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Seakeeping Analysis of Small Displacement High-Speed Vessels

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THESIS

SEAKEEPING ANALYSIS OF SMALL DISPLACEMENT HIGH-SPEED VESSELS

by

Sarah E. Rollings

March 2003

Thesis Advisor: Fotis Papoulias

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13. ABSTRACT

In developing designs for high speed vessels, the engineer must account for the response of the ship in the environment while operating at mission essential speeds. This thesis presents a seakeeping analysis of David Taylor Model Basin's Series 64 models scaled to a 2500-ton displacement using the SHIPMO and MATLAB software. It also discusses the current technology associated with high speed vessels (HSV's) and the relation to the US Navy. Series 64 models provided the benchmark for resistance data. To expand upon this well known series, this research develops seakeeping data trends for scaled-up models. SHIPMO allows the user to specify the ship's characteristics and the environmental conditions such as wave specifications and spectrum. Using the output files from SHIPMO, the MATLAB program designed during this thesis, produced contour plots for the models' response in pitch and heave. Seakeeping trends were observed based on the plots and further compared to calculations of the seakeeping rank, R, a formula originally developed by Nathan Bales. The results of the research can be used by engineers in application to the design of small displacement, high speed ships, both monohulls and multi-hulls.

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SEAKEEPING ANALYSIS OF SMALL DISPLACEMENT HIGH-SPEED VESSELS

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ABSTRACT

Today, high speed vessels are the focus of many ship designers in both the military and commercial maritime industries. High speed vessels provide versatility in accomplishing a range of missions. In developing designs for high speed vessels, the engineer must account for the response of the ship in the environment while operating at mission essential speeds. Much of the design and simulations are computer automated and rely on background data that comes from existing ship designs or experimental results. Series 64, which was developed by the David Taylor Model Basin, now known as Naval Surface Warfare Center, Carderock Division, sets the benchmark for resistance data commonly used by naval architects. To expand upon this well known series, this research attempts to develop seakeeping data trends for scaled-up Series 64 models. The scale used is based on a small displacement ship of 2500 tons. The results of the research can then be used by engineers in application to the design of small displacement, high speed ships.

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TABLE OF CONTENTS

LIST OF FIGURES

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LIST OF TABLES

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I. INTRODUCTION

A. BACKGROUND

As the Navy adjusts to the global climates and the necessary demands, the missions and associated equipment must also transition. The Navy has always produced large war fighting ships as the backbone for naval missions, and history shows the success of utilizing these ships in naval tactics. As the Navy goes into the future, the need for smaller, faster, multi-mission ships grows exponentially. Using smaller ships that travel at higher speeds allows for the necessary versatility needed in a multi-threat theater. This versatility also lends itself to the commercial marine industry. Much of the work in research and development of high speed vessels (HSV's) has taken place in the commercial industry. The trend in the commercial realm has followed the path of increasing transit speeds, but with that, increasing ship size. Finding a meeting ground between the needs of the Navy and an optimal small displacement, high speed platform is a challenge for today's Naval leaders.

B. SCOPE OF THIS WORK

There have been successfully built and tested high speed vessels, promising designs and prototypes, but also limiting factors. Many of these limiting factors come from design constraints, which could be anything from technology to materials. Another design and production factor, which is vital and sometimes becomes the limiting factor in the design process, specifically when establishing the "weighted sum," is the economic considerations. HSV's must combine high speed hull forms, lightweight structures and compact power plants while keeping the ship cost effective. HSV's have seen tremendous success in the commercial realm, particularly with ferries. The mission of ferries lends it to optimize on the current technology available for designing and constructing HSV's. Ferries are usually used for relatively short distances for personnel transport, allowing for lower payloads and the ability to use lighter materials such as aluminum.

Naval architects continue to expand the use of computer aided design in building both commercial and military vessels. These designs rely on data from scaled models, prototypes and full-scale ships. It is possible to build a ship in the computer, but how will it handle at sea? The seakeeping ability of a ship is as important to the completion of a luxury voyage as it is to the success of a military mission. Seakeeping is the dynamic response of a ship in the water. Knowing the seakeeping abilities of vessels during the early stages of design would enhance the design process, simulations and final product. There are programs that will estimate the seakeeping ability of a ship, but these programs are for specific ship designs. One specific computer program, SHIPMO, takes the ship's characteristics and the wave input to produce data and graphs on the expected wave reactions with the hull for the specified conditions. This program is based on standard strip theory assumptions and is very closely related to the Navy's standard ship motions prediction (SMP) program. This specific computer program and its abilities give rise to the motivation for this thesis.

The focus of this thesis is two-fold:

1. Compile and compare existing HSV designs and information, while extracting useful technology and information for military applications.

2. Correlate seakeeping trends in computer scaled models for small displacement vessels based on changing environmental conditions.

Chapter II will focus on developing a technical tutorial on the state of high speed vessels and associated technology in the commercial and military realm. Chapter III will look at the trends of a seakeeping analysis of six computer-scaled Series 64 models. The scaling will be based on a 2500 ton small displacement ship. Finally, Chapter IV will present the conclusions of this thesis and recommendation for further research.

II. HIGH SPEED VESSELS YESTERDAY AND TODAY

A. DEFINING AND DEVELOPING HIGH SPEED VESSELS

High speed vessels are considered to be vessels that can travel at a sustained speed equal to or greater than 35 knots with bursts of high speeds of 40-60 knots. Two interpretations of high speed bursts are provided by Navy Warfare Development Command, NWDC, and are mission oriented definitions. One is defined as a twenty-one day patrol, averaging 8 knots with 20-minute 55 knot bursts, and the second is a five day mission intense period, averaging 10 knots with 15-minute 55 knot bursts. Speed aids military ships both operationally and tactically. HSV's are also fully accepted and available in the commercial maritime role. High speed ferries are a prime example of this, with some, like the ferry made by the Australian company INCAT, traveling at 45 knot transit speeds.

Factors that can combine to give rise to HSV designs include propulsion, payload, mission, range and building material. As many designers know, some of these factors will be sacrificed to enable the rest to succeed. High speeds means using compact power units and lightweight structural materials while maintaining a low displacement, which gives rise to the necessity of smaller payloads with less fuel capacity. Although this is a typical overview of design priorities, the key design factor could be and many times is the ship's mission. For example, commercial ferries can be made of lightweight aluminum for max speed, but aluminum may not be a feasible material for military use due to the need for high combat survivability.

To start incorporating the design factors into the design process, several comparison tools for vessels have been developed. These comparison tools are non-dimensional relationships that are applied to a given design. Naval architects use four main non-dimensional numbers. They are Transport Efficiency (TE), Lift to Drag ratio (L/D), Transport Factor (TF), [1], and Froude number (Fr). The associated equations are presented on the next page.

$$TF = \frac{K * W}{\frac{SHP_{TI}}{V_K}}$$

$$TE = \frac{K * W}{\frac{SHP_{TI}}{V}}$$

$$Fr = \frac{V}{\sqrt{gL}}$$

K:	non-dimensionalized constant
W:	full-load weight
V_K:	design speed
V:	max speed
SHP_{TI}:	total installed power for propulsion
V:	ship's speed
L:	ship's length
g:	gravity

TE relates the sum of a vessel's installed propulsion and auxiliary power to the vessel's weight and maximum speed, where TF uses design speed. These two factors are then unique to each ship, but the L/D ratio changes with speed for the individual vessels. The trend of TF for vessels, as developed by Kennell [1], is that high values of TF, TE and L/D are considered to represent good design characteristics which imply increased cargo carrying capacity, increased speed and reduced power. The TF values for the 30-70 knot range fell below 20, with those near 20 being considered optimal designs. The data presented by Kennell indicates that there were not any monohulls in the 50-70 knot range that achieved a TF value near 20. Small displacement monohulls have achieved comparable speeds, but resulted in low TF values of 1-2 because of their limited range and/or cargo capabilities. When looking at designing and building high speed ships, calculating a TF value can help for comparison and also as a benchmark goal when specifically looking at designing small displacement HSV's. In fact, NSWC, Carderock Division developed a list of ships and designs and calculated the TF for each, [2]. Froude number allows for another way to hydrodynamically classify ships. Naval architects use the Froude number when vessels deal with the interaction of the water's free surface and the hull. High speed vessels are typically defined with Fr > 0.4.

A ship design may meet all the specified requirements, but the technology may not be developed to support the design. One area that is expected to favorably impact the development of HSV's is the improvement of propulsion systems. This impact is significant because it is commonly referenced that a ship's power requirement is proportional to the increase in ship's speed cubed, i.e. to double the ship's speed means multiplying the ship's installed power requirements by eight. Table 1 shows a break down of propulsion technology compared to near-term and far-term technology in relation to payload, speed and range, as presented by Kennell, Lavis and Templeman, [3].

	Power (hp)	Range (nm)	Speed (knots)	Payload (stons)
Today LMSR design		12,000	24	19,000
TAKR design		12,000	27	12,000
Near-Term [3]	Gas Turbines 70,000	500	40 60	35,000 7,500
	Diesel Engines 40,000-50,000	10,000	40 60	54,000 15,000
Far-Term [3]	Gas Turbines 125,000	500	40 60	12,000 n.a.
	Diesel Engines* 80,000-100,000	10,000	40 60	19,000 2,000

*Government funded prediction (commercial evolution prediction: 60-70 khp).

Far and Near Term Propulsion Technology
Table 1

Other important propulsion advancements are happening in electric drive, fuel cells, and water jet propulsors. The Navy has funded extensive research in electric drive with Electric Boat, General Dynamics taking the lead on developing the propulsion for the Navy's future destroyer. Fuel cells can be used for ships' power and/or propulsion. The Office of Naval Research (ONR) is planning to have a 625 kW molten carbonate demonstration unit ready by 2004 that is being build by FuelCell Energy. This unit will convert NATO F-76 distillate fuel to 450vac, 3-phase power and be primarily used for ship's installed power, [4]. Siemens-Westinghouse plans to build a 320 kW and 1000 kW commercial solid oxide fuel cell (SOFC) for propulsion use, [4]. Unfortunately, fuel cell technology still would fall under far-term technology for use in the marine environment. Water jet propulsion is also a good alternative to conventional propellers and is actively being pursued. The water jet propulsion system is usually connected to the drive shaft through an internal combustion system still, and can achieve higher overall efficiencies if the engine and jet drive are well matched. Currently, off-the-shelf waterjets are available up to 60,000 SHP which are designed for speeds of 30-60 knots, [5].

Another area that will favorably impact the future of high speed ships is advancements in light-weight hull and machinery material. Using lighter construction materials would decrease the lightship displacement to allow for more available payload or achieving a higher speed at the lighter load for the same power requirements. Aluminum is already an accepted construction material in the commercial world, reducing the weight by a quarter based on traditional steel construction. One of the problems with aluminum is the lack in technology of joining. An option that is seeing success, LASCOR, which is essentially a metal sandwich joined by laser to produce panels that surpassed the equivalent conventional plate beam during mechanical tests (tension, bending, compression). Structures have been successfully installed on the *USS Mt. Whitney* (LCC-20) and *USS Blue Ridge* (LCC-19). The future of technology for high speed ships is to find the most advantageous combination of these lightweight materials and propulsion options with an appropriate hull form.

B. SUCCESSFUL HIGH SPEED VESSELS

There are multiple options available for high speed vessels for different purposes. Classifying these based on hull form breaks down to include monohulls, catamarans, trimarans, small waterplane twin hull (SWATH) types, surface effects ships, and hydrofoils. This section will look at these available designs and illustrate the advantages and disadvantages of the high speed potential of the design. In particular, the areas of concern will be speed, displacement, pay load, propulsion and hull form. Some designs also have characteristics that are pertinent to the viability of that design, but may not be common to all designs.

1. Monohulls

Monohulls have long dominated the maritime world from shipping to military combat. Typically, monhulls have lower total resistance in operation, which is a factor of the slenderness, making them the optimal hull form from a purely hydrodynamic resistance roll, [6]. The key to slenderness is vessel length, but the optimal length for decreased resistance is much longer than normally accepted. The problem with slenderness in monohulls is that as it increases; the lateral stability decreases, making them more susceptible to large roll responses. This has given rise to designs that add roll stabilizers in the form of structural attachments, tanks or foils while maintaining the main hull’s slenderness. Monohulls also give rise to a range of propulsion choices from water jets to conventional propellers or electric drive.

