Because the hull material is constructed entirely of steel, a constant value, 13,400 ltons/in², is used for the modulus of elasticity.¹¹⁷

Following the previously described procedure results in the still water deflection for the FFG61 in full load condition. To investigate the effects of altering the loading condition, three other load conditions are checked. They are:

1) full load except for an 80 percent fuel load,

2) full load except for a 60 percent fuel load, and

3) minimum operating condition.

The hull flexure is calculated for a condition of all loads at full load except for fuel, which is at 80% of full load. This second load condition depicts a probable

¹¹⁷"Longitudinal Strength Calculations", Design Data Sheet (DDS) 2900-1-q, Department of the Navy, 27 December 1950.
operational condition. Fuel is the only load item of any significant weight to fluctuate during routine operations. Warships typically operate with replenishment vessels and take on fuel and stores often. Frigates will usually refuel when close to the point of 80% fuel remaining.

The fuel is next reduced to 60% of full load. This condition is a realistic lower limit for actual operational conditions. US Navy ships will rarely go below the 60% fuel point. As with the 80% fuel condition, all loads except ship's fuel are left at their full load values. Ballast seawater is added at the 60% fuel condition. This is discussed later in this chapter.

The minimum operating condition is used as a lower limit for load conditions. Minimum operating condition, or Condition B, is a load condition both recognized and well defined by the US Navy. Appendix A shows how the various loads are adjusted for the minimum operating condition.\[^{18}\]

The minimum operating condition is often used for stability predictions. For this reason, items typically stored high on the ship (missiles, torpedoes, depth charges, and aircraft) are at their full load values. Most of the other load items (i.e., aircraft and ship fuel, lube oil, provisions, and ammunition) are at one-third of their full load values in the minimum operating condition.\[^{19}\]

The minimum operating condition denotes a worst case load condition from an operational standpoint. A US Navy frigate at sea would rarely, if ever, reach the minimum operating condition.


\[^{19}\]Ibid.
The FFG7 class has fuel oil storage tanks distributed longitudinally from frame 56 to frame 250. How fuel is distributed between these tanks influences the hull deflection. Each class of US Navy ship is provided with fuel and ballast sequence tables. These inform the crew as to what order fuel and ballast tanks should be used. The fuel and ballast sequence tables for the FFG7 class are used for determining the fuel and ballast distributions for the conditions involving fuel amounts below that of full load.

**Figure 4-3: Hull Deflections for Full Load, 80% Fuel, 60% Fuel, and Min. Ops.**

The calculations for the hull deflections, starting with the SHCP generated moment distributions, are included in Appendix C. Figure 4-3 presents a summary of the hull deflections for the full load, 80% fuel, 60% fuel, and minimum operating conditions. The FFG61 is in a hogging condition at full load. This can be predicted by examining the
SHCP plot of weight and buoyancy distribution for the full load still water condition included in Appendix B. The hogging condition increases at the 80% load, 60% load, and minimum operating condition. This is primarily because the larger fuel tanks are located towards amidship. These fuel tanks amidship are also the first to be emptied, as dictated in the FFG7 fuel and ballast sequence tables.

The 60% load and minimum operating condition result in similar deflections. This is because the primary load item is ship’s fuel. As fuel is reduced from 60% to the 33% specified for the minimum operating condition, seawater ballast is added to empty fuel tanks. This results in only a small change in weight and its longitudinal distribution.

No seawater ballast is specified at the full load or 80% fuel conditions. At the 60% fuel condition two ballast tanks are full. At minimum operating condition eight tanks are full of seawater ballast. These eight tanks include all four of the ship’s dedicated seawater ballast tanks. Some of these ballast tanks are towards the ends of the ship, thus further contributing to the higher hogging deflections at the 60% fuel and minimum operating condition.

The eight tanks containing ballast water at minimum operating condition include four fuel tanks that were emptied as fuel was consumed. Ballast water placed in empty fuel tanks is referred to as dirty ballast. Operators are very hesitant to use fuel tanks for ballast, even when doing so is specified for stability reasons. The ballast water inevitably contains some fuel which is discharged overboard when the tanks are emptied. There are also small amounts of seawater that remain in the fuel tanks and can contaminate the next load of fuel. The fuel and ballast sequence tables recommend that dirty ballast commence at a point when approximately 60% of the ship’s fuel is remaining. Below the point of
about 40% fuel remaining, only dirty ballast tanks remain to be filled. The 60% fuel condition represents the lowest fuel load attainable without resorting to using dirty ballast, as prescribed by the fuel and ballast sequencing tables.
5. **Hull Deflections Due to Wave Induced Bending Moment**

Analyzing hull deflections due to wave induced bending moments involves the basic steps presented at the beginning of Chapter 4. Instead of varying the load conditions, the hull is superimposed on a wave profile of varying height. Wave stresses are low-frequency dynamic loads that result in negligible dynamic amplification. This neglects any effects of slamming and hull whipping.

Wave primary stresses in the hull girder are often examined using quasi-static methods. Typically, the ship is considered in a state of static equilibrium on either the trough or the crest of a wave. The wavelength is usually taken as equal to the ship’s length to achieve the maximum effect on hull bending moment. As in a still water case, the weight of water displaced by the hull equals the ship’s weight. The longitudinal buoyancy distribution is calculated using the wave surface instead of the still water draft. The computations for load, shear, and moment distribution are identical to those for the still water condition.

SHCP uses the quasi-static method to calculate longitudinal distributions of hull bending moment in waves. Various combinations of wavelength, height, and longitudinal position can be specified. Regular trochoidal waves are used. For each wave profile, SHCP determines the draft that results in the correct displacement.

The quasi-static approach is an approximate method. It neglects the motions of the vessel and the hydrodynamic pressures between the hull and waves. Experimental data has shown the quasi-static method tends to overestimate the bending moments caused by waves.\(^{[20]}\)

A standard for US Navy hull structural design is the wave stress from a wave of height equal to $1.1\sqrt{LB\text{P}}^{[21]}$. For the FFG7, this results in a wave height of 22.2 feet for initial hull strength design criteria. It was decided to examine the effects of waves having heights equal to the mean values of the significant wave heights for seastates 2, 4, and 6. Seastate 6 has a average significant wave height of 16.4 feet. This is considered a sensible upper limit for purposes of evaluating the effects on combat system alignment. At seastates in this region, a frigate’s ability to fight is degraded from other causes. Ship motions at these higher seastates make conducting combat operations extremely difficult. Warships of frigate dimensions are typically required only to maintain mobility and maneuverability in higher seastates.

Table 5-1: Seastate 2, 4, and 6 Characteristics in North Atlantic

<table>
<thead>
<tr>
<th>SEASTATE NUMBER</th>
<th>AVERAGE SIGNIFICANT WAVE HEIGHT, ft.</th>
<th>MODAL WAVE PERIOD, T sec.</th>
<th>WAVELENGTH, BASED ON $L=5.118T^2$ ft.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MOST PROBABLE</td>
<td>RANGE</td>
<td>MOST PROBABLE</td>
</tr>
<tr>
<td>2</td>
<td>1.0</td>
<td>7.5</td>
<td>3.3-12.8</td>
</tr>
<tr>
<td>4</td>
<td>6.2</td>
<td>8.8</td>
<td>6.1-15.2</td>
</tr>
<tr>
<td>6</td>
<td>16.4</td>
<td>12.4</td>
<td>9.8-16.2</td>
</tr>
</tbody>
</table>

Table 5-1[22] contains statistical data on seastate occurrences in the North Atlantic. It must be noted that actual sea conditions are not usually the regular trochoidal

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waves that SHCP uses in its quasi-static analysis. Actual sea conditions are irregular and better represented by a spectrum of frequencies. To use such a spectral representation of the sea for these purposes would be beyond the scope of this thesis. The quasi-static method using regular trochoidal waves will yield results that are accurate enough to be of value.

A constant wavelength equal to the FFG7's LBP is used. Similar to using regular waves, using a constant value for the wavelength is a practice that simplifies the character of actual ocean waves. It is a simplification that will provide conservative results. A wave of any height will have a maximum effect on bending moment when its length is the same as that of the ship.

The SHCP output for the analyses of the ship in waves are included in Appendix B. The output lists tabular values for both the quasi-static buoyancy and the shear and bending moments. Each SHCP output file contains both hogging and sagging calculations for one wave height. The SHCP graphic output depicts the actual wave profile as well as the buoyancy, shear, and moment distributions. Figure 5-1 shows the hull deflection from the full load condition in seastates 0, 4, and 6. The deflections for seastate 2 are not included in Figure 5-1 because they are not appreciably different from the deflection at still water. It must be remembered that the deflections shown in Figure 5-1 are due to wave action and are dynamic with respect to the seastate 0 deflection. An interesting observation is that the hull experiences a true sagging moment only in the trough of a wave of seastate 6 height. As discussed in Chapter 4, this is due to the still water hogging condition of the ship.
**Figure 5-1:** Full Load Deflections in Seastates 0, 4, and 6
6. **Effects on Combat System Alignment**

The vertical deflections caused by load variations and seastate (Figure 4-3 and Figure 5-1) do not directly effect the combat system alignment. The maximum deflection from the full load still water condition calculated is about 6.6 inches in the seastate 6 sagging condition. What could pose a problem for the combat system alignment is the rotation between combat system components due to the hull deflection. As described in Chapter 3, all alignments are specified in minutes of arc. The angular displacement between the combat system components must be calculated to assess the impact of load variations and seastate on combat system alignment.