The largest monohull to date is the *SS United States*, which is 940 feet, and 45,450 LT with a full load. She has a range of 10,000 nm and a sustaining speed on 35 knots. According to the *High Speed Sealift Technology Workshop* in 1997, several designs were entertained that proposed a 1500 foot ship that could achieve a sustaining speed of 50 knots, [5]. Although this may be interesting, draft and length limitation, not to mention the economic viability may limit this design to paper only. Purely looking at speed, the transatlantic speed record belongs to the 68 meter motor yacht *Destriero* which averaged 53 knots, starting with full load at 42 knots and finishing at 63 knots using three GE LM 1600 engines with three KaMeWa 125 waterjets. Monohulls will always be a consideration, especially in the US Navy, but the future to small displacement high speed ships may not lie with monohulls.

2. Catamarans

Catamarans are fast taking over as the most viable hull form for HSV's. They perform better than monohulls in minimizing wave resistance, but there is the possibility for a high amount of wave interaction between the hulls. Catamarans become stable in the ship's roll response but are more susceptible to pitch and heave responses. Some catamarans have been clocked at speeds over 45 knots. Another advantage to catamarans is the draft. If a monohull and a catamaran of equal displacement were compared, the catamarans will have a lower draft. This is an advantage for missions that require littoral proximity. The catamaran also provides greater beam. INCAT's EV10B achieves speeds of 47 knots when lightly loaded, but only 38 knots fully loaded. It uses four 7080 kW diesel engines with four waterjets and measures 97 meters with only a 3.4 meter draft. Other designs have been proposed with speeds of close to 65 knots, like INCAT's proposed design of a 130 meter catamaran with a 63 knot service speed, [5]. A disadvantage to catamarans is wave interaction between the hulls. Many of the same advantages and disadvantages can be found in trimarans.

3. Trimarans

Trimarans may possibly be able to combine the best of both worlds between monohulls and catamarans. Hydrodynamically the main hull can maintain the optimal slenderness of a monohull while achieving lateral stability with the addition of the side hulls. In fact, trimarans are better than monohulls in minimizing wave resistance by 53% and catamarans by 19%, [6]. Having the additional side hulls also increases the deck space, which could allow for more cargo carrying capabilities or even more armament. The Royal Navy already has a trimaran test ship, *Triton* that they are looking at. This ship is 95 meters with a 3 meter draft. The *Triton* was not built as a HSV and only achieves 20 knots using two 2 MW diesel generators and a single screw. Wave interaction between the hulls must also be considered for trimarans.

4. SWATH (Small Waterplane Area Twin Hulls), Semi-SWATH

SWATH type vessels use the concept of lifting bodies, generating lift from their hydrodynamic shape and from buoyancy. SWATH's have two lifting bodies attached beneath the main hull but other designs such as the Sea Slice have four. The advantage is that these vessels can easily reach high cruising speeds while maintaining low drag resistance. The Slice reduces wave making resistance 35% more than the standard SWATH design according to Lockheed Martin's web information. SWATH hull forms have higher stability over catamarans and trimarans. One disadvantage is the high stress concentration on the hull versus more conventional designs where the stress levels are more evenly distributed. The SWATH hull form can achieve speeds greater than 25 knots but require much more horsepower than other hull forms at those speeds. Lockheed Martin's Slice prototype is 104 feet with a 55 foot beam that can maintain 30 knots in waves up to 12 feet in height. The Slice hull form allows for higher speeds using the same horsepower, which may make it a viable hull form for HSV's. In 2002, the Slice was used by the Navy as a Littoral Combat Ship (LCS) option during the Navy's fleet battle experiment in San Diego.

5. Surface Effects Ship (SES)

SES's are interesting because at cruising speeds, the catamaran type main hull completely clears the water and an aircushion, which is typically made of Kevlar, supports the ship. This reduces the drag significantly over that which conventional ships experience. The Navy has been interested in an SES type ship for many years, developing a design for a DDSG (Surface Effect Guided Missile Destroyer) by the late 1970's with a prediction of a speed in excess of 90 knots in average conditions, [7]. This SES would employ either water jet propulsion or supercavitating water screw propulsion. SES's have virtually no frictional resistance and low wave resistance which gives rise to the claim of the ship with the highest TF, [6]. These values are achieved at 50 knots. Also, Bell Aerospace completed a prototype that tested to run at 100 knots in 6 foot seas and became the basis for the Navy's current landing craft air cushion vessel (LCAC). Its propulsion is lift fans, gas turbine engines and supercavitating propellers. A disadvantage of SES's is that the air cushion causes a destabilizing effect on the roll restoring moment due to the water level inside the aircushion being lower than the waterline. SESs' use less power and maintain higher speeds than a catamaran, but the speed loss in waves is more significant than catamarans, [8].

6. Hydrofoils

Hydrofoils are monohulls with structural attachments that behave like aircraft wings to lift the main hull clear of the water. Hydrofoils have large advantages at high speeds but the foil is detrimental to the ship's resistance during low to medium speeds, possibly doubling the ship's drag. Several countries have successfully built hydrofoils, which include the Navy's hydrofoil fleet of PHM's. The *USS Plainview* (AGEH 1) was 212 feet (320 LT) and reached 50 knots. The Canadian Navy's hydrofoil was 150 feet and reached between 50-60 knots. Foilcatamarans have also been developed by both Japan and Norway. Ohkusu pointed out that deck diving in following waves is a danger to catamarans, [8]. Another disadvantage is to take care to avoid cavitations that can quickly destroy the materials and machinery, destroying the lift advantages of the ship. Cavitations can limit speeds to less than 50 knots on certain designs. Lastly, hydrofoils can lose all lift effects on the backside of a wave, causing the elevated main hull to crash to the water, [5].

C. NAVAL OPTIONS AND APPLICATIONS

Many of the designs discussed in the previous section can lend themselves to military applications while many are not as useful. Choosing the priorities in military applications can be subjective. The NSWC, Carderock Division developed a qualitative analysis method that allows weighting factors to be assigned by the user to specific attributes that relate the relative importance to the mission, [3]. Using such a tool as this allows the users, who could be an engineer or politician, to prioritize and easily look and compare different options. One mission that is contributing to extensive design research is the Littoral Combatant Ship (LCS). Small displacement HSV research and development will be useful in the Navy's development of the LCS, which is scheduled to begin construction in the fiscal year 2005. The goal of the LCS is to be a multi-mission capable ship with speed and agility. The possible design limiting, mission critical parameter is that the LCS must sustain operations during periods from non-hostile transit environments to sustained combat. This is design limiting in the sense that the ship cannot necessarily take advantage of all the high speed technology that is available. An example is the usage of aluminum to reduce weight. Aluminum is not as strong as steel, which makes it less likely to survive in a combat environment. The LCS could take advantage of some of the non-traditional hull forms in the preceding section such as a trimaran or Slice hull form.

Other examples of innovative designs have been developed and presented by such groups as the Total Ship Systems Engineering (TSSE) students at the Naval Post Graduate School. This group of students from various curriculums collaborates on a design to meet the mission requirements provided by the Systems Engineering and Analysis students. In the past five years, four of the designs have incorporated multihull configurations. The missions range from an aviation platform to a maritime propositioning ship to a littoral warfare combat system. One design, the Sea Archer, used a hull form related to an SES catamaran with a threshold speed of 40 knots and a surge speed of 60 knots. Many of these designs culminated in the Crossbow project presented in December 2001.

III. SEAKEEPING ANALYSIS

A. DEFINING SEAKEEPING

As previously mentioned seakeeping is the dynamic response of the ship affected by environmental forces, primarily wind and waves. It is often a limiting factor in operability, specifically speed loss. By incorporating seakeeping into the initial ship design, the ship's performance and efficiency can improve. The primary parameters that affect seakeeping are the ship proportions, including waterplane geometry and weight distribution. Secondarily, unique hull characteristics such as transom sterns, bulbous bows or motion damping devices also affect the ship's seakeeping abilities. There are some general seakeeping design guidelines that should be always kept in mind during the design process, [9].

- Longer lengths are better for a ship's seakeeping abilities
- Wave excitation comes in through the waterplane area. Smaller waterplane area ships experience fewer motions, but also have less damping which results in pronounced resonant peaks.
- Wave excitation also comes through pressure, which reduces exponentially with depth.

The primary motions that need controlling are roll in monohulls and heave and pitch in multi-hulls.

The seakeeping response of a ship is a random process and must combine several elements. The key elements are ship characteristics, required functions for mission achievement and a specified sea environment for the given mission, [9]. Table 2 identifies the top level performance requirements for the Navy. The sea states and their conditions mentioned in Table 2 are the seakeeping requirements that the Navy demands of its ship designs. These requirements lead to defined limiting criteria for specific operations and for embarked personnel. Table 3 defines the Navy's current criteria, [9]. As a seakeeping analysis is preformed, the output usually is a speed polar grid, which maps the waves based on ship's heading with increasing speed. These plots and the design criteria, such as what is displayed in Table 3 are then used to develop operating envelopes for a specific ship design.

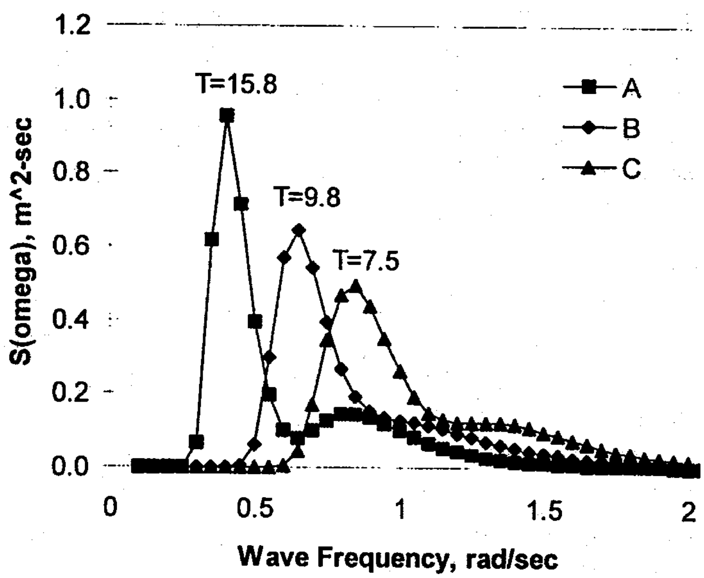
Performance Requirements	Sea State	Environmental Conditions
Operation of embarked helicopter.	5	Significant wave height 10.2 feet Wind velocity 20 knots Ship takes best heading for helicopter
Replenish and strike-down underway.	5	Significant wave height 10.2 feet Wind velocity 20 knots Ship takes best heading
Continuous efficient mission fulfillment without significant degradation.	6	Significant wave height 16.9 feet Wind velocity 30 knots All ship headings
Limited mission operation without returning to port for repairs after seas subsides.	7	Significant wave height 30.6 feet Wind velocity 44 knots Ship takes best heading
Survivability without serious damage to mission essential subsystems.	8	Significant wave height 51 feet or greater Wind velocity 63 knots or greater Ship takes best heading

Top Level Performance Requirements for the Navy
Table 2

Subsystem	Dynamic Response	Limiting Design Criteria
Helicopter	Roll Pitch Vertical velocities at landing pad Slamming Deck Wetness	6.4 deg 3.0 deg 6.5 ft/sec 20 occurrences/hr 30 occurrences/hr
Replenishment	Roll Pitch Slamming Deck Wetness	5.0 deg 3.0 deg 20 occurrences/hr 30 occurrences/hr
Personnel	Roll Pitch Vertical accelerations at Bridge Lateral accelerations at Bridge Slamming Deck Wetness	10.0 deg 3.0 deg 12.8 ft/sec^2(0.4g) 6.4 ft/sec^2(0.2g) 20 occurrences/hr 30 occurrences/hr

Design Limiting Criteria for the Navy
Table 3

Further information to incorporate into the design criteria is the location of the ship's general operation. The defined Sea State is not only affected by the significant wave height and wind speed, but also the modal period, which contributes to developing an accepted wave spectrum. The wave spectrum must also be considered when developing a ship's operating envelopes. The wave spectrum is the wave height time history and can be thought of as representing the distribution of energy as a function of wave frequency, [10]. Remember that the plotted wave frequency is representing the modal period for a geographic region. The wave height time history is geographically based, producing a wave spectrum that shows a range of wave energy levels for the same wave height. Figure 1 shows a sample wave spectrum for a wave height of 6.17 feet, which is associated with Sea State 4, [10].