The steps taken in assessing the angular displacements are as follows:

1. Fit a curve to the displacements calculated in Chapters 4 and 5.
2. Take the derivative of the curve.
3. Use the derivative to obtain values for the slope of the hull at various longitudinal locations. Convert slopes to minutes of arc units.
4. Determine amount of rotation between various elements in combat system.
5. Evaluate these inter-element rotations relative to the full load condition.

This procedure has been used successfully by at least one shipyard for determining if a vessel complies with the intent of the 80% and 90% displacement requirements at the time of combat system alignment.\[23\]

The first step is to fit a curve to the calculated displacements. A fourth order polynomial is used for this purpose. The polynomial has the form

The coefficients in Equation (8), C, D, E, and F, are computed so the resulting polynomial will provide a least squares fit. The coefficients are found using the following matrix operations:

\[
A = \begin{bmatrix}
1 & x_0 & x_0^2 & x_0^3 & x_0^4 \\
1 & x_1 & x_1^2 & x_1^3 & x_1^4 \\
\vdots & \vdots & \vdots & \vdots & \vdots \\
1 & x_n & x_n^2 & x_n^3 & x_n^4 \\
\end{bmatrix}
\]

\[
U = \begin{bmatrix}
C \\
D \\
E \\
F \\
G \\
\end{bmatrix}
\]

\[
b = \begin{bmatrix}
b\sub{0} \\
b\sub{1} \\
b\sub{2} \\
b\sub{3} \\
b\sub{n} \\
\end{bmatrix}
\]

where \( x_1, x_2, \ldots, x_n \) = longitudinal locations where deflections are calculated

\( b_1, b_2, \ldots, b_n \) = calculated displacement values at locations \( x_1, x_2, \ldots, x_n \)

The matrix \( U \) containing the coefficients for Equation (8) is computed by the following group of operations involving matrices \( A \) and \( b \).

\[
U = (A^T A)^{-1} A^T b 
\]

where \( A^T \) = the transpose of matrix \( A \)

\( (A^T A)^{-1} \) = the inverse of the matrix product of \( A^T \) and \( A \)

The resulting matrix \( U \) contains the coefficients for the least squares fourth order polynomial curve. The actual matrix calculations are done on spreadsheets. The curve coefficients for each case are included in Appendix C.
The remaining steps in the calculations are straightforward. The spreadsheets in Appendix C show slopes and rotations in minutes of arc for the following components of the combat system:

- Mk 13 Missile Launcher (70 feet aft FP)
- CAS Fire Control Radar Antennae (120 feet aft FP)
- STIR Fire Control Illuminator (208 feet aft FP)
- Mk 75 Gun (240 feet aft FP)

These items were selected for analysis for two reasons. First, the Mk 13 and Mk 75 represent fore and aft limits of the FFG7's combat system. Second, they all are components associated with the fire control system and have relatively tight alignment tolerances. Other longitudinal locations can be investigated by using the derivatives of the appropriate deflection curves in Appendix C.

Table 6-1 shows the effects of the load variations on the inter-element alignment relative to the full load condition. It is assumed that the combat system is initially aligned when the ship is at full load. The still water deflection present in the full load condition would be taken into account during the alignment procedure. For this reason, Table 6-1 presents inter-element rotations relative to the full load state.

The rotations shown in Table 6-1 are largely influenced by the elements' longitudinal separation. The Mk 13 launcher and the Mk 75 gun show the largest rotation because they are the elements farthest away from each other. Likewise, the CAS and the Mk 13 are relatively close longitudinally and the alignment between them is not affected as much by hull flexure.
Table 6-1: Load Condition Effects on Inter-Element Alignment

<table>
<thead>
<tr>
<th>Combat System Element Pairs (not all element pairs shown)</th>
<th>Rotation Between Elements of Combat System Relative to Full Load at Specified Load Condition in arc-minutes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>80% Fuel Condition</td>
</tr>
<tr>
<td>Mk 75 - STIR</td>
<td>0.13</td>
</tr>
<tr>
<td>Mk 75 - CAS</td>
<td>0.41</td>
</tr>
<tr>
<td>Mk 75 - Mk 13</td>
<td>0.50</td>
</tr>
<tr>
<td>STIR - CAS</td>
<td>0.28</td>
</tr>
<tr>
<td>STIR - Mk 13</td>
<td>0.37</td>
</tr>
<tr>
<td>CAS - Mk 13</td>
<td>0.09</td>
</tr>
</tbody>
</table>

The inter-element rotational displacements are determined for the wave induced deflection cases using the procedure previously described. Figure 6-1 shows the inter-element rotations of the Mk 13, CAS, STIR, and Mk75 at seastates 0, 2, 4, and 6. As with the rotations in Table 6-1, those in Figure 6-1 are relative to the baseline full load seastate 0 condition. It must be remembered that the deflections caused by wave action are dynamic while those caused by load variations are effectively static. For example, the alignment between the CAS and the STIR in seastate 4 would be varying from -2.3 to +2.2 arc minutes as the vessel passes from wave crest to trough.

Comparing the magnitudes of the deflections in Table 6-1 with Figure 6-1 indicates that the deflections caused by seastate can be much more severe than those caused by load variations. The hull deflection caused from varying the load from full load to minimum operating condition is similar to the deflection caused by a wave.
slightly larger than the seastate 2 wave height used, about 2 feet.

It was initially intended to run combinations of load variations and seastates in order to obtain a matrix of results. The difference in magnitudes between the effects of the two indicated that this effort would be unproductive. A frigate is much more likely to encounter a seastate in the 4-6 range than it is in obtaining a minimum operating load condition.

The rotations calculated for both the load conditions and the seastate conditions are in the vertical centerline plane. The effects that the predicted rotations will have on the combat system will depend on the actual train and elevation to which the elements are directed. If, for example, the Mk 75 gun and the Mk 13 missile launcher are both
trained to 90° (from the bow) and at zero elevation, the rotations previously described will be along the pointing lines of the gun and launcher and will not effect the alignment. As the train deviates from 90° and/or the elevation angle increases from zero, the effects become pronounced.

The load variations examined have an insignificant effect on combat system alignment. The highest inter-element deflection is 1.14 arc minutes between the Mk 75 gun and the Mk 13 missile launcher. This is well within the gun's operational roller path inclination tolerance of ±3 arc minutes. Additionally, there is no actual need for the gun and the missile launcher to be precisely aligned. They are both directionally steered by the Mk 92 fire control system. The Mk 92 fire control system relies on the CAS, STIR, and WSN-2 gyrocompass for bearing and elevation input. It then feeds this information to the gun and launcher. The most demanding tolerance is for the WSN-2 gyrocompass and is ±1 arc minute for its operational roller path inclination. Since the CAS, STIR, and WSN-2 are longitudinally between the gun and missile launcher, the relative roller plane inclinations for "drive-driven" combinations of elements will be less than one minute of arc.

The effects of load variations on alignment becomes even less significant when one considers how infrequently a frigate attains a load case like the 60% fuel or minimum operating condition. The 80% fuel condition examined represents a much more realistic fluctuation from full load. At the 80% fuel condition, the relative inter-element inclinations are about one-half of the inclinations at the 60% fuel and minimum operating condition.
The effects of seastate on combat systems alignment are more significant than the effects of load variations. As previously mentioned, the element with the most demanding alignment tolerance is the WSN-2 gyrocompass at ±1 arc minute. The CAS and STIR radars have a tolerance of ±2 arc minutes. The Mk 75 gun has an elevation tolerance of ±2 arc minutes and a RPI tolerance of ±3 arc minutes. As shown in Figure 6-1, only pairs of elements very close to each other (Mk 13-CAS, STIR-Mk 75) have relative deflections of less than ±1 arc minute at seastate 4. Other combinations (CAS-STIR, Mk 13-STIR, and CAS-Mk 75) and are in the range of ±2 to ±3 arc minutes at seastate 4. This amount of rotation is at the limits of the RPI tolerances for these elements.

There are several operational consequences of the combat system components being out of alignment. The gun could be misaligned with its controlling radar. In the FFG 7 class the CAS performs both search and track functions for the Mk 92 fire control system. The gun could also be misaligned with the WSN-2 gyrocompass. The gun is depending on the gyrocompass for roll and pitch stabilization and the actual aim point would be fluctuating about the desired target. Both the WSN-2 and the CAS are longitudinally far from the gun. This amplifies the effects of any hull flexure.[24]

Ships with different combat systems can experience other problems. Many modern US Navy destroyers and cruisers depend on the accurate pointing of radar target illuminators for AAW engagements. The illuminators have a very narrow beamwidth and are aimed at the target by a separate tracking radar. Misalignment between the track

radar and the illuminator could cause an in-flight missile to lose its guidance signal. The FFG7's missile fire control illuminator, the STIR, has its own tracking capability and does not depend on another radar for train and elevation information once it has acquired a target. Precision remote electro-optical target designation devices also are sensitive to alignment variables. The FFG7 class uses an manual optical target designation transmitter for gun fire control, but it is not as sensitive as newer automated systems. The SPY-1D phased array radar system aboard the CG47 class cruiser is sensitive to having the array faces, which are mounted on separate deckhouses, maintaining alignment with respect to each other. The newer cruisers and destroyers also carry more modern AAW missiles having inertial reference units for midcourse guidance. These units are also sensitive to alignment.\[25\]

At seastate 6 all element combinations examined are outside of ±2 arc minutes of deflection relative to calm water. Two combinations, Mk13-STIR and Mk 75-CAS, are in the ±7 to ±10 arc minute range. This is well outside the RPI tolerances for all of these elements except the Mk 13 launcher. The launcher does have a ±5 arc minute tolerance for elevation alignment which is exceeded.

The element combination with the most severe relative deflection, the Mk 75 gun aft and Mk13 launcher forward, is not considered as significant as gun-radar or launcher-radar combinations. This is because the gun and launcher lack any direct functional relationship, i.e., one does not direct the other. This is taking a different approach than the alignment procedure, described in Chapter 3, takes. The alignment procedure uses the Mk 75 gun's roller path plane as the reference plane for aligning all

other elements. After an alignment, we are more concerned with how various factors degrade the operability of the system. To do this, the interdependence of the combat system components must be considered.
7. **Conclusions**

It has been shown that load variations do not significantly affect the operational alignment of the combat system of the FFG61. These results should apply to all of the LAMPS III equipped frigates in the class (FFG8, FFG36-61). Fuel is the only major load item that typically varies. Since the LAMPS I versions of the FFG7 class have similar fuel capacities, it follows that these results should also apply to the LAMPS I versions as well.

The effect of waves are also calculated. The results indicate that the waves cause enough flexure in the hull to be of concern. At seastate 4, the inter-element alignment fluctuates with magnitudes near the alignment tolerance for several of the components. At seastate 6, hull deflections result in misalignments on the order of 9 arc minutes between the CAS and Mk 75 gun and between the STIR and Mk 13 launcher. This exceeds the elements' individual operational roller path inclination and operational elevation alignment tolerances.

There are several assumptions made in determining the wave induced hull bending moments. One assumption involves the use of the quasi-static method. As mentioned in Chapter 5, the quasi-static method tends to overestimate the wave induced bending moment somewhat. It neglects ship motion and hydrodynamic pressures on the hull. A second assumption consists of the use of regular waves of length equal to LBP. Like the quasi-static method, the use of regular waves of length equal to LBP represents a conservative simplification of a complex situation.

A possibility for future research in this area would be to conduct a study on the effects of waves using a program based on strip theory. Strip theory would result in a
more accurate prediction of the moment distribution along the hull girder. This approach could also be combined with a statistical representation of waves at various seastates. Together, these two refinements would yield more accurate results.

This thesis does not attempt to account for misalignment due to deflections in masts, equipment supporting structures, and/or the ship's superstructure. The analysis of these structures would be best handled by finite element methods.

This thesis also omits the effects of structural distortions caused by temperature differences. Thermal distortions can affect the hull girder, the superstructure, and individual equipment foundations. When a hull encounters both cool water and warm air it will tend to hog. This flexure would add to the flexure caused by fuel being consumed. The combination may be significant. The combination of thermal effects and wave effects should not be of concern because extreme thermal deflections would typically not occur in unison with high seastates. Finite element analysis would be required to assess thermal effects.

The Ship Specifications for the DDG51 class of destroyer, the US Navy's most modern surface combatant, requires the computation of inter-element alignment variances for changes in loading, sea and air temperature, and wind speed. Based on the findings of this study, the effects of seastate should be included in this requirement.

The general US Navy requirements specifying a minimum vessel displacement for alignment purposes, mentioned in Chapter 1, are not effective. The intent is to insure that the hull is in a state of deflection during alignment that is similar to that at full load condition. For the FFG61, the displacement at minimum operating condition is 96% of the displacement at full load. The loads at minimum operating condition are reasonably
distributed because much of the consumed fuel is replaced by ballasting empty fuel tanks. If the displacement is only at the 80% full load specification, whether from the absence of loads or the removal of lightship items, the weight distribution could be considerably different than those analyzed in this thesis. Many load items are removed when a vessel is in a shipyard for repair or overhaul. Shipyard equipment on board also affects the weight distribution. It is possible to comply with the letter of this requirement without complying with the intent of the requirement.

During new construction combat system testing and checkout is usually done concurrently with the final stages of outfitting. Scheduling difficulties often necessitate conducting alignment procedures before the ship is near the full load condition. In this circumstance it would be possible to use the method presented to predict the flexure of the hull as compared to the flexure at full load condition. The differences could be included in the alignment process. As a result, the combat system would approach its desired alignment condition as the ship approaches the full load condition.

Modern naval combat systems have strict alignment tolerances. There is little that can be done to remedy the alignment problems mentioned after a ship is built. It would be beneficial to analyze potential problems with combat system alignment during contract design to ensure against compromising the combat system effectiveness in the conditions specified by the Top Level Requirements.
Appendix A: Longitudinal Weight Distributions

FULL LOAD AND 80% FUEL CONDITION ........................................ 52
FULL LOAD AND 60% FUEL CONDITION ........................................ 54
FULL LOAD AND MINIMUM OPERATING CONDITION ...................... 56
The spreadsheets in this Appendix A present the loads in the FFG61 Final Weight report in a tabular form. The full load condition is presented in the second column. If less than full load is desired, the adjustments can be entered, as a percentage of full load, in the third column. Ballast can be added in a similar fashion. If a load item has a capacity load (i.e., tanks) which is higher than its full load value, the capacity load is used for the percentage. The second portion of each spreadsheet computes a full load longitudinal 20-station weight distribution based on the FFG36-61 Longitudinal Strength Drawing. For less than full load conditions, the weight distribution by longitudinal section is adjusted accordingly.
**FFG61 LOADS AND LCQ's **
**FULL LOAD AND 80% FUEL CONDITION**

<table>
<thead>
<tr>
<th>LOAD ITEM</th>
<th>WT CAP</th>
<th>WT % OF FULL</th>
<th>WT AT</th>
<th>WT GIVEN</th>
<th>WT % OF GIVEN</th>
<th>WT FL</th>
<th>LCQ-MS</th>
<th>LCQ-EP</th>
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<tbody>
<tr>
<td>OFFICERS, CREW, &amp; EFFECTS</td>
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<td>100%</td>
<td>24.39</td>
<td>0.00</td>
<td>54.2</td>
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<td>100%</td>
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<td>0.00</td>
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<td>212.9</td>
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<td>MISSILES</td>
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<td>100%</td>
<td>24.55</td>
<td>0.00</td>
<td>130.0</td>
<td>74.0</td>
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<td>100%</td>
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<td>240.0</td>
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<td>3.15</td>
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<td>143.0</td>
<td>61.0</td>
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<td>100%</td>
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<td>SONOBUOYS</td>
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<td>153.0</td>
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**EXHAUST PIZER

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<th>WT % OF GIVEN</th>
<th>WT FL</th>
<th>LCQ-MS</th>
<th>LCQ-EP</th>
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<td>-94.0</td>
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**COLLECTING & HOLDING TANK

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<th>WT FL</th>
<th>LCQ-MS</th>
<th>LCQ-EP</th>
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**LUBE OIL STORAGE

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<th>WT FL</th>
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<th>LCQ-EP</th>
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<td>-70.6</td>
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<td>3-278-2 F</td>
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<tr>
<td>4-208-2 F</td>
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**LUBE OIL SETTLING

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<th>WT GIVEN</th>
<th>WT % OF GIVEN</th>
<th>WT FL</th>
<th>LCQ-MS</th>
<th>LCQ-EP</th>
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<tr>
<td>3-278-1 F</td>
<td>3.58</td>
<td>0.00</td>
<td>100%</td>
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<td>3.58</td>
<td>-77.9</td>
<td>281.9</td>
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<td>3-286-1 F</td>
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<td>100%</td>
<td>2.42</td>
<td>2.42</td>
<td>-84.7</td>
<td>288.7</td>
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**DIESEL OIL STORAGE