Wave Spectrum for 6.17 feet (Sea State 4)
Figure 1

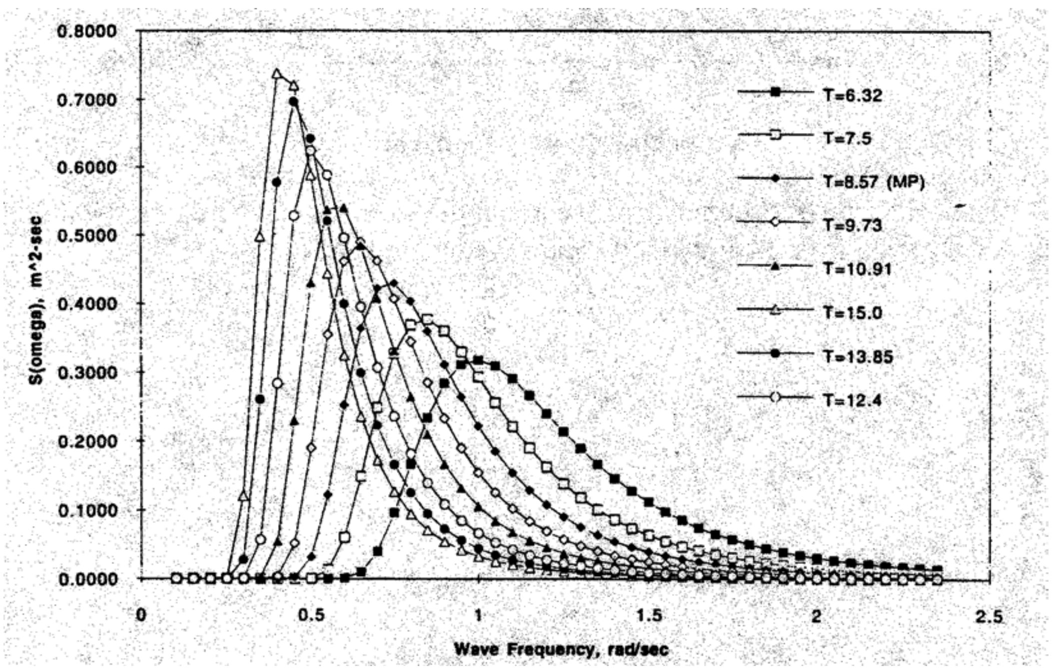
The peaks are associated with the maximum energy and indicate the associated wave frequencies, i.e. modal periods. There are several ways to develop a wave spectrum. The two most common methods are the Pierson - Moskowitz and the Bretschneider spectrums. Pierson – Moskowitz uses wind speed (V) as its primary parameter and the wave spectrum is developed based on the following formula, [11].

$$S(\omega) = \left[\frac{8.1e^{-3} g^2}{\omega^5} \right]^{\left(-0.74 \left(\frac{g}{V\omega} \right)^4 \right)} ; m^2 s$$

The spectrum recommended by the International Towing Tank Conference is the Bretschneider spectrum, which is based on the significant wave height ($\xi_{1/3}$) and modal frequency (ω_m). The associated equations are noted below, [10].

$$S(\omega) = \left(\frac{1.25}{4} \right) \left(\frac{\omega_m^4}{\omega^5} \right) \xi_{1/3}^2 \left(-1.25 \left(\frac{\omega_m}{\omega^4} \right)^4 \right)$$

Figure 2 shows the Bretschneider wave spectrum for a 6.17 foot significant wave height (Sea State 4).



Bretchneider Wave Spectrum for 6.17 feet
Figure 2

The Bretschneider wave spectrum uses the modal period information from a given locale based on the information provided by the Spectral Ocean Wave Model (SOWM), which is a hind cast mathematical model to generate the climatology database, [10]. Table 4 shows the relationship of modal period to Sea State based on the SOWM database.

Sea State	Significant Wave Height (ft)	Modal Period Range (sec)	Sustained Wind Speed (kts)
0-1	0 - 0.33	-	0 – 6
2	0.33 - 1.64	3.3 – 12.8	7 – 10
3	1.64 - 4.10	5.0 – 14.8	11 – 16
4	4.10 – 8.20	6.1 – 15.2	17 – 21
5	8.20 – 13.12	8.3 – 15.5	22 – 27
6	13.12 – 19.69	9.8 – 16.2	28 – 47
7	19.69 – 29.53	11.8 – 18.5	48 – 55
8	29.53 – 45.93	14.2 – 18.6	56 – 63
>8	> 45.93	15.7 – 23.7	>63

* It is customary to use statistics from the North Atlantic when geographic location is not specified for the ship design.

North Atlantic Sea State Table*
Table 4

The Navy uses this information as the design criteria for its engineers. The information from Table 4 on the relationship between modal period and Sea State is pertinent to the analysis process used in this project, as well as both the Pierson – Moskowitz and Bretschneider formulations.

B. BACKGROUND AND SET-UP FOR ANALYSIS

In looking at seakeeping trends in various sea states, this project choose specific models to scale for the comparative analysis while using specific software to collect the data. As previously discussed, there are numerous options for HSV's but a good starting point for analysis is the monohull. The results from analyzing monohulls can also be applied to other ship designs. The ship characteristics used in the seakeeping analysis came from the Series 64 models that were designed, constructed and tested at the David Taylor Model Basin, [12]. This series of models was chosen because Series 64 has become a benchmark series for resistance data. The scaled-up ship characteristics were entered into and evaluated with SHIPMO, the software developed by Maritime Research Institute Netherlands (MARIN), [13].

1. Series 64

In ship design, engineers often use data from existing ships as well as from results of experiments. Data from experiments on a methodical series of models can prove very useful in looking at trends and in developing an optimal ship design. David Taylor Model Basin's Series 64, as presented by Yeh [12], is a key example of this. The motivation for Series 64 came from the lack of existing data at the time for the performance of ships at high speeds, speeds with a speed-length equal to or greater than 2. The engineers were particularly looking for ship resistance data. The parent model was based on its high speed performance (above the speed-length ration of 2.6) during bare-hull resistance tests in comparison to existing models at the Model Basin. Because this was an initial series, only three parameters were selected to develop the models.

The parameters selected were B/H, $\Delta/(0.01L)^3$, and the block coefficient, C_B. Three models for each change in parameter were deemed adequate to determine a trend in the effect of the change, resulting in 27 models. B/H was selected over L/B because naval architects were accustomed to seeing this parameter in contours and 2, 3 and 4 were selected because they covered most ships. Block coefficient was selected because its variance in resistance effects was greater than varying prismatic coefficient, C_p. 0.35, 0.45 and 0.55 also cover the range for block coefficient of most ships. C_p was subsequently set at 0.63 for all models. $\Delta/(0.01L)^3$ was chosen because displacement is an excellent indicator of payload. For most ships the range of this parameter is 15-55 and is coupled with the block coefficient, lower values apply to lower values for block coefficient.

2. SHIPMO

In accordance with MARIN's website description, [13], this software program calculates the motions and behavior of a ship using a program based on 'strip theory'. This program uses characteristic points from the ship's geometric shapes, specifically the body plan view. It uses station characteristics for its calculations, as well as specific ship speed and wave characteristics. The product is based on the slenderness of the ship's hull and on the linearity of the hydrodynamic forces. The program integrates the ship's response at the individual stations over the length of the ship to produce the resultant ship motions.

SHIPMO uses full scale ships, so to collect data for a small displacement ship the selected Series 64 models were scaled to size with a fixed displacement of 2500 tons. 2500 tons was selected because it is comparable to the displacement for a Corvette style small displacement, high speed ship. Six Series 64 models were selected to use with SHIPMO.

These models were selected based on the same parameters as the original series, but specifically using C_B and B/H. Table 4 shows the models chosen, their applicable parametric data and their scaled data.

Series 64 Models				**Scaled Characteristics (displacement = 2500 tons)**		
Number	**Cb**	**B/H**	**(disp)/(0.01L)^3**	**L (ft)**	**B (ft)**	**H (ft)**
4787	0.55	2	55	357.00	29.86	14.93
4794	0.55	4	40	357.00	36.01	9.00
4796	0.45	2	45	381.57	31.94	15.96
4802	0.45	4	45	381.57	45.14	11.28
4805	0.35	2	35	414.91	36.54	18.27
4812	0.35	4	25	464.16	46.42	11.60

Series 64 Models and Scaled Ship Characteristics
Table 5

The model body plan diagrams are located in Appendix A. The full-scale data from these curves was entered into SHIPMO to obtain the resulting data, which is discussed in further detail in the following section.

3. Bales Estimator

Nathan Bales from David Taylor Naval Ship Research and Development Center developed a comparative parameter for seakeeping, [14]. The seakeeping rank, R, was based on the optimization of 20 destroyer type hulls in long-crested, head seas. The analysis was based on a 4300 ton displacement. A total of six parameters were selected to develop the estimator. The parameters used were the waterplane coefficient forward of amidships (C_{WF}) and aft of amidships (C_{WA}), the draft to length ratio (T/L), the cut-up ratio (c/L), and the vertical prismatic coefficient forward of amidships (C_{VPF}) and aft of amidships (C_{VPA}). Bales went the step further to normalize the values he obtained to fit the scale of 1.0-10.0 with hull receiving a 10.0 to have the best seakeeping ability. The following equation is Bale's seakeeping rank equation.

$$R = 8.422 + 45.104\ C_{WF} + 10.078\ C_{WA} - 378.465\left(\frac{T}{L}\right) + 1.273\left(\frac{c}{L}\right) - 23.501\ C_{VPF} - 15.875\ C_{VPA}$$

This equation is a good tool for comparison of hull types and their performance in the water. To accurately fall on the 1.0-10.0 scale, the hull and its parameters must meet the constraints set forth in [14]. The above equation was used to calculate a seakeeping rank for each of the six Series 64 models to further establish the seakeeping trends of the hulls and will be presented in the discussion of results.

C. ANALYSIS

Not only does SHIPMO need user defined ship characteristics, wave data must be defined. This project set the waves as long crested with wavelengths from 20 to 1000 feet in increments of 20 feet and the regular waves have wave amplitudes of 1 foot. This is set for all program runs in SHIPMO. The two parameters that varied between programs runs were the wave angle and ship speed. Each run only changed one of the two parameters at a time. The wave angle was varied from 0 degrees (head seas) to 180 degrees (following seas) in reference to the ship's bow in increments of 15 degrees. The ship's speed was varied from 0 to 100 ft/sec (approximately 0 to 60 knots) in increments of 10 ft/sec. This resulted in a total of 143 programs runs for each model. Appendices B.1 through B.6 includes SHIPMO input file with waves at 0 degrees and the ship traveling at 0 ft/sec. The output file for each program run presented a summary of the input data, computed hydrostatic data and the ship's seakeeping response. Appendix C presents an example output file for Model 4787 with the waves at 0 degrees and the ship traveling at 0 ft/sec. The program also produced a corresponding MATLAB file to be used with further analysis.

The associated MATLAB files were then used with the m-file *v_speed_long.m*, which is located in Appendix D. The MATLAB program prompts the user to specify the ship, the significant wave height in feet and the wave spectrum method to use. Pierson – Moskowitz is indicated with "0" and Bretschneider is indicated by "1". If Bretschneider is chosen, then the user is also prompted to indicate the modal period in seconds. The program then uses all 143 runs for the specified ship to produced two plots of the ship's response in pitch and heave. The roll response was not calculated due to the high dependence on the metacentric height, which is specific to a ship's loading configuration. Contour plots for each ship were plotted using a significant wave height of 10 feet which falls under Sea State 5 and corresponds to the lowest top level performance requirement by the Navy as indicated in

Table 2. This is the only wave height looked at due to the fact that *v_speed_long.m* normalizes the wave height, allowing the contour curves to be an indication of the ship's response regardless of wave height. The contour plots using the Pierson – Moskowitz spectrum are located in Appendix E. The contour plots for the Bretschneider spectrum used the extremis of the modal period range (9.8 and 16.2 seconds) as well as the average modal period (13.0 seconds) corresponding to Sea State 5. These contour plots are located in Appendix F. Due to space limitations, only the two primary responses in heave and pitch are presented. Derived responses such as those shown in Table 3 can be generated from the primary responses. A ship that possesses favorable response characteristics in both heave and pitch, will in general exhibit acceptable seakeeping behavior in all other derived responses.