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<th>LCQ-EP</th>
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<td>5-56-0 F</td>
<td>14.83</td>
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<td>5-64-0 F</td>
<td>42.05</td>
<td>100%</td>
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<td>129.6</td>
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<td>5-84-162 F</td>
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<td>100%</td>
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<td>111.8</td>
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<td>5-100-364 F</td>
<td>65.40</td>
<td>66%</td>
<td>43.16</td>
<td>-22.24</td>
<td>92.3</td>
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<tr>
<td>5-116-162 F</td>
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<td>100%</td>
<td>133.72</td>
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<td>75.6</td>
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<td>5-140-162 F</td>
<td>57.86</td>
<td>87%</td>
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<tr>
<td>5-164-263 F</td>
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<td>100%</td>
<td>19.61</td>
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<tr>
<td>5-250-162 F</td>
<td>68.40</td>
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<td>0.00</td>
<td>-68.40</td>
<td>-59.8</td>
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**DIESEL OIL SERVICE

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<th>WT % OF GIVEN</th>
<th>WT FL</th>
<th>LCQ-MS</th>
<th>LCQ-EP</th>
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<tr>
<td>5-204-162 F</td>
<td>94.6</td>
<td>64.58%</td>
<td>50%</td>
<td>47.30</td>
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<td>0.00</td>
<td>50%</td>
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<td>1.22</td>
<td>1.7</td>
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<tr>
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<td>2.58</td>
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<td>50%</td>
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**JP-5

<table>
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**TOTAL LOADS:** 891.53 841.38 740.49
** SW BALLAST **

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** TONS BAL.: 0 0 **

** TOTAL LOADS, INCLUDING BALLAST: 740.5 -100.9 **

SPREADSHEET FOR COMPUTING LONGITUDINAL WEIGHT DISTRIBUTION

FG36-61

BASED ON THE LONG. STRENGTH DRAWINGS

DESIRED DISPLACEMENT 3987.7 ltons From FFG61 FINAL WT REPT (JULY 1989)

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Total: 1495.3 3987.7 3886.8

53
**FUll LOAD AND 60% FUEL CONDITION**

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<tr>
<th>LOAD ITEM</th>
<th>WT CAP</th>
<th>WT FULL</th>
<th>WT % OF WT FULL</th>
<th>WT AT</th>
<th>DIFF WT FROM MID-SHIP</th>
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** SW BALLAST **

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<th>LOAD</th>
<th>LOAD GIVEN %</th>
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TONS BAL.: 104 104

TOTAL LOADS, INCLUDING BALLAST: 724.4 -116.9

SPREADSHEET FOR COMPUTING LONGITUDINAL WEIGHT DISTRIBUTION

FFG36-61

BASED ON THE LONG. STRENGTH DRAWINGS

DESIRED DISPLACEMENT 3987.7 ltons From FFG61 FINAL WT REPT (JULY 1989)

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TOTALS: 1495.3 3987.7 3870.8
** FFGS 1 LOADS AND LGOS **  
** FULL LOAD AND MINIMUM OPERATING CONDITION **

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<th>DIFF LGO FROM LGO FROM CAP</th>
<th>WT LGO FROM MID-SHIP</th>
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** LIQUID LOADS **

| POTABLE WATER                  |        |        |                |                            |                      |                 |
| 5-252-263 W                    | 17.44  | 67%    | 11.63          | -5.81                      | -94.0                | 298.0           |
| 5-308-162 W                    | 15.76  | 67%    | 10.51          | -5.25                      | -116.0               | 320.0           |

| COLLECTING & HOLDING TANK      |        |        |                |                            |                      |                 |
| 4-170-0 W                      | 2.96   | 0.00   | 2.96           | 2.96                       | 30.1                 | 173.9           |

| LUBE OIL STORAGE               |        |        |                |                            |                      |                 |
| 3-272-2 F                      | 3.50   | 33%    | 1.17           | -2.33                      | -70.6                | 274.6           |
| 3-278-2 F                      | 4.00   | 33%    | 1.33           | -2.67                      | -78.0                | 282.0           |
| 3-286-2 F                      | 2.75   | 33%    | 0.92           | -1.83                      | -85.1                | 289.1           |

| SSGD LUBE OIL                  |        |        |                |                            |                      |                 |
| 4-208-2 F                      | 0.95   | 33%    | 0.32           | -0.63                      | -6.3                 | 210.3           |
| 3-236-162 F                    | 2.10   | 33%    | 0.70           | -1.40                      | -34.3                | 238.3           |
| 3-292-8 F                      | 0.92   | 33%    | 0.31           | -0.61                      | -89.1                | 293.1           |

| LUBE OIL SETTLING              |        |        |                |                            |                      |                 |
| 3-278-1 F                      | 3.58   | 0.00   | 3.19           | 1.19                       | -77.9                | 281.9           |
| 3-286-1 F                      | 2.42   | 0.00   | 0.81           | 0.81                       | -84.7                | 288.7           |

| DIESEL OIL STORAGE             |        |        |                |                            |                      |                 |
| 5-56-0 F                       | 14.83  | 100%   | 14.83          | 0.00                       | 143.9                | 60.1            |
| 5-64-0 F                       | 42.05  | 100%   | 42.05          | 0.00                       | 129.6                | 74.4            |
| 5-84-162 F                     | 112.74 | 100%   | 112.74         | 0.00                       | 111.8                | 92.2            |
| 5-100-364 F                    | 65.40  | 0%     | 0.00           | -65.40                     | 92.3                 | 111.7           |
| 5-116-162 F                    | 133.72 | 0%     | 0.00           | -133.72                    | 75.6                 | 128.4           |
| 5-140-162 F                    | 57.86  | 0%     | 0.00           | -57.86                     | 51.8                 | 152.2           |
| 5-164-263 F                    | 19.61  | 0%     | 0.00           | -19.61                     | 32.0                 | 172.0           |
| 5-250-162 F                    | 68.40  | 0%     | 0.00           | -68.40                     | -59.8                | 263.8           |

| DIESEL OIL SERVICE             |        |        |                |                            |                      |                 |
| 5-204-162 F                    | 94.6   | 64.58  | 47.30          | -17.28                     | -4.0                 | 208.0           |
| 5-201-163 F                    | 2.44   | 0.00   | 50%            | 1.22                       | 1.22                 | 202.4           |
| 5-240-162 F                    | 5.16   | 0.00   | 50%            | 2.58                       | 2.58                 | 244.7           |
| 5-292-466 F                    | 2.49   | 0.00   | 50%            | 1.25                       | 1.25                 | 293.2           |
| 2-276-2 J                      | 1.08   | 0.00   | 50%            | 0.54                       | 0.54                 | 277.1           |

| JP-5                           |        |        |                |                            |                      |                 |
| 5-328-0 J                      | 26.51  | 33%    | 8.84           | -17.67                     | -131.7               | 335.7           |
| 5-344-0 J                      | 29.80  | 33%    | 9.93           | -19.87                     | -150.8               | 354.8           |
| 3-316-1 J                      | 3.80   | 33%    | 1.27           | -2.53                      | -114.9               | 318.9           |
| 3-322-1 J                      | 3.70   | 33%    | 1.23           | -2.47                      | -120.8               | 324.8           |

** TOTAL LOADS: ** 891.53 841.38 379.06

56
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**TONS BAL.:** 290 290

TOTAL LOADS, INCLUDING BALLAST: 669.1 -172.3

SPREADSHEET FOR COMPUTING LONGITUDINAL WEIGHT DISTRIBUTION

FFG36-61

BASED ON THE LONG. STRENGTH DRAWINGS

DESIRERED DISPLACEMENT: 3987.7 itons FROM FFG36 FINAL WT REPT (JULY 1989)

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TOTALS: 1495.3 3987.7 3815.4
Appendix B: SHCP Graphic and Numerical Output

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FULL LOAD, SEASTATE 0

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SS  SS  HH  HH  CC  CC  PP
SSSSSS  HH  HH  CCOCOC  PP
SSSS  HH  HH  CCOC  PP

SHIP HULL CHARACTERISTICS PROGRAM

0 DESIGN DISPLACEMENT  3987.720 TONS SW at DENSITY =  35.000 FT3/TON
DESIGN DRAFT  (+ ABOVE BL)  15.935 FT
DESIGN LCG  (+ FWD MID)  -6.110 FT  |  DESIGN LCB  (+ F MID)  -6.110 FT
DESIGN VCG  (+ ABOVE BL)  0. FT  |  DESIGN VCB  (+ ABL)  9.971 FT
DESIGN TCG  (+ STBD)  0. FT  |  DESIGN TCB  (+ STBD)  0. FT
DESIGN TRIM  (+ BY STERN)  0.993 FT  |  DESIGN LIST  (+ STBD)  0. DEG