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IV. CONCLUSIONS AND RECOMMENDATIONS

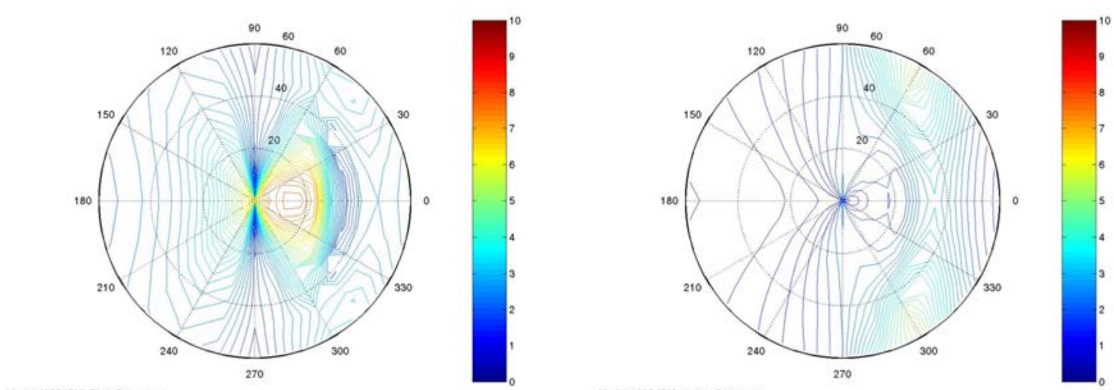
A. TRENDS IN SEAKEEPING

The plots showed that the wave response patterns from the models are the same but with varying levels of intensity. The plots also indicate that the six models fall into two distinct groups based on the pitch and heave response pair. Initial inspection shows the two groupings by response are formed due to the beam to draft ratio (B/T) of the models. Table 6 groups the models by B/T as well as by increasing intensity in the response.

Model	Cb	Cx	B/T	(disp)/ (0.01L)^3	Ax (sq. in.)	S (sq. ft.)	Cpv	R
Group 1								
4787	0.55	0.873	2	55	43.96	11.388	0.723	3.70
4796	0.45	0.714	2	45	35.97	10.411	0.591	-0.47
4805	0.35	0.556	2	35	27.98	9.907	0.460	-0.46
Group 2								
4802	0.45	0.714	4	45	35.97	11.109	0.591	6.22
4794	0.55	0.873	4	40	31.98	10.151	0.723	3.70
4812	0.35	0.556	4	25	19.99	8.996	0.460	1.68

Seakeeping Response Groups
Table 6

Figure 3 shows samples plots for model 4805 using the Pierson-Moskowitz spectrum that is a good representation of the wave patterns produced by all models.



Contour Plots for Model 4805
Figure 3

As background, the plots illustrate the ship's motion based on the direction of the waves interacting with the ship relative to the bow which is oriented at 0 degrees and the speed of the ship which increases from the center to the outer ring. A scale of 0-10 feet illustrates the intensity of the motion. For example, the ship has a high intensity response in pitch when traveling under 25 knots with head seas versus following seas at any speed.

All models showed the highest pitch response with ship speeds between 0 and 25 knots and a concentration of motions from the bow of the ship to 30 degrees port and starboard. Group 1 had a high response in pitch with all models and modal periods showing an intensity level of 10 feet. Group 2 had a relatively mild response in all models and all modal periods with having an intensity level at or below 7 feet except for the 13-second modal period which reached 10 feet. Model 4794 and 4812 showed an intensity level of 10 feet for the 13-second modal period. In heave, the largest response occurred for speeds over 40 knots with the wave pattern motions concentrated 30 to 60 degrees off the bow for both port and starboard sides of the ship. This time Group 1 had the lower response with a max intensity level of 6 feet except for model 4805 reached a level of 6.5 feet in the 13-second modal period. Group 2 showed a higher response in heave, reaching an intensity level of 10 feet for ship 4812 in the 13-second model period. Overall, Group 1 has a very predictable seakeeping response regardless of modal period. Group 2 has a range of levels in responses. The hull with the least seakeeping abilities comes from Group 2, 4812. The optimum hull for seakeeping abilities also comes from Group 2, model 4802. This model has a low intensity response for both pitch and heave, a highly desirable quality for seakeeping.

Another tool that was looked at to predict the seakeeping abilities of the models was the Bales seakeeping rank, (R). The trend in intensity in each group is dictated by the models' size in terms of length, waterplane area (Ax) and wetted surface area (S). Table 6 also shows the Bales rank trend for the groups. The Bales rank for model 4802 further indicates that its hull has higher seakeeping abilities over the other hull forms. The trend for R decreases as the intensity of the seakeeping response increases. This was expected, but the actual calculated values were not. The table shows several low values and two negative values. Upon further inspection, this is attributed to the fact that the parameters used to calculate R fell outside the constraints documented by Bales. Table 7 quickly shows the key parameters for each model and how each relates to the specified constraints. The other factor is Bales based his rank formula on a displacement of 4300 tons.

Model	4787	4794	4796	4802	4805	4812
u =	0.753	0.843	0.828	0.818	0.862	0.833
L/u =	*474.010*	423.389	*460.575*	*466.389*	*481.109*	*557.060*
B/u =	39.647	42.707	*38.553*	*55.174*	42.370	*55.711*
T/u =	19.823	10.674	*19.265*	13.787	*21.185*	13.922
Cwf =	*0.554*	*0.554*	*0.514*	*0.526*	*0.468*	*0.424*
Cwa =	*1.013*	*1.013*	*0.936*	*0.945*	0.868	*0.784*
T/L =	*0.025*	*0.025*	*0.042*	*0.030*	*0.044*	*0.025*
Cvpf =	*0.944*	*0.944*	0.796	0.752	0.691	0.752
Cvpa =	0.580	0.580	*0.504*	*0.479*	*0.430*	*0.482*
R =**	**3.70**	**3.70**	**-0.47**	**6.22**	**-0.46**	**1.68**

**italics indicate values outside of constraint ranges*
**a value of c/L = 0.8 for all models was used

Model Parameters for Bales Seakeeping Rank
Table 7

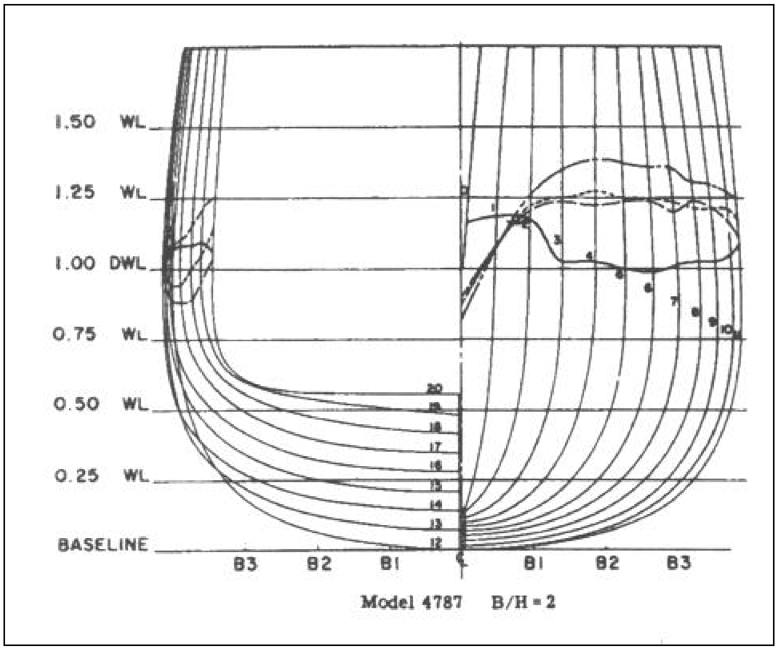
The information from this study can be used in a variety of different ways. It can obviously be used from a purely analytical point by looking for trends in hull forms for seakeeping. Engineers can also use it as a stepping-stone in the pursuit of a hull form with optimal seakeeping abilities. The research and information presented here gives a large enough range of information that a choice of hull form can be made based on desired speed, specifically seakeeping performance at high speeds. The information can be applied to the pursuit of multihull vessels or SWATH type hulls. The information and process produced from the study has use in the immediate future as the Navy develops the design of its Littoral Combat Ship (LCS).

B. RECOMMENDATIONS

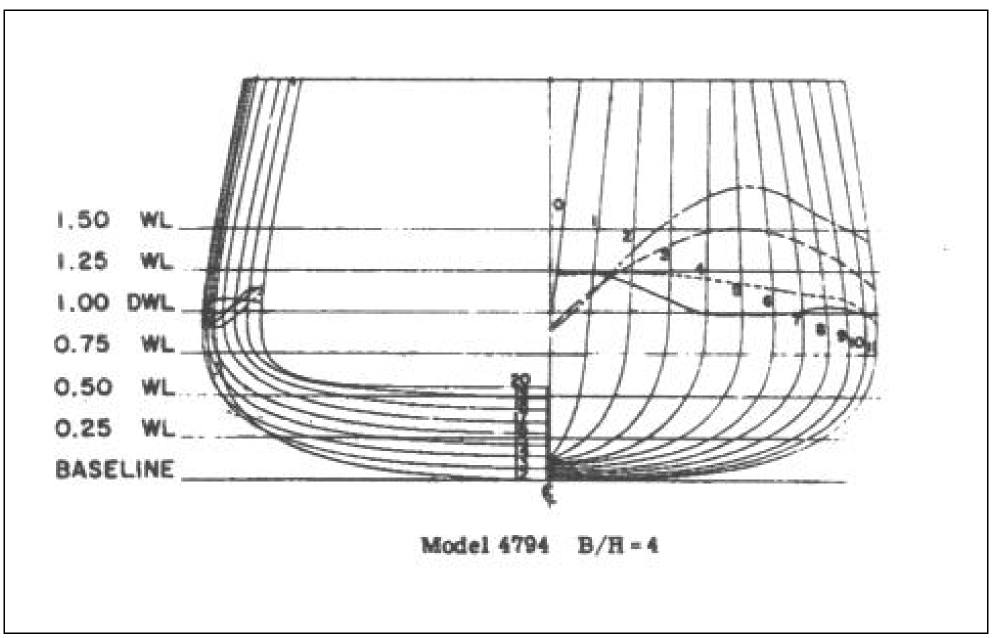
As an initial seakeeping study, this research gives an overview and introduction to the trends of seakeeping abilities for monohulls. To further predict the seakeeping trends for hull forms as well as increase the accuracy of information, a continuation of this study looking at all the Series 64 models should be conducted. Doing this would produce a solid base of information on how a large variety of accepted hull forms are expected to perform in the seas. Another tool to increase the analysis is SHIPMO. SHIPMO is a versatile program and this study looked at a relatively small range of the possible wave parameters. The engineer could vary the wave amplitude, change the ship's velocity or wave direction as well as look at other modal period ranges. Looking at other values and ranges would only increase the accuracy of information on seakeeping trends. Lastly, doing a similar seakeeping analysis for mulithulls would round out the base of knowledge on seakeeping performance. A full base of information allows engineers to accurately weight the hull performance during the design process when choosing a hull form for a specific mission.

V. APPENDICIES

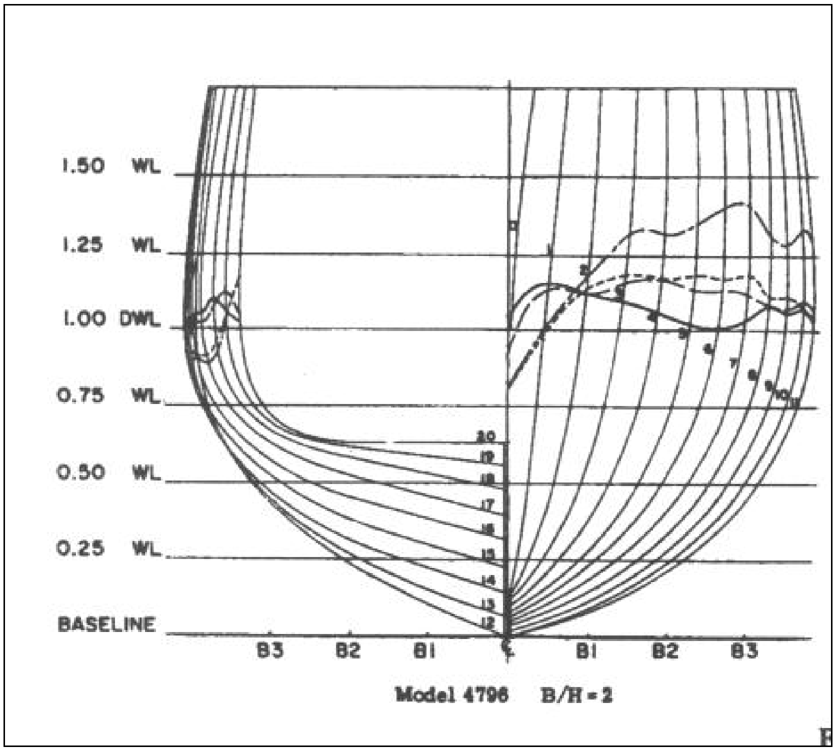
APPENDIX A. MODEL BODY PLANS



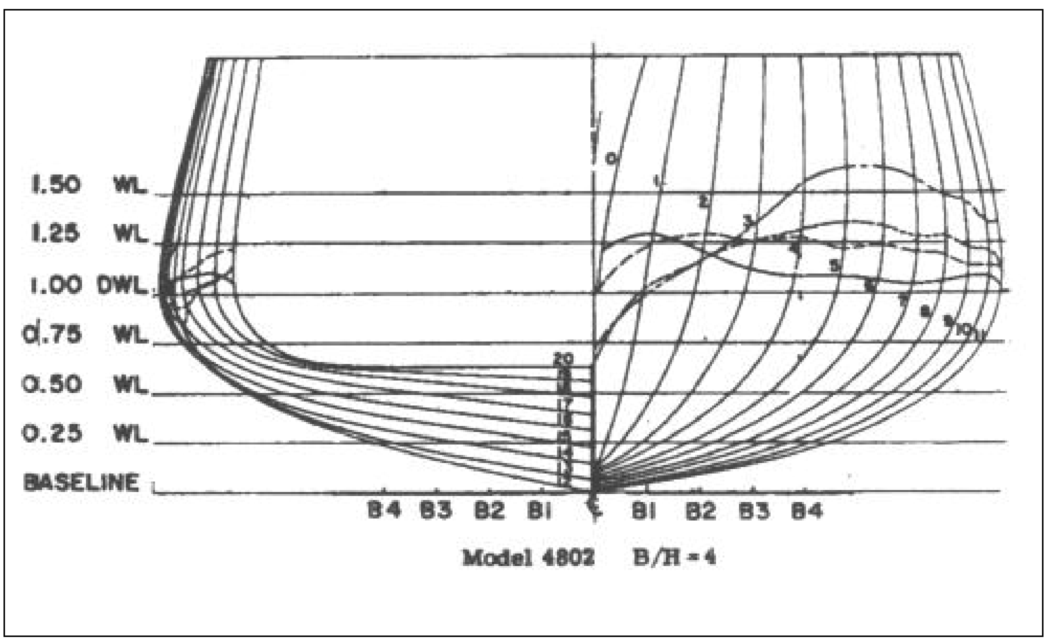
Model 4787



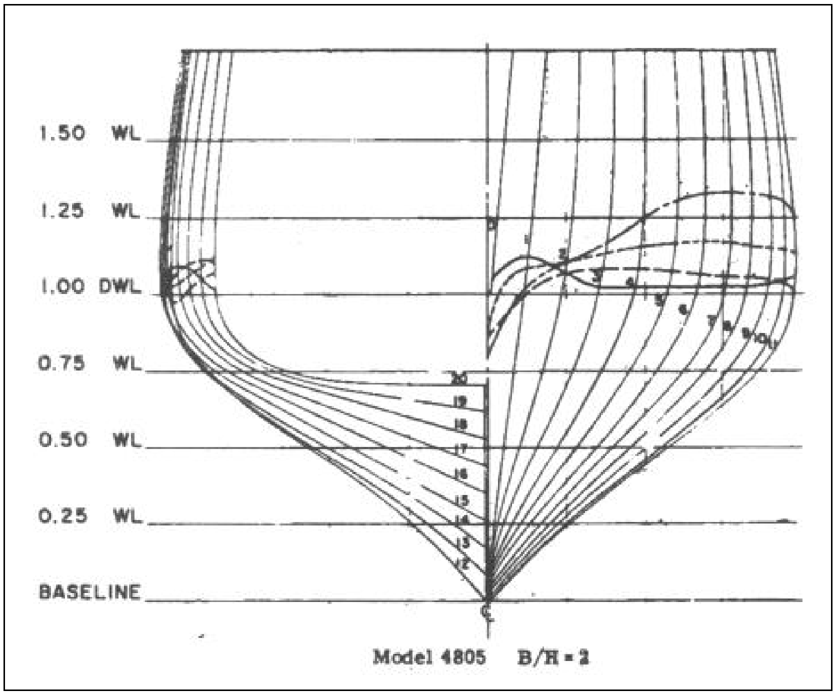
Model 4794



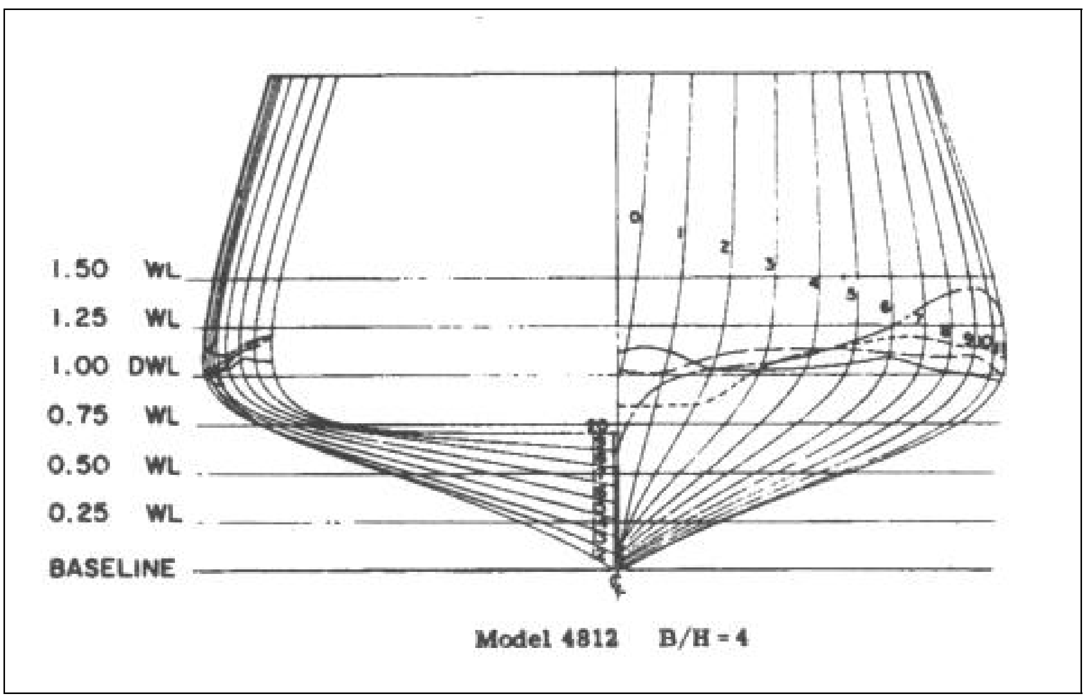
Model 4796



Model 4802



Model 4805



Model 4812

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APPENDIX B.1 MODEL 4787 SHIPMO INPUT FILE

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    0.0000  -13.1250
    0.6667  -11.4580
    1.3333   -7.7080
    1.6667   -3.7500
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    0.0000  -13.1250
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    1.6667  -11.4580
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    4.5830   -7.7080
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    9.5833  -11.4580
   11.2500   -9.3750
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14.1667   -3.7500
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 6.2500  -15.0000
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15.0000   -3.7500
15.0000    0.0000
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APPENDIX B.2 MODEL 4794 SHIPMO INPUT FILE

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   10.4762   -8.0953
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   15.9524   -4.0476
   16.6667   -2.3810
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14.5238   -6.9148
18.0952   -4.0476
19.0476   -2.3810
19.0476    0.0000
 6  -71.4000    0.0000    0
 0.0000   -8.0953
 7.8571   -7.6191
13.0952   -6.9148
18.0952   -4.0476
19.2857   -2.3810
19.2857    0.0000
 6  -89.2500    0.0000    0
 0.0000   -7.8572
 9.5238   -6.9148
14.2857   -5.4762
17.1429   -4.0476
18.8095   -2.3810
18.8095    0.0000
 6 -107.1000    0.0000
 0.0000   -6.1905
 6.1905   -5.9524
11.4286   -5.4762
15.9524   -4.0476
18.5714   -2.3810
18.8095    0.0000
 6 -124.9500         0.0000
 0.0000   -5.4762
 6.1905   -5.4762
11.4286   -4.7619
14.2857   -4.0476
17.6190   -2.3810
18.8095    0.0000
 6 -142.8000    0.0000
 0.0000   -4.7619
 6.1905   -4.7619
11.4286   -4.0476
15.2381   -3.8096
17.1492   -2.3810
17.6190    0.0000
 6 -160.6500    0.0000
```

```
 0.0000   -4.0476
 6.1905   -4.0476
11.4286   -3.3333
14.7619   -3.5715
16.1905   -2.3810
16.6667    0.0000
 6 -178.5000    0.0000
 0.0000   -3.5714
 6.1905   -3.5714
11.4286   -3.3333
14.7619   -3.5715
15.7143   -2.3810
15.7143    0.0000
   -2.0    0.0000
 9999.0       0.0       0.0
 1.0000   20.0000 1000.0000   20.0000    0.0000    0.0000    0.0000
 0.0000  000.0000   00.0000
```

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APPENDIX B.3 MODEL 4796 SHIPMO INPUT FILE

```
Model 4796
    0    0    0    0    0    0    1    0    1    0    1    0    0   20    0
  381.5714    1.9905   32.1740       1.26E-05            0.0    0.0000
   33.0000  -26.0000    1.0000
    5  163.5309    0.0000    0
    0.0000  -14.1666
    0.5556  -12.2222
    1.1111   -8.0556
    1.6667   -3.8889
    1.9444    0.0000
    5  145.3608    0.0000    0
    0.0000  -14.1666
    1.1111  -12.2222
    2.5000   -8.0556
    3.3333   -3.8889
    3.8889    0.0000
    6  127.1907    0.0000    0
    0.0000  -14.4444
    1.9444  -12.2222
    3.0556  -10.0000
    3.8889   -8.0556
    5.0000   -3.8889
    5.8333    0.0000
    6  109.0206    0.0000    0
    0.0000  -14.7222
    2.7778  -12.2222
    4.1667  -10.0000
    5.2778   -8.0556
    6.6667   -3.8889
    7.7778    0.0000
    6   90.8505    0.0000    0
    0.0000  -15.2777
    3.8889  -12.2222
    5.5556  -10.0000
    6.9444   -8.0556
    8.6111   -3.8889
    9.4444    0.0000
    7   72.6804    0.0000    0
    0.0000  -15.5555
    1.6667  -14.4444
    4.4444  -12.2222
    6.6667  -10.0000
    8.0556   -8.0556
   10.0000   -3.8889
   11.1111    0.0000
    7   54.5103    0.0000    0
    0.0000  -15.5555
    2.5000  -14.4444
    5.5556  -12.2222
    7.7778  -10.0000
    9.4444   -8.0556
   11.3889   -3.8889
   12.2222    0.0000
    7   36.3402    0.0000    0
    0.0000  -15.8333
    3.3333  -14.4444
    6.6667  -12.2222
    8.8889  -10.0000
   10.5556   -8.0556
   12.5000   -3.8889
   13.3333    0.0000
    7   18.1701    0.0000    0
    0.0000  -16.1111
    4.4444  -14.4444
    7.7778  -12.2222
   10.0000  -10.0000
```