0 LENGTH OVERALL  447.780 FEET
LENGTH BETWEEN PERPENDICULARS  408.000 FEET
LENGTH ON DESIGN WATERLINE  409.645 FEET
0 STATION OF MAX AREA (AT DWL)  211.429 FEET FROM FP
BEAM AT STATION OF MAX AREA  45.407 FEET
SECTION AREA COEFFICIENT  0.7667
PRISMATIC COEFFICIENT  0.6160
BLOCK COEFFICIENT  0.4723

0 Specified Tolerances of Volume  =0.00001000 and LBP  =0.00005000
Maximum Iteration for Volume  =  20 and LBP  =  20

+  0 Approximate Bounding Cubie Values:
  Forward X location  -27.948 Ft (+ Aft FP)
  After X location  419.832 Ft (+ Aft FP)
  Maximum Y value on Station  46.938 Ft
  Minimum Z value on Station  0. Ft (+ Abv BL)
  Maximum Z value on Station  41.893 Ft (+ Abv BL)

+  0 Work List and Requested Options:

  KK  3 NO Main Hull INITIAL & INTERPOLATED OFFSETS Printed
  IPLOT  3 Plot Main Hull both BODY PLAN and ISOMETRIC
  IPDF  F Plots will be SHIP NEUTRAL PLOTFILE format.
  MKAP  3 NO Appendage INITIAL & INTERPOLATED OFFSETS Printed
  IPLTRAP  0 NO Appendage PLots
  IPLOCON  0 Connection from Station ENDS to Centerline & DAE SHOWN
  MSQSAV  0 Do not save HULL/APPENDAGE Evaluation Messages if Successful
  IUNIT  0 Input/Output units selected are ENGLISH-ENGLISH
  ISHIP-  FFG61 FULL LOAD  SERIAL NUMBER-  1 DATE-  6-Aug-90

1 SHIP- LONTUDINAL STRENGTH CALCULATIONS
  0 WAVE CENTER FROM AMIDSHIPS  0. FEET (+ FWD)
  0 WAVE LENGTH/LBP  1.000
  0 WAVE HEIGHT=1.1*SQR(LBP)  22.22 FEET

0 Specified Tolerances of Volume  =0.00001000 and LBP  =0.00005000
Maximum Iteration for Volume  =  20 and LBP  =  20

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1 SHIP: FF61 FULL LOAD SERIAL NUMBER: 1 DATE: 6-Aug-90

DISPLACEMENT 3987.72 TONS SW LCG -6.009 FT FROM AMIDSHIPS (+ FWD)

LOCATION WEIGHT BUOYANCY SHEAR BENDING MOM WEIGHT BUOYANCY SHEAR MOMENT
STRESS (TONS/IN^2) FT FM FF TONS TONS FOOT-TONS ORD ORD ORD ORD

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**MOMENT AT ZERO SHEAR=** 28870.5 FOOT-TONS *LOCATED 207.120 FT FROM FP*
Figure B-1: SHCP Results, Full Load, Seastate 6

15FFG61 FULL LOAD COND. (COND. D) 10-Aug-90

SCALES
LENGTH 1 INCH = 20.400 FEET
WEIGHT 1 INCH = 3.2579 TONS/FOOT
BUOYANCY 1 INCH = 3.2579 TONS/FOOT
SHEAR 1 INCH = 132.92 TONS
MOMENT 1 INCH = 8135. FOOT-TONS

Figure B-1: SHCP Results, Full Load, Seastate 6
80% FUEL CONDITION, SEASTATE 0

SHIP HULL CHARACTERISTICS PROGRAM

1SHIP- FFG61 80% FUEL COND. SERIAL NUMBER- 7 DATE-17-Aug-90

0DESIGN DISPLACEMENT 3987.720 TONS SW at DENSITY = 35.000 FT3/TON
DESIGN DRAFT (+ ABOVE BL) 15.935 FT |
DESIGN LCB (+ FWD MID) -6.110 FT | DESIGN LCB (+ F MID) -6.110 FT
DESIGN VCB (+ ABOVE BL) 0. FT | DESIGN VCB (+ ABL) 9.971 FT
DESIGN TCG (+ STBD) 0. FT | DESIGN TCB (+ STBD) 0. FT
DESIGN TRIM (+ BY STERN) 0.993 FT | DESIGN LIST (+ STBD) 0. DEG

0LENGTH OVERALL 447.780 FEET
LENGTH BETWEEN PERPENDICULARS 408.000 FEET
LENGTH ON DESIGN WATERLINE 409.645 FEET
0STATION OF MAX AREA (AT DWL) 211.429 FEET FROM FP
BEAM AT STATION OF MAX AREA 45.407 FEET
SECTION AREA COEFFICIENT 0.7667
PRISMATIC COEFFICIENT 0.6160
BLOCK COEFFICIENT 0.4723

0Specified Tolerances of Volume =0.000001000 and LBP =0.00000500
Maximum Iteration for Volume = 20 and LBP = 20

0 Approximate Bounding Cube Values:

  +
  Forward X location -27.948 Ft (+ Aft FP)
  After X location 419.832 Ft (+ Aft FP)
  Maximum Y value on Station 46.938 Ft
  Minimum Z value on Station 0. Ft (+ Abv BL)
  Maximum Z value on Station 41.893 Ft (+ Abv BL)

0 Work List and Requested Options:

  +
  1 3 Longitudinal Strength

KK 3 NO Main Hull INITIAL & INTERPOLATED OFFSETS Printed
IPLOR 3 Plot Main Hull both BODY PLAN and ISOMETRIC
IPLDF F Plots will be SHIP NEUTRAL PLOTILE format
NXAF 3 NO Appendage INITIAL & INTERPOLATED OFFSETS Printed
IPLZAP 0 NO Appendage PLOTS
IPLCON 0 Connection from Station ENDS to Centerline & DAE SHOWN
MSGSAV 0 Do not save HULL/APPENDAGE Evaluation Messages if Successful
IUNIT 0 Input/Output units selected are ENGLISH-ENGLISH

1SHIP- FFG61 80% FUEL COND. SERIAL NUMBER- 7 DATE-17-Aug-90

0 WAVE CENTER FROM AMIDSHIPS 0. FEET (+ FWD)
WAVE LENGTH/LBP 1.000
WAVE HEIGHT=1.1*SQRT(LBP) 22.22 FEET
Specified Tolerances of Volume = 0.00001000 and LBP = 0.00000500
Maximum Iteration for Volume = 20 and LBP = 20

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165
## DISPLACEMENT

- **Weight**: 3866.82 TONS SW
- **LCG**: -6.002 FT FROM AMIDSHIPS (+ FWD)

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**1SHIP**
- **FFG61**: 80% FUEL COND.
- **SERIAL NUMBER**
- **DATE**: 17-Aug-90
- **LOCATION, WEIGHT, BUOYANCY**
- **SHEAR, BENDING MOM**
- **WEIGHT, BUOYANCY, SHEAR, MOMENT**

**STRESS (TONS/IN**2**)**

**1SHIP - FFG61 80% FUEL COND.**

**SERIAL NUMBER**

**DATE**: 17-Aug-90

**LOCATION, WEIGHT, BUOYANCY**

**SHEAR, BENDING MOM**

**WEIGHT, BUOYANCY, SHEAR, MOMENT**

**STRESS (TONS/IN**2**)**
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MOMENT AT ZERO SHEAR = 30526.2 FOOT-TONS  LOCATED 212.926 FT FROM FP
Figure B-2: SHCP Results, 80% Fuel Condition, Seastate 0
60% FUEL CONDITION, SEASTATE 0

SSSS HH HH CCOC PPCPPP
SSSS HH HH CCOC PPCPPP
SS HH HH CC CC PP PP
SS SS HH HH CC CC PP PP
SS HH HH CC CC PP PP
SS SS HH HH CC CC PP PP
SS HH HH CC CC PP PP
SSSS HH HH CCOC PPCPPP
SSSS HHHHHH HH PPCPPP

1SHIP- FFG61 60% FUEL COND. SERIAL NUMBER- 1 DATE-17-Aug-90

O DESIGN DISPLACEMENT 3987.720 TONS SW at DENSITY = 35.000 FT3/TON
DESIGN DRAFT (+ ABOVE BL) 15.935 FT |
DESIGN LCG (+ FWD MID) -6.110 FT | DESIGN LCB (+ F M ID) -6.110 FT
DESIGN VCG (+ ABOVE BL) 0. FT | DESIGN VCB (+ ABL) 9.971 FT
DESIGN TCG (+ STBD) 0. FT | DESIGN TCB (+ STB D) 0. FT
DESIGN TRIM (+ BY STERN) 0.993 FT | DESIGN LIST (+ STBD) 0. DEG