```
11.6667   -8.0556
13.6111   -3.8889
14.4444    0.0000
 7    0.0000    0.0000    0
 0.0000  -16.1111
 5.2778  -14.4444
 8.3333  -12.2222
10.8333  -10.0000
12.2222   -8.0556
14.4444   -3.8889
15.2778    0.0000
 8  -18.1701    0.0000    0
 0.0000  -16.1111
 3.0556  -15.5555
 5.8333  -14.4444
 9.1667  -12.2222
11.3889  -10.0000
13.0556   -8.0556
15.0000   -3.8889
15.8333    0.0000
 7  -36.3402    0.0000    0
 0.0000  -16.1111
 8.6111  -12.2222
11.6667  -10.0000
13.3333   -8.0556
15.8333   -3.8889
16.1111   -2.2222
16.3889    0.0000
 7  -54.5103    0.0000    0
 0.0000  -15.2777
 7.7776  -12.2222
11.1111  -10.0000
13.3333   -8.0556
15.8333   -3.8889
16.3889   -2.2222
16.9444    0.0000
 7  -72.6804    0.0000    0
 0.0000  -14.1666
 5.5556  -12.2222
10.2778  -10.0000
12.7778   -8.0556
15.8333   -3.8889
16.3889   -2.2222
16.9444    0.0000
 7  -90.8505    0.0000    0
 0.0000  -12.5000
 8.3333  -10.0000
11.6667   -8.0556
13.8889   -9.4444
15.8333   -3.8889
16.1111   -2.2222
16.6667    0.0000
 6 -109.0206    0.0000
 0.0000  -11.6667
10.2778   -8.0556
12.7778   -9.4444
15.2778   -3.8889
15.8333   -2.2222
16.3889    0.0000
 6 -127.1907         0.0000
 0.0000   -9.7223
10.5556   -6.9445
12.5000   -5.5556
14.4444   -3.8889
15.5556   -2.2222
16.1111    0.0000
 5 -145.3608    0.0000
 0.0000   -8.3334
11.1111   -5.5556
```

```
13.8889   -3.8889
14.7222   -2.2222
15.5556    0.0000
 6 -163.5309    0.0000
 0.0000   -6.9445
10.0000   -5.5556
11.9444   -5.2778
13.3333   -3.8889
14.4444   -2.2222
14.7222    0.0000
 6 -181.7010    0.0000
 0.0000   -6.9445
10.0000   -5.5556
11.3889   -5.2778
12.7778   -3.8889
13.3333   -2.2222
13.8889    0.0000
   05.0    0.0000
 9999.0       0.0       0.0
 1.0000   20.0000 1000.0000   20.0000    0.0000    0.0000    0.0000
 0.0000  000.0000   00.0000
```

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APPENDIX B.4 MODEL 4802 SHIPMO INPUT FILE

```
Model 4802
    0    0    0    0    0    0    1    0    1    0    1    0    0   20    0
  381.5714    1.9905   32.1740       1.26E-05            0.0    0.0000
   33.0000  -26.0000    1.0000
    5  163.5309    0.0000    0
    0.0000   -9.3182
    0.6818   -8.1818
    1.3636   -5.4545
    2.2727   -2.7273
    2.7273    0.0000
    5  145.3608    0.0000    0
    0.0000   -9.5454
    1.5909   -8.1818
    3.4091   -5.4545
    4.7727   -2.7273
    5.6818    0.0000
    5  127.1907    0.0000    0
    0.0000   -9.5454
    2.7273   -8.1818
    5.4545   -5.4545
    7.2727   -2.7273
    8.6364    0.0000
    5  109.0206    0.0000    0
    0.0000   -9.7727
    3.6364   -8.1818
    7.7273   -5.4545
    9.7727   -2.7273
   10.9091    0.0000
    5   90.8505    0.0000    0
    0.0000   -9.7727
    5.2273   -8.1818
    9.5455   -5.4545
   12.2727   -2.7273
   13.6364    0.0000
    5   72.6804    0.0000    0
    0.0000  -10.2273
    6.5909   -8.1818
   11.3636   -5.4545
   14.3182   -2.7273
   15.9091    0.0000
    6   54.5103    0.0000    0
    0.0000  -10.2273
    4.0909   -9.5454
    8.6364   -8.1818
   13.4091   -5.4545
   19.3636   -2.7273
   17.7273    0.0000
    6   36.3402    0.0000    0
    0.0000  -10.6818
    5.2273   -9.5454
    9.5455   -8.1818
   15.0000   -5.4545
   17.9545   -2.7273
   19.5455    0.0000
    6   18.1701    0.0000    0
    0.0000  -10.9091
    6.5909   -9.5454
   10.9091   -8.1818
   16.5909   -5.4545
   19.5455   -2.7273
   20.9091    0.0000
    6    0.0000    0.0000    0
    0.0000  -10.9091
    7.7273   -9.5454
   12.2727   -8.1818
   17.7273   -5.4545
```

```
20.6818   -2.7273
22.0455    0.0000
 6  -18.1701    0.0000    0
 0.0000  -10.9091
 8.6364   -9.5454
13.1818   -8.1818
19.0909   -5.4545
21.8182   -2.7273
22.7273    0.0000
 5  -36.3402    0.0000    0
 0.0000  -10.9091
12.2727   -8.1818
19.0909   -5.4545
22.9545   -2.7273
23.8636    0.0000
 5  -54.5103    0.0000    0
 0.0000  -10.2273
11.1364   -8.1818
19.0909   -5.4545
22.9545   -2.7273
23.8636    0.0000
 5  -72.6804    0.0000    0
 0.0000   -9.3182
 7.2727   -8.1818
18.6364   -5.4545
22.5000   -2.7273
23.6364    0.0000
 7  -90.8505    0.0000    0
 0.0000   -8.4091
 1.5909   -8.1818
13.6364   -7.5000
17.2727   -5.4545
19.0909   -4.3182
22.5000   -2.7273
23.6364    0.0000
 5 -109.0206    0.0000
 0.0000   -7.5000
14.5455   -5.4545
19.3182   -4.3182
21.8182   -2.7273
23.1818    0.0000
 6 -127.1907         0.0000
 0.0000   -6.5909
 9.7727   -5.4545
16.8182   -4.3182
20.9091   -2.7273
22.2727   -1.3636
22.7273    0.0000
 6 -145.3608    0.0000
 0.0000   -5.6818
 1.5909   -5.4545
15.4545   -4.0909
20.0000   -2.7273
21.5909   -1.3636
22.0455    0.0000
 5 -163.5309    0.0000
 0.0000   -4.7728
16.1364   -3.8637
19.0909   -2.7273
20.6818   -1.3636
21.1364    0.0000
 5 -181.7010    0.0000
 0.0000   -4.0909
16.1364   -3.8637
18.1818   -2.7273
19.5455   -1.3636
20.0000    0.0000
   -2.0    0.0000
 9999.0       0.0       0.0
```

```
1.0000   20.0000 1000.0000   20.0000    0.0000    0.0000    0.0000
0.0000  000.0000   00.0000
```

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APPENDIX B.5 MODEL 4805 SHIPMO INPUT FILE

```
   0    0    0    0    0    0    1    0    1    0    1    0    0   20    0
 414.9133    1.9905   32.1740       1.26E-05            0.0    0.0000
  33.0000  -26.0000    1.0000
   5  177.8202    0.0000    0
   0.0000  -15.5263
   0.5263  -13.9474
   1.0526   -9.4737
   1.5789   -4.7368
   2.1053    0.0000
   5  158.0624    0.0000    0
   0.0000  -16.0527
   0.7895  -13.9474
   1.8421   -9.4737
   3.1579   -4.7368
   4.4737    0.0000
   5  138.3046    0.0000    0
   0.0000  -16.0527
   1.0526  -13.9474
   2.8947   -9.4737
   5.0000   -4.7368
   6.5789    0.0000
   5  118.5468    0.0000    0
   0.0000  -16.3158
   1.5789  -13.9474
   4.2105   -9.4737
   6.8421   -4.7368
   8.6842    0.0000
   5   98.7890    0.0000    0
   0.0000  -17.1053
   2.1053  -13.9474
   5.2632   -9.4737
   8.4211   -4.7368
  10.5263    0.0000
   6   79.0312    0.0000    0
   0.0000  -17.1053
   2.6316  -13.9474
   6.5789   -9.4737
  10.0000   -4.7368
  11.5789   -2.3684
  12.3684    0.0000
   6   59.2734    0.0000    0
   0.0000  -17.1053
   3.1579  -13.9474
   7.3684   -9.4737
  11.5789   -4.7368
  13.1579   -2.3684
  13.9474    0.0000
   6   39.5156    0.0000    0
   0.0000  -17.3685
   3.6842  -13.9474
   8.4211   -9.4737
  12.8947   -4.7368
  14.4737   -2.3684
  15.2632    0.0000
   6   19.7578    0.0000    0
   0.0000  -18.1579
   4.2105  -13.9474
   9.4737   -9.4737
  14.2105   -4.7368
  15.7895   -2.3684
  16.5789    0.0000
   6    0.0000    0.0000    0
   0.0000  -18.9474
   4.7368  -13.9474
  10.5263   -9.4737
  15.2632   -4.7368
  16.8421   -2.3684
```

```
17.3684    0.0000
 6  -19.7578    0.0000    0
 0.0000  -18.9474
 4.7368  -13.9474
10.7895   -9.4737
16.0526   -4.7368
17.8947   -2.3684
18.1579    0.0000
 6  -39.5156    0.0000    0
 0.0000  -18.9474
 3.9474  -13.9474
10.7895   -9.4737
16.8421   -4.7368
18.4211   -2.3684
18.9474    0.0000
 6  -59.2734    0.0000    0
 0.0000  -17.1053
 3.6842  -13.9474
10.5263   -9.4737
16.8421   -4.7368
18.4211   -2.3684
19.4737    0.0000
 6  -79.0312    0.0000    0
 0.0000  -15.2632
 1.8421  -13.9474
 9.7368   -9.4737
16.8421   -4.7368
18.4211   -2.3684
19.4737    0.0000
 5  -98.7890    0.0000    0
 0.0000  -13.6841
 8.1579   -9.4737
16.3158   -4.7368
18.4211   -2.3684
19.4737    0.0000
 5 -118.5468    0.0000
 0.0000  -12.1053
 5.7895   -9.4737
15.5263   -4.7368
17.8947   -2.3684
18.9474    0.0000
 5 -138.3046         0.0000
 0.0000  -10.5263
 3.1579   -9.4737
14.4737   -4.7368
17.3684   -2.3684
18.4211    0.0000
 4 -158.0624    0.0000
 0.0000   -8.9473
13.6842   -4.7368
16.8421   -2.3684
17.6316    0.0000
 5 -177.8202    0.0000
 0.0000   -5.5263
12.6316   -4.7368
15.0000   -3.4211
16.0526   -2.3684
16.8421    0.0000
 5 -197.5780    0.0000
 0.0000   -7.3684
11.8421   -4.7368
14.2105   -3.6842
15.2632   -2.3684
16.3158    0.0000
   -2.0    0.0000
 9999.0       0.0       0.0
 1.0000   20.0000 1000.0000   20.0000    0.0000    0.0000    0.0000
 0.0000  000.0000   00.0000
```

APPENDIX B.6 MODEL 4812 SHIPMO INPUT FILE

```
Model 4812
    0    0    0    0    0    0    1    0    1    0    1    0    0   20    0
  464.1589    1.9905   32.1740       1.26E-05            0.0    0.0000
   33.0000  -26.0000    1.0000
    5  198.9252    0.0000    0
    0.0000  -10.0000
    0.6667   -8.6667
    1.3333   -6.0000
    2.0000   -3.0000
    2.6667    0.0000
    5  176.8224    0.0000    0
    0.0000  -10.0000
    1.0000   -8.6667
    2.3333   -6.0000
    4.0000   -3.0000
    5.6667    0.0000
    5  154.7196    0.0000    0
    0.0000  -10.0000
    1.3333   -8.6667
    3.6667   -6.0000
    6.6667   -3.0000
    8.6667    0.0000
    5  132.6168    0.0000    0
    0.0000  -10.3334
    1.6667   -8.6667
    5.3333   -6.0000
    8.6667   -3.0000
   11.3333    0.0000
    5  110.5140    0.0000    0
    0.0000  -10.3334
    2.3333   -8.6667
    6.6667   -6.0000
   10.6667   -3.0000
   13.6667    0.0000
    5   88.4112    0.0000    0
    0.0000  -10.6667
    3.0000   -8.6667
    8.3333   -6.0000
   13.0000   -3.0000
   16.0000    0.0000
    6   66.3084    0.0000    0
    0.0000  -11.0000
    4.0000   -8.6667
    9.6667   -6.0000
   14.6667   -3.0000
   17.0000   -1.3333
   18.0000    0.0000
    6   44.2056    0.0000    0
    0.0000  -11.0000
    4.3333   -8.6667
   11.0000   -6.0000
   16.3333   -3.0000
   18.6667   -1.3333
   19.6667    0.0000
    6   22.1028    0.0000    0
    0.0000  -11.6667
    5.3333   -8.6667
   12.3333   -6.0000
   18.0000   -3.0000
   20.0000   -1.3333
   21.0000    0.0000
    6    0.0000    0.0000    0
    0.0000  -11.6667
    6.0000   -8.6667
   12.3333   -6.0000
   19.6667   -3.0000
   21.3333   -1.3333
```

```
22.6667    0.0000
 6  -22.1028    0.0000    0
 0.0000  -11.6667
 6.0000   -8.6667
13.6667   -6.0000
20.3333   -3.0000
22.3333   -1.3333
23.3333    0.0000
 6  -44.2056    0.0000    0
 0.0000  -11.6667
 5.6667   -8.6667
13.6667   -6.0000
21.6667   -3.0000
24.3333   -1.3333
25.0000    0.0000
 6  -66.3084    0.0000    0
 0.0000  -10.6667
 4.6667   -8.6667
13.6667   -6.0000
21.6667   -3.0000
24.3333   -1.3333
25.0000    0.0000
 6  -88.4112    0.0000    0
 0.0000   -9.3334
 3.0000   -8.6667
12.0000   -6.0000
21.6667   -3.0000
24.0000   -1.3333
24.6667    0.0000
 5 -110.5140    0.0000    0
 0.0000   -8.6667
10.3333   -6.0000
20.6667   -3.0000
23.3333   -1.3333
24.6667    0.0000
 5 -132.6168    0.0000
 0.0000   -8.0000
 7.6667   -6.0000
19.6667   -3.0000
23.3333   -1.3333
24.0000    0.0000
 5 -154.7196         0.0000
 0.0000   -6.6667
 3.6667   -6.0000
18.6667   -3.0000
22.6667   -1.3333
23.3333    0.0000
 4 -176.8224    0.0000
 0.0000   -5.6667
18.0000   -3.0000
21.6667   -1.3333
22.6667    0.0000
 4 -198.9252    0.0000
 0.0000   -4.6667
17.3333   -3.0000
20.6667   -1.3333
22.0000    0.0000
 4 -221.0280    0.0000
 0.0000   -3.6667
16.6667   -3.0000
20.0000   -1.3333
20.6667    0.0000
   -2.0    0.0000
 9999.0       0.0       0.0
 1.0000   20.0000 1000.0000   20.0000    0.0000    0.0000    0.0000
 0.0000  000.0000   00.0000
```

APPENDIX C SAMPLE SHIPMO OUTPUT FILE FOR MODEL 4787

```
Model 4787
0OPTION CONTROL TAGS -  A  B  C  D  E  F  G  H  I  J  K  L  M  N NS NPAC
                        0  0  0  0  0  0  1  0  1  0  1  0 20  0 20  0
0***BASIC INPUT DATA***

          *******   INFINITE DEPTH  *******
0 LENGTH=   357.000
  DENSITY=    1.9905  GAMMA=   64.0423  GNU=   0.126000E-04  GRAVITY=   32.1740
0BILGE KEEL DATA:  XFOR=   33.0000  XAFT=  -26.0000  LENGTH=   59.0000  WIDTH=    1.0000
0STA NO   XAXIS     1/2BEAM    DRAFT    AREA     AREA COEF   ZBAR    BILGE R  AREA COEF2
     1   160.6500    1.8750   13.1250   33.7668    0.6861   -5.1895    0.0000    0.6861
     2   142.8000    3.5417   13.1250   72.3909    0.7787   -5.5049    0.0000    0.7787
     3   124.9500    5.4166   25.4163  160.3840    0.5825   -9.3555    0.0000    0.5825
     4   107.1000    7.0830   13.7500  164.0813    0.8424   -6.0174    0.0000    0.8424
     5    89.2500    8.5417   19.5830  226.2390    0.6763   -6.8682    0.0000    0.6763
     6    71.4000   10.0283   14.1666  232.6713    0.8189   -6.0524    0.0000    0.8189
     7    53.5500   11.4583   14.7910  280.0273    0.8261   -6.3950    0.0000    0.8261
     8    35.7000   12.5000   14.7910  295.4970    0.7991   -6.0616    0.0000    0.7991
     9    17.8500   13.3330   15.0000  369.4937    0.9238   -7.0913    0.0000    0.9238
    10     0.0000   14.1667   15.2080  386.9037    0.8979   -7.0487    0.0000    0.8979
    11   -17.8500   14.5833   15.2080  391.7454    0.8832   -6.9214    0.0000    0.8832
    12   -35.7000   15.0000   15.2080  399.6873    0.8760   -6.9166    0.0000    0.8760
    13   -53.5500   15.4167   14.1663  382.0205    0.8746   -6.3868    0.0000    0.8746
    14   -71.4000   15.4167   13.1250  348.5149    0.8612   -5.8033    0.0000    0.8612
    15   -89.5200   15.4167   11.8750  318.6611    0.8703   -5.3806    0.0000    0.8703
    16  -107.1000   15.0000   11.0413  283.7609    0.8567   -4.9000    0.0000    0.8567
    17  -124.9500   14.5830    9.9996  246.7169    0.8459   -4.4404    0.0000    0.8459
    18  -142.8000   14.1670    8.9580  212.9712    0.8391   -3.9494    0.0000    0.8391
    19  -160.6500   13.7500    7.9163  183.4139    0.8425   -3.4852    0.0000    0.8425
    20  -178.5000   12.9167    6.6666  165.0161    0.9582   -3.2250    0.0000    0.9582
0THE FOLLOWING STATIONS AND OFFSETS ARE USED FOR TWO-DIMENSIONAL CALCULATIONS
  STA NO=  1  XAXIS=  160.6500  NT=  5  ILID=  0
    0.0000  -13.1250
    0.6667  -11.4580
    1.3333   -7.7080
    1.6667   -3.7500
    1.8750    0.0000
  STA NO=  2  XAXIS=  142.8000  NT=  7  ILID=  0
    0.0000  -13.1250
    1.0417  -12.2913
    1.6667  -11.4580
    2.5000   -9.4997
    2.9583   -7.7080
    3.4167   -3.7500
    3.5417    0.0000
  STA NO=  3  XAXIS=  124.9500  NT=  8  ILID=  0
    0.0000  -25.4163
    1.4583  -24.5830
    2.5833  -11.4580
    3.0833   -9.4997
    4.5830   -7.7080
    5.0000   -9.3750
    5.2083   -3.7500
    5.4166    0.0000
  STA NO=  4  XAXIS=  107.1000  NT=  7  ILID=  0
    0.0000  -13.7500
    1.8750  -13.4580
    3.3333  -12.7080
    4.5834  -11.4580
    6.6667   -7.7080
    7.0830   -3.7500
    7.0830    0.0000
  STA NO=  5  XAXIS=   89.2500  NT=  7  ILID=  0
    0.0000  -14.7499
    3.1250  -13.4580
    4.5833   -9.4997
    5.9167  -11.4580
```

```
  7.9167  -19.5830
  8.5417   -3.7500
  8.5417    0.0000
STA NO=  6  XAXIS=   71.4000  NT=  8  ILID=  0
  0.0000  -14.1666
  4.1667  -13.4580
  6.0417   -9.4997
  7.2917  -11.4580
  8.7500   -9.3750
  9.3750   -7.7080
 10.0000   -3.7500
 10.0283    0.0000
STA NO=  7  XAXIS=   53.5500  NT=  8  ILID=  0
  0.0000  -14.7910
  2.9167  -14.1666
  5.8333  -13.1250
  8.3330  -11.4580
 10.0000   -9.3750
 10.8330   -7.7080
 11.2500   -3.7500
 11.4583    0.0000
STA NO=  8  XAXIS=   35.7000  NT=  8  ILID=  0
  0.0000  -14.7910
  2.9167  -13.1250
  5.4583  -11.9583
  9.5833  -11.4580
 11.2500   -9.3750
 12.0830   -7.7080
 12.5000   -3.7500
 12.5000    0.0000
STA NO=  9  XAXIS=   17.8500  NT=  8  ILID=  0
  0.0000  -15.0000
  2.9167  -14.7910
 11.4583  -14.7500
 10.8333  -11.4580
 12.0830   -9.3750
 12.9167   -7.7080
 13.5416   -3.7500
 13.3330    0.0000
STA NO= 10  XAXIS=    0.0000  NT=  9  ILID=  0
  0.0000  -15.2080
  2.9167  -15.2080
  6.2500  -15.0000
 10.0000  -14.5830
 10.4167  -13.0410
 12.9167   -9.3750
 13.7500   -7.7080
 14.1667   -3.7500
 14.1667    0.0000
STA NO= 11  XAXIS=  -17.8500  NT=  8  ILID=  0
  0.0000  -15.2080
  2.9167  -15.2080
  6.2500  -15.0000
 10.4167  -13.0410
 13.5417   -9.3750
 14.1667   -7.7080
 14.5833   -3.7500
 14.5833    0.0000
STA NO= 12  XAXIS=  -35.7000  NT=  7  ILID=  0
  0.0000  -15.2080
  5.6250  -15.2080
 10.8330  -12.9166
 12.5000  -11.4580
 14.1667   -7.7080
 15.0000   -3.7500
 15.0000    0.0000
STA NO= 13  XAXIS=  -53.5500  NT=  7  ILID=  0
  0.0000  -14.1663
  6.0416  -13.9580
```

```
    11.8750  -11.4580
    13.5416   -9.5830
    14.7916   -7.7080
    15.4167   -3.7500
    15.4167    0.0000
   STA NO= 14  XAXIS=  -71.4000  NT=  6  ILID=  0
     0.0000  -13.1250
     6.0416  -12.4996
    11.8750  -10.4163
    14.7916   -7.7080
    15.4167   -3.7500
    15.4167    0.0000
   STA NO= 15  XAXIS=  -89.5200  NT=  6  ILID=  0
     0.0000  -11.8750
     4.7917  -11.8750
    10.0000  -10.6250
    13.9583   -7.7080
    15.2083   -3.7500
    15.4167    0.0000
   STA NO= 16  XAXIS= -107.1000  NT=  6  ILID=  0
     0.0000  -11.0413
     4.7917  -10.8330
    10.0000   -9.3750
    12.9167   -7.7080
    15.0000   -3.7500
    15.0000    0.0000
   STA NO= 17  XAXIS= -124.9500  NT=  6  ILID=  0
     0.0000   -9.9996
     4.7917   -9.7850
     9.7916   -8.5413
    12.9167   -6.2500
    14.1667   -3.7500
    14.5830    0.0000
   STA NO= 18  XAXIS= -142.8000  NT=  6  ILID=  0
     0.0000   -8.9580
     4.7917   -8.5413
     9.3750   -7.7080
    12.5000   -5.8333
    13.5417   -3.7500
    14.1670    0.0000
   STA NO= 19  XAXIS= -160.6500  NT=  6  ILID=  0
     0.0000   -7.9163
     4.7917   -7.4997
     9.3750   -6.6666
    12.0830   -5.4166
    13.1250   -3.7500
    13.7500    0.0000
   STA NO= 20  XAXIS= -178.5000  NT=  6  ILID=  0
     0.0000   -6.6666
     4.7917   -6.6666
     9.3750   -6.6666
    11.4583   -5.8333
    12.9167   -3.7500
    12.9167    0.0000
 0COMPARISON OF INPUT AND COMPUTED DATA
   INPUT       DISPL=      2579.7871  XCG=  -21.9409 RELATIVE TO ORIGIN AT MIDSHIP
   HYDROSTSTIC DISPL=      2579.7871  XCG=  -21.9409 RELATIVE TO ORIGIN AT MIDSHIP
 0BLOCK COEFFICIENT=    0.5866
 0STABILITY PARAMETERS
           LCF =  -35.3216  ZCG =   -2.0000  ZCB =   -6.0841
           WATERPLANE AREA =      8096.8198
           BML =  659.4050  GML =  655.3209
           BMT =    5.4405  GMT =    1.3565
 0RADII OF GYRATION
           KYY =   89.2500 KXX =    9.9167 PRODUCT OF INERTIA(I46) =   0.788154E+07
 1Model 4787