LENGTH OVERALL 447.780 FEET
LENGTH BETWEEN PERPENDICULARS 408.000 FEET
LENGTH ON DESIGN WATERLINE 409.645 FEET
0 STATION OF MAX AREA (AT DWL) 211.429 FEET FROM FP
BEAM AT STATION OF MAX AREA 45.407 FEET
SECTION AREA COEFFICIENT 0.7667
PRISMATIC COEFFICIENT 0.6160
BLOCK COEFFICIENT 0.4723

OSpecified Tolerances of Volume =0.00001000 and LBP =0.00000500
Maximum Iteration for Volume = 20 and LBP = 20

Approximate Bounding Cube Values:

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0 Work List and Requested Options:

KK 3 NO Main Hull INITIAL & INTERPOLATED OFFSETS Printed
I PLOT 3 Plot Main Hull both BODY PLAN and ISOMETRIC
LDXF F Plots will be SHCP NEUTRIL PLOTFILE format
KGAP 3 No Appendage INITIAL & INTERPOLATED OFFSETS Printed
IPLOTAP 0 No Appendage Plots
IPLOCN 0 Connection from Station ENDS to Centerline & DAE SHOWN
MSGSAV 0 Do not save HULL/APPENDAGE Evaluation Messages if Successful
IUNIT 0 Input/Output units selected are ENGLISH-ENGLISH

1SHIP- FFG61 60% FUEL COND. SERIAL NUMBER- 1 DATE-17-Aug-90

0 LONGITUDINAL STRENGTH CALCULATIONS
0 WAVE CENTER FROM AMIDSHIPS 0. FEET (+ FWD)
WAVE LENGTH/LBP 1.000
WAVE HEIGHT=1.1*SQRT(LBP) 22.22 FEET

OSpecified Tolerances of Volume =0.00001000 and LBP =0.00000500
Maximum Iteration for Volume = 20 and LBP = 20
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**O WEIGHT SIATION**

- **WEIGHT**: 
  - Weight of weight (tons) from amidships (ft, +fwd)
  - Dek area
  - Keel area

- **LOCATION**
  - Location
  - Draft
  - Sectional area

- **MOMENT AT ZERO SHEAR**: 87372.9 foot-tons

- **LOCATION AND SECTIONAL AREAS AT VARIOUS INPUT STATIONS**

- **DATE**: 17-Aug-90

- **SHIP**: FFG-61
  - Serial number: 1
  - Fuel condition: 60% fuel cond.
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SHIP - FF666 60% FUEL COND.  SERIAL NUMBER- 1  DATE- 17-Aug-90

DISPLACEMENT 3870.77 TONS SW  LCG -5.602 FT FROM AMIDSHIPS (+ FWD)

LOCATION  WEIGHT  BUOYANCY  SHEAR  BENDING  MOM  WEIGHT  BUOYANCY  SHEAR  MOMENT
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**MOMENT AT ZERO SHEAR** = 32048.3 FOOT-TONS

**LOCATED** 209.188 FT FROM FP
Figure B-3: SHCP Results, 60% Fuel, Seastate 0

2 FFG61 60% FUEL COND. 19-Aug-90

SCALES
LENGTH 1 INCH = 20.400 FEET
WEIGHT 1 INCH = 3.1624 TONS/FOOT
BUOYANCY 1 INCH = 3.1624 TONS/FOOT
SHEAR 1 INCH = 129.03 TONS
MOMENT 1 INCH = 7696. FOOT-TONS
MINIMUM OPERATING CONDITION, SEASTATE 0

SHIP HULL CHARACTERISTICS PROGRAM

1SHIP- FFG61 MIN. OP. COND. (COND. B) SERIAL NUMBER- 2 DATE-15-Aug-90

0DESIGN DISPLACEMENT 3817.301 TONS SW at DENSITY = 35.000 FT3/TON
DESIGN LCG (+ ABOVE BL) 15.441 FT |
DESIGN VCG (+ ABOVE BL) 0. FT |
DESIGN TCG (+ STBD) 0. FT |
DESIGN TRIM (+ BY STERN) 1.984 FT |

LENGTH OVERALL 447.780 FEET
LENGTH BETWEEN PERPENDICULARS 408.000 FEET
LENGTH ON DESIGN WATERLINE 409.498 FEET
0STATION OF MAX AREA (AT DWL) 214.460 FEET FROM FP
BEAM AT STATION OF MAX AREA 45.363 FEET
SECTION AREA COEFFICIENT 0.7598
PRISMATIC COEFFICIENT 0.6133
BLOCK COEFFICIENT 0.4660

0Specified Tolerances of Volume =0.00001000 and LBP =0.00000500
Maximum Iteration for Volume = 20 and LBP = 20

Approximate Bounding Cube Values:

Forward X location -27.948 Ft (+ Aft FP)
After X location 419.832 Ft (+ Aft FP)
Maximum Y value on Station 46.938 Ft
Minimum Z value on Station 0. Ft (+ Abv BL)
Maximum Z value on Station 41.893 Ft (+ Abv BL)

Work List and Requested Options:

1 3 Longitudinal Strength

IIK 3 NO Main Hull INITIAL & INTERPOLATED OFFSETS Printed
IPL0T 3 Plot Main Hull both BODY PLAN and ISOMETRIC
LDF 3 F Plots will be SHCP NEUTRAL PLOTFILE format
NGAP 3 NO Appendage INITIAL & INTERPOLATED OFFSETS Printed
IPLAPP 0 NO Appendage PLOTS
IPLCON 0 Connection from Station ENDS to Centerline & DAE SHOWN
MSGS0V 0 Do not save HULL/APPENDAGE Evaluation Messages if Successful
IUNIT 0 Input/Output units selected are ENGLISH-ENGLISH

1SHIP- FFG61 MIN. OP. COND. (COND. B) SERIAL NUMBER- 2 DATE-15-Aug-90
0 LONGITUDINAL STRENGTH CALCULATIONS

OWAVE CENTER FROM AMIDSHIPS 0. FEET (+ FWD)
WAVE LENGTH/LBP 1.000
WAVE HEIGHT=1.1*SQRT(LBP) 22.22 FEET

0Specified Tolerances of Volume =0.00001000 and LBP =0.00000500
Maximum Iteration for Volume = 20 and LBP = 20
0 WEIGHT -- SECTION MODULUS --
STATION (TONS) FROM AMIDSHIP (INCH**2-FEET)
(FROM FP) (FT, +FWD)
0. 28.68 218.15
20.40 42.43 193.80
40.80 80.51 173.40
61.20 141.81 153.00
81.60 204.55 132.60
102.00 233.93 112.20
122.40 296.49 91.80
142.80 215.79 71.40
163.20 174.84 51.00
183.60 132.74 30.60
204.00 132.74 30.60
224.40 224.40 10.20
244.80 244.80 -10.20
265.20 265.20 -30.60
285.60 285.60 -51.00
306.00 306.00 -71.40
326.40 326.40 -112.20
346.80 346.80 -132.60
367.20 367.20 -153.00
387.60 387.60 -173.40
408.00 408.00 -193.80
420.00 420.00 -210.00

1SHIP-  FFG61 MIN. OP. COND. (COND. B) SERIAL NUMBER- 2 DATE-15-Aug-90
LONGITUDINAL STRENGTH CALCULATIONS - STILL WATER
DRAFTS AND SECTIONAL AREAS AT VARIOUS INPUT STATIONS

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MOMENT AT ZERO SHEAR = 32441.3 FOOT-TONS LOCATED 196.834 FT FROM FP
Figure B-4: SHCP Results, Minimum Operating Condition, Seastate 0

2 FFG61 MIN. OP. COND. (COND. B) 15-Aug-90

DISPLACEMENT: 361,246 TONS
FARthest WATER CONDITION:
WAVE LENGTH: 7.213 FEET
WAVE HEIGHT: 2.513 FEET (+ FWD MID)

SCALES
LENGTH 1 INCH = 20.400 FEET
WEIGHT 1 INCH = 3.117 TONS/FOOT
BUOYANCY 1 INCH = 3.117 TONS/FOOT
SHEAR 1 INCH = 121.18 TONS
MOMENT 1 INCH = 7783. FOOT-TONS
FULL LOAD, SEASTATE 2

SHIP HULL CHARACTERISTICS PROGRAM

0DESIGN DISPLACEMENT  3987.720 TONS SW at DENSITY = 35.000 FT3/TON
DESIGN DRAFT (+ ABOVE BL) 15.935 FT |
DESIGN LCG (+ FWD MID) -6.110 FT | DESIGN LCB (+ F MID) -6.110 FT
DESIGN VCG (+ ABOVE BL) 0. FT | DESIGN VCB (+ ABL) 9.971 FT
DESIGN TCG (+ STBD) 0. FT | DESIGN TCB (+ STBD) 0. FT
DESIGN TRIM (+ BY STERN) 0.993 FT | DESIGN LIST (+ STBD) 0. DEG
LENGTH OVERALL 447.780 FEET
LENGTH BETWEEN PERPENDICULARS 408.000 FEET
LENGTH ON DESIGN WATERLINE 409.645 FEET
OSTATION OF MAX AREA (AT DWL) 211.429 FEET FROM FP
BEAM AT STATION OF MAX AREA 45.407 FEET
SECTION AREA COEFFICIENT 0.7667
PRISMATIC COEFFICIENT 0.6160
BLOCK COEFFICIENT 0.4723
0Specified Tolerances of Volume =0.00001000 and LBP =0.00000500
Maximum Iteration for Volume = 20 and LBP = 20
Approximate Bounding Cube Values:
Forward X location -27.948 Ft (+ Aft FP)
After X location 419.832 Ft (+ Aft FP)
Maximum Y value on Station 46.938 Ft
Minimum Z value on Station 0. Ft (+ Abv BL)
Maximum Z value on Station 41.893 Ft (+ Abv BL)
0Work List and Requested Options:
1 3 Longitudinal Strength

 KK 3 NO Main Hull INITIAL & INTERPOLATED OFFSETS Printed
 I PLOT 3 Plot Main Hull both BODY PLAN and ISOMETRIC
 LDXF F Plots will be SHOP NEUTRAL PLOTFILE format
 PKAP 3 NO Appendage INITIAL & INTERPOLATED OFFSETS Printed
 I PLTAP 0 NO Appendage PLOTS
 IPLCON 0 Connection from Station ENDS to Centerline & DAE SHOWN
 MSGSAV 0 Do not save HULL/APPENDAGE Evaluation Messages if Successful
 IUNIT 0 Input/Output units selected are ENGLISH-ENGLISH

1SHIP- FFG61 FULL LOAD COND. (COND. D) SERIAL NUMBER- 15 DATE-10-Aug-90
0LONGITUDINAL STRENGTH CALCULATIONS
OWAVE CENTER FROM AMIDSHIPS 0. FEET (+ FWD)
WAVE LENGTH/LBP 1.000
WAVE HEIGHT INPUT 1.01 FEET
0Specified Tolerances of Volume =0.00001000 and LBP =0.00000500
Maximum Iteration for Volume = 20 and LBP = 20

0 WEIGHT  WEIGHT LOG OF WEIGHT -- SECTION MODULUS --
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SHIP-FFG61 FULL LOAD CONDITION (COND. D) SERIAL NUMBER-15 DATE-10-Aug-90

LONGITUDINAL STRENGTH CALCULATIONS - SAGGING

DRAFTS AND SECTIONAL AREAS AT VARIOUS INPUT STATIONS

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<th>SECTIONAL AREA SQUARE FEET</th>
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1SHIP - FFG61 Full Load Cond. (Cond. D) Serial Number - 15 Date - 10-Aug-90

Longitudinal Strength Calculations - Sagging

Wave Height, 1.01 ft Center 0. ft from Amidships (+ Fwd) Length/LBP 1.000

Displacement 3987.72 Tons SW Log - 6.009 ft from Amidships (+ Fwd)

Location Weight Buoyancy Stress (Tons/In**2)

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MOMENT AT ZERO SHEAR = 25578.5 FOOT-TONS  LOCATED 205.608 FT FROM FP

SHIP - FFG61 FULL LOAD COND. (COND. D)  SERIAL NUMBER - 15  DATE - 10-Aug-90

DRAFTS AND SECTIONAL AREAS AT VARIOUS INPUT STATIONS

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MOMENT AT ZERO SHEAR = 32127.0 FOOT-TONS Located 208.230 FT FROM FP
Figure B-6: SHCP Results, Full Load, Seastate 2, Sagging
FULL LOAD, SEASTATE 4

SHIP HULL CHARACTERISTICS PROGRAM

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0Specified Tolerances of Volume =0.00001000 and LBP =0.00000500
Maximum Iteration for Volume = 20 and LBP = 20
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Work List and Requested Options:

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61.20 106.63 153.00
81.60 204.55 193.80
102.00 233.93 112.20
122.40 282.89 91.80
142.80 290.51 71.40
163.20 196.93 51.00
183.60 191.49 30.60
204.00 241.54 10.20
224.40 255.69 -10.20
244.80 245.90 -30.60
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285.60 302.47 -71.40
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346.80 181.70 -132.60
367.20 124.04 -153.00
387.60 181.70 -132.60
408.00 132.74 -193.80
420.00 16.00 -210.00

ISHIP- FFG61 FULL LOAD COND. (COND. D) SERIAL NUMBER- 12 DATE- 9-Aug-90
0 DRAFTS AND SECTIONAL AREAS AT VARIOUS INPUT STATIONS

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**Moments at Zero Shear:**
- 2395.5 Foot-Tons located 59.111 ft from FP
- 2377.5 Foot-Tons located 65.230 ft from FP
- 8390.4 Foot-Tons located 182.064 ft from FP
- 4503.1 Foot-Tons located 303.014 ft from FP
- 4513.3 Foot-Tons located 307.927 ft from FP

**DRAFTS AND SECTIONAL AREAS AT VARIOUS INPUT STATIONS:**

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**Locales:**
- Located 59.111 ft from FP
- Located 65.230 ft from FP
- Located 182.064 ft from FP
- Located 303.014 ft from FP

**Ship:**
- FFG61 Full Load Cond. (Cond. D)

**Serial Number:** 12

**Date:** 9-Aug-90
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1ST- FFG61 FULL LOAD (COND. D) SERIAL NUMBER- 12 DATE- 9-Aug-90

LONGITUDINAL STRENGTH CALCULATIONS - HOGGING

WAVE HEIGHT, 6.20 FT CENTER 0. FT FROM AMIDSHIPS (+ FWD) LENGTH/LBP 1.000

DISPLACEMENT 3987.72 TONS SW LOC -6.009 FT FROM AMIDSHIPS (+ FWD)

MOMENT AT ZERO SHEAR= 47908.7 FOOT-TONS LOCATED 211.012 FT FROM FP
Figure B-7: SHCP Results, Full Load, Seastate 4, Hogging
Figure B-8: SHCP Results, Full Load, Seastate 4, Sagging

16FP661 FULL LOAD (COND. D) 14-Aug-90

SCALES
LENGTH 1 INCH = 20.400 FEET
WEIGHT 1 INCH = 3.2579 TONS/FOOT
BOUNCY 1 INCH = 3.2579 TONS/FOOT
SHEAR 1 INCH = 132.92 TONS
MOMENT 1 INCH = 8135. FOOT-TONS
FULL LOAD, SEASTATE 6

SSSS HH HH CC COCC PFPFPFP FPFPFP
SSSS HH HH CC COCOCC PFPFPFP
SS SS HH HH CC CC PP PP
SS SS HH HH CC CC PP PP
SS HH HH CC CC PP PP
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SHIP HULL CHARACTERISTICS PROGRAM

0DESIGN DISPLACEMENT 3987.720 TONS SW at DENSITY = 35.000 FT3/TON
DESIGN DRAFT (+ ABOVE BL) 15.935 FT |
DESIGN LCG (+ FWD MID) -6.110 FT | DESIGN LCB (+ F MID) -6.110 FT
DESIGN VCG (+ ABOVE BL) 9.971 FT |
DESIGN TCG (+ STBD) 0. FT | DESIGN TCB (+ STBD) 0. FT
DESIGN TRIM (+ BY STERN) 0.993 FT | DESIGN LIST (+ STBD) 0. DEG
0LENGTH OVERALL 447.780 FEET
LENGTH BETWEEN PERPENDICULARS 408.000 FEET
LENGTH ON DESIGN WATERLINE 409.645 FEET
0STATION OF MAX AREA (AT DWL) 211.429 FEET FROM FP
BEAM AT STATION OF MAX AREA 45.407 FEET
SECTION AREA COEFFICIENT 0.7667
PRISOMATIC COEFFICIENT 0.6160
BLOCK COEFFICIENT 0.4723
0Specified Tolerances of Volume =0.00001000 and LBP =0.00000500
Maximum Iteration for Volume = 20 and LBP = 20
0 Approximate Bounding Cube Values:
+
Forward X location -27.948 Ft (+ Aft FP)
After X location 419.832 Ft (+ Aft FP)
Maximum Y value on Station 46.938 Ft
Minimum Z value on Station 0. Ft (+ Abv BL)
Maximum Z value on Station 41.893 Ft (+ Abv BL)
0 Work List and Requested Options:
+
1 3 Longitudinal Strength
KK 3 NO Main Hull INITIAL & INTERPOLATED OFFSETS Printed
IPLOT 3 Plot Main Hull both BODY PLAN and ISOMETRIC
IDXF F Plots will be SHCP NEUTRAL PLOTFILE format
K GAP 3 NO Appendage INITIAL & INTERPOLATED OFFSETS Printed
IPLOTAP 0 NO Appendage PLOTS
IPICON 0 Connection from Station ENDS to Centerline & DAE SHOWN
MSGSAV 0 Do not save HULL/APPENDAGE Evaluation Messages if Successful
IUNIT 0 Input/Output units selected are ENGLISH-ENGLISH
1SHIP-- FFG61 FULL LOAD COND. (COND. D) SERIAL NUMBER-- 13 DATE-- 9-Aug-90
0 LONITUDINAL STRENGTH CALCULATIONS
0WAVE CENTER FROM AMIDSHIPS 0. FEET (+ FWD)
WAVE LENGTH/LBP 1.000
WAVE HEIGHT INPUT 16.40 FEET
0Specified Tolerances of Volume =0.00001000 and LBP =0.00000500
Maximum Iteration for Volume = 20 and LBP = 20
0 WEIGHT WEIGHT LCG OF WEIGHT -- SECTION MODULUS --
### LNGITUDINAL STRENGTH CALCULATIONS

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2. **LTRANSPORTI F MSN AGE- 60 FT CENTER 0. FT FROM AMIDSHIPS (+ FWD) LENGTH/LBP 1.000**
3. **DISPLACEMENT 3987.72 TONS SW LCG -6.009 FT FROM AMIDSHIPS (+ FWD)**
4. **LOCATION WEIGHT BUOYANCY SHEAR BENDING MCM WEIGHT BUOYANCY SHEAR MMENT STRESS (TONS/IN.**
5. **C)**

Column headers:
- FT
- FF
- FP
- DECK
- TONS
- TONS
- FOOT-TONS
- ORD
- ORD
- ORD
- ORD

Values in the table represent various calculations for longitudinal strength and sagging. The table includes weight, buoyancy, shear, bending moments, and stress values, all in tons/in.**2.
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**MOMENT AT ZERO SHEAR**: 73854.1 FOOT-TONS  
**LOCATED**: 210.836 FT FROM FP
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Figure B-10: SHCP Results, Full Load, Seastate 6, Sagging
## Appendix C: Hull Flexure, Displacement and Rotation

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FORTH ORDER LEAST-SQUARES POLYNOMIAL CURVE FIT (x=ft Aft FP, y=2nd Iter.,ft)
Y = -0.000725 + 0.000025 x^1 + 5.47E-07 x^2 + -1.69E-08 x^3 + 1.49E-11 x^4
dz/dx = 0.000025 x^0 + 1.09E-06 x^1 + -5.08E-08 x^2 + 5.95E-11 x^3

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dz/dx = 0.000025 x^0 + 1.09E-06 x^1 + -5.08E-08 x^2 + 5.95E-11 x^3

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**FORWARD LEAST-SQUARES POLYNOMIAL CURVE FIT (x=Aft FP, ft; y=2nd Iter., ft)**

\[
y = -0.000861 x^0 + 0.000219 x^1 + 7.18E-07 x^2 + 1.44E-06 x^3 - 1.88E-08 x^4 - 1.88E-08 x^5 - 1.64E-11 x^6
\]

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102
60% FUEL CONDITION, SEASTATE 0

CONDITION: 60% FUEL LOAD
SEASTATE: 0
HCG/SAG: N/A

E: 13400 ltons/in²
Station Spacing: 20.4 ft
Max Dist Fwd FP: 29.0 ft
Max Dist Aft FP: 420.0 ft

Station Dist Aft FP, ft
Moment I ft·ltons
M/E/I ft⁻¹
1st Int
2nd Int
2nd Int

-1.42 0 0
0 0
1 0
2 0
3 0
4 0
5 0
6 0
7 0
8 0
9 0
10 0
11 0
12 0
13 0
14 0
15 0
16 0
17 0
18 0
19 0
20 0

FORTH ORDER LEAST-SQUARES POLYNOMIAL CURVE FIT (x=ft Aft FP, ft; y=2nd Iter., ft)

Y = -0.000642 x⁰ 0.000044 x¹ 4.50E-07 x² 1.98E-08 x³ 1.82E-11 x⁴
         0.000044      9.00E-07    -5.94E-08    7.28E-11
         x¹      x²      x³      x⁴

ITEM X-LOCATION Y X-LOCATION SLOPE MINUTES ARC. DIFFERENCE MATRIX (ARC-MIN)
FT AFT FP FT AFT FP

MK 13 GML 70 -0.000159 -0.55 0
CAS 120 -0.000578 -1.99 1.44 0.00
STIR 208 -0.001694 -5.79 5.24 3.80 0.00
MK 75 GUN 240 -0.002155 -7.41 6.86 5.42 1.62

103
MINIMUM OPERATING CONDITION, SEASATE 0

CONDITION: MINIMUM OPERATING LOAD
SEASATE: 0
HOG/SAG: N/A

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FORTH ORDER LEAST-SQUARES POLYNOMIAL CURVE FIT (x=ft Aft FP, ft; y=2nd Iter., ft)

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3.47E-07 x^1 \quad \frac{dx}{dx} = 3.47E-07 x^1 \\
-2.01E-08 x^2 \quad \frac{dx}{dx} = -2.01E-08 x^2 \\
1.26E-11 x^3 \quad \frac{dx}{dx} = 1.26E-11 x^3 \\
\]

ITEM X-LOCATION SLOPE MINUTES ARC DIFFERENCE MATRIX (ARC-MIN)

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## Full Load, Seastate 2, Hogging

### Condition: Full Load
### Seastate: 2
### Hog/Sag: Hogging

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#### Fourth Order Least-Squares Polynomial Curve Fit (x=ft Aft FP, ft; y=2nd Iter., ft)

\[
y = -0.0000905 x^5 + 0.000262 x^4 + 7.62E-07 x^3 -1.95E-08 x^2 + 1.77E-11 x + 0.0000
\]

#### Item X-Location Slope Minutes Arc Difference Matrix (ARC-MIN)

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Max Dist Aft FP: 420.0 ft

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FORTH ORDER LEAST-SQUARES POLYNOMIAL CURVE FIT (x=ft Aft FP, ft; y=2nd Iter., ft)

\[ Y = -0.000592 + 0.0000249x + 3.69E-07x^2 + -1.50E-08x^3 + 1.29E-11x^4 \]

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**4th ORDER LEAST-SQUARES POLYNOMIAL CURVE FIT** (x=Aft FP, ft; y=2nd Iter., ft)

\[
y = -0.00179 \times x^0 + 0.000236 \times x^1 + 1.88E-06 \times x^2 + -3.22E-08 \times x^3 + 3.76E-06 \times x^4
\]

**ITEM** | **X-LOCATION** | **SLOPE** | **MINUTES ARC** | **DIFFERENCE MATRIX (ARC-MIN)**
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| GML | 120 | -0.000711 | 2.45 | 1.94 | 0.00 |
| STIR | 208 | -0.002302 | -7.91 | 7.41 | 5.47 | 0.00 |
| MK 75 GUN | 240 | -0.002991 | -10.28 | 9.78 | 7.84 | 2.37 | 0.00 |
FULL LOAD, SEASTATE 4, SAGGING

CONDITION: FULL LOAD
SEASTATE: 4
HDG/SAG: SAGGING

E: 13400 ltons/in^2
Station Spacing: 20.4 ft
Max Dist Fwd FP: 23.0 ft
Max Dist Aft FP: 420.0 ft

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FOURTH ORDER LEAST-SQUARES POLYNOMIAL CURVE FIT (x=Ft Aft FP, ft; y=2nd Iter., ft)

\[
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\]

ITEM X-LOCATION SLOPE MINUTES ARC DIFFERENCE MATRIX (ARC-MIN)

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108
**FULL LOAD, SEASTATE 6, HOGGING**

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**SEASTATE:** 6  
**HOG/SAG:** HOGGING  

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**FOURTH ORDER LEAST-SQUARES POLYNOMIAL CURVE FIT**

\[
Y = -0.003548 \times^0 + 9.72E-06 \times^1 + 4.09E-06 \times^2 + 8.18E-06 \times^3 - 1.64E-07 \times^4 + 2.18E-10 \times^5
\]

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### FULL LOAD, SEASTATE 6, SAGGING

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**SEASTATE:** 6  
**HOG/SAG:** SAGGING  
**E:** 13400 ltons/in^2

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Max Dist Fwd FP: 29.0 ft  
Max Dist Aft FP: 420.0 ft

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**FORWARD LEAST-SQUARES POLYNOMIAL CURVE FIT**  
(x=Ft Aft FP, ft; y=2nd Iter., ft)  
Y = 0.0010591 x^0  
\( \frac{dy}{dx} = -2.90E-05 \) x^1  
\( -1.22E-06 \) x^2  
6.71E-08 x^3  
-8.74E-11 x^4

**ITEM**  
X-LOCATION  
SLOPE  
MINUTES ARC  
DIFFERENCE MATRIX (ARC-MIN)

<table>
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<th>FT AFT FP</th>
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<th>MK75</th>
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