  ***CONDITIONAL INPUT DATA***
```

```
 WAVE AMPLITUDE=    1.0000
 INITIAL WAVELENGTH=   20.0000 FINAL WAVELENGTH= 1000.0000 DELTA WAVELENGTH=   20.0000
 INITIAL VEL=    0.0000 FINAL VEL=    0.0000  DELTA VEL=    0.0000
 INITIAL WAVE HEADING ANGLE=    0.0000 FINAL WAVE HEADING ANGLE=    0.0000
                            DELTA WAVE HEADING ANGLE=    0.0000



 ***UNITS OF OUTPUT***
         NONDIMENSIONAL OUTPUT
           OUTPUT IS DIVIDED BY:
              LINEAR MOTIONS - WAVE AMPLITUDE (WA)
              ROTATIONAL MOTIONS - WAVE SLOPE (WA*WAVEN)
              VELOCITIES - WA*SQRT(GRAV/BPL)
              ACCELERATIONS - WA*GRAV/BPL
              SHEAR - WA*GAMMA*BEAM*BPL
              BENDING MOMENTS - WA*GAMMA*BEAM*BPL**2
1Model 4787
0 SPEED =  0.0000      WAVE ANGLE =    0.00 DEG.
+                                                   VERTICAL PLANE RESPONSES
+                                                                       (NON-
DIMENSIONAL)

0    WAVE     ENCOUNTER    WAVE   WAVE/SHIP
+                                            S U R G E      H E A V E      P I T C H
  F R E Q U E N C I E S   LENGTH   LENGTH
+                                            AMPL.  PHASE    AMPL.  PHASE    AMPL.  PHASE
```

WAVE FREQUENCY	ENCOUNTER FREQUENCY	WAVE LENGTH	WAVE/SHIP LENGTH	SURGE AMPL.	SURGE PHASE	HEAVE AMPL.	HEAVE PHASE	PITCH AMPL.	PITCH PHASE
3.17927	3.17927	20.000	0.0560	0.0021	148.8	0.0002	-113.2	0.0000	-118.9
2.24808	2.24808	40.000	0.1120	0.0088	-9.6	0.0023	-62.3	0.0003	83.7
1.83555	1.83555	60.000	0.1681	0.0135	173.2	0.0069	-133.3	0.0013	124.9
1.58964	1.58964	80.000	0.2241	0.0146	-81.0	0.0358	-26.5	0.0089	-136.2
1.42181	1.42181	100.000	0.2801	0.0272	118.4	0.0805	109.7	0.0087	121.3
1.29793	1.29793	120.000	0.3361	0.0181	-15.6	0.1635	-132.6	0.0711	47.5
1.20165	1.20165	140.000	0.3922	0.0317	-82.3	0.0938	-53.3	0.0349	-5.5
1.12404	1.12404	160.000	0.4482	0.0222	-152.2	0.0455	140.5	0.0837	-67.2
1.05976	1.05976	180.000	0.5042	0.0379	143.0	0.1320	160.9	0.1040	-82.4
1.00537	1.00537	200.000	0.5602	0.0484	118.1	0.1608	169.3	0.0895	-101.8
0.95859	0.95859	220.000	0.6162	0.0424	94.2	0.1464	174.7	0.0707	-140.6
0.91778	0.91778	240.000	0.6723	0.0325	46.9	0.1049	-179.8	0.0901	171.4
0.88177	0.88177	260.000	0.7283	0.0493	-9.5	0.0488	-168.1	0.1429	146.6
0.84970	0.84970	280.000	0.7843	0.0880	-33.4	0.0232	-46.0	0.2046	134.8
0.82088	0.82088	300.000	0.8403	0.1336	-44.4	0.0847	-14.3	0.2667	127.9
0.79482	0.79482	320.000	0.8964	0.1809	-50.8	0.1487	-9.0	0.3256	123.4
0.77109	0.77109	340.000	0.9524	0.2276	-55.1	0.2099	-6.7	0.3803	120.1
0.74936	0.74936	360.000	1.0084	0.2725	-58.3	0.2672	-5.4	0.4305	117.5
0.72937	0.72937	380.000	1.0644	0.3151	-60.9	0.3203	-4.5	0.4761	115.5
0.71091	0.71091	400.000	1.1204	0.3550	-62.9	0.3692	-3.8	0.5174	113.8
0.69377	0.69377	420.000	1.1765	0.3922	-64.6	0.4139	-3.3	0.5548	112.3
0.67782	0.67782	440.000	1.2325	0.4268	-66.1	0.4548	-2.9	0.5885	111.0
0.66292	0.66292	460.000	1.2885	0.4587	-67.3	0.4921	-2.6	0.6191	109.9
0.64897	0.64897	480.000	1.3445	0.4882	-68.5	0.5261	-2.3	0.6467	109.0
0.63585	0.63585	500.000	1.4006	0.5155	-69.4	0.5572	-2.1	0.6718	108.1
0.62351	0.62351	520.000	1.4566	0.5407	-70.3	0.5856	-1.9	0.6945	107.3
0.61185	0.61185	540.000	1.5126	0.5640	-71.1	0.6115	-1.8	0.7152	106.6
0.60083	0.60083	560.000	1.5686	0.5855	-71.8	0.6352	-1.6	0.7341	105.9
0.59038	0.59038	580.000	1.6247	0.6054	-72.4	0.6570	-1.5	0.7513	105.3
0.58045	0.58045	600.000	1.6807	0.6239	-73.0	0.6770	-1.4	0.7670	104.7
0.57101	0.57101	620.000	1.7367	0.6410	-73.6	0.6953	-1.3	0.7814	104.2
0.56202	0.56202	640.000	1.7927	0.6569	-74.1	0.7123	-1.2	0.7946	103.7
0.55344	0.55344	660.000	1.8487	0.6717	-74.5	0.7279	-1.2	0.8068	103.3
0.54524	0.54524	680.000	1.9048	0.6855	-74.9	0.7423	-1.1	0.8180	102.9
0.53739	0.53739	700.000	1.9608	0.6984	-75.3	0.7556	-1.0	0.8284	102.5
0.52988	0.52988	720.000	2.0168	0.7104	-75.7	0.7680	-1.0	0.8380	102.1
0.52267	0.52267	740.000	2.0728	0.7216	-76.0	0.7795	-0.9	0.8468	101.8
0.51575	0.51575	760.000	2.1289	0.7321	-76.4	0.7902	-0.9	0.8551	101.4
0.50909	0.50909	780.000	2.1849	0.7419	-76.6	0.8001	-0.8	0.8627	101.1
0.50269	0.50269	800.000	2.2409	0.7512	-76.9	0.8094	-0.8	0.8698	100.8
0.49652	0.49652	820.000	2.2969	0.7598	-77.2	0.8180	-0.8	0.8764	100.5

0.49057	0.49057	840.000	2.3529	0.7680	-77.4	0.8261	-0.7	0.8826	100.3
0.48483	0.48483	860.000	2.4090	0.7757	-77.7	0.8337	-0.7	0.8884	100.0
0.47929	0.47929	880.000	2.4650	0.7830	-77.9	0.8408	-0.7	0.8938	99.8
0.47394	0.47394	900.000	2.5210	0.7899	-78.1	0.8474	-0.6	0.8989	99.6
0.46876	0.46876	920.000	2.5770	0.7964	-78.3	0.8537	-0.6	0.9036	99.3
0.46374	0.46374	940.000	2.6331	0.8025	-78.4	0.8596	-0.6	0.9081	99.1
0.45889	0.45889	960.000	2.6891	0.8083	-78.6	0.8651	-0.6	0.9123	98.9
0.45418	0.45418	980.000	2.7451	0.8138	-78.8	0.8703	-0.5	0.9162	98.7
0.44962	0.44962	1000.000	2.8011	0.8191	-78.9	0.8753	-0.5	0.9200	98.5

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APPENDIX D MATLAB CODE FOR *V_SPEED_LONG.M*

```
% Vertical Plane
% Dimensional version (U.S. units)
% Contour plots (heading/wave height)
% Fully developed Pierson-Moskowitz spectrum - Long crested seas
%
ship=input('Enter ship number = ');
i_Sea=input('Enter 0 for Pierson-Moskowitz spectrum or 1 otherwise = ');
HS  =input('Significant Wave Height (feet) = ');
if i_Sea == 0
    omega_m=0.4*sqrt(32.2/HS);
else
    T_m=input('Enter modal period (sec) = ');
    omega_m=2*pi/T_m;
end
warning off
%
lambda_min  =20;                                        % Min wave length (ft)
lambda_max  =1000;                                     % Max wave length (ft)
delta_lambda=20;                                       % Wave length increment (ft)
rho         =1.9905;                                   % Water density
zeta        =1;                                         % Regular wave height
L           =357;                                       % Reference length for
nondimensionalization
shipname    =num2str(ship);                             % Ship model
beta_incr   =15;                                        % Increment in sea direction (deg)
lambda      = lambda_min:delta_lambda:lambda_max;        % Vector of wavelengths
wavenumber  = 2.0*pi./lambda;                            % Wave number
g           = 32.2;
omega       = sqrt(wavenumber*g);                        % Wave frequency
xarm        = -0.25*L;                                   % Point for motion calculation
period      = 2.0*pi./omega;
filesize    = size(lambda);
V_min       = 0;
V_max       = 100;
delta_V     = 10;
%
% Set up file reading format.
%
iSpeed=0;
for V=V_min:delta_V:V_max,       % Loop on speed
    iSpeed=iSpeed+1;
    V_string   =num2str(V);
    ibeta=0;
    for beta=0:beta_incr:360, % Loop on sea direction
        if beta>180
            beta=360-beta;
        end
        beta_string=num2str(beta);
        if beta < 100
            beta_string=strcat('0',num2str(beta));
        end
        if beta < 10
            beta_string=strcat('00',num2str(beta));
        end
        ibeta=ibeta+1;
        trigg = 27;
        f3loc = 26; f5loc=27;
        if beta==0
            trigg = 27;
            f3loc = 26; f5loc=27;
        elseif beta==180
        trigg = 27;
        f3loc = 26; f5loc=27;
        end
        %
        % Load ship data file msvhV_beta.txt
        %
```

```
load_filename=strcat(shipname,'_',V_string,'_',beta_string,'.txt');
filename=load(load_filename);
%
% GENERAL DATA
%
omegae     = omega-wavenumber*V*cos(beta*pi/180);          % Frequency of encounter
periode    = 2.0*pi./omegae;
omegae     = omegae';
lambda_size= trigg*filesize(2);
%
% VERTICAL PLANE RESPONSE CALCULATIONS
%
% Set mass matrix elements
%
M33=filename(3:trigg:lambda_size,3);
M35=filename(3:trigg:lambda_size,5);
M53=filename(5:trigg:lambda_size,3);
M55=filename(5:trigg:lambda_size,5);
%
% Added mass terms
%
A33=filename(9:trigg:lambda_size,3);
A35=filename(9:trigg:lambda_size,5);
A53=filename(11:trigg:lambda_size,3);
A55=filename(11:trigg:lambda_size,5);
%
% Damping terms
%
B33=filename(15:trigg:lambda_size,3);
B35=filename(15:trigg:lambda_size,5);
B53=filename(17:trigg:lambda_size,3);
B55=filename(17:trigg:lambda_size,5);
%
% Hydrostatic terms
%
C33=filename(21:trigg:lambda_size,3);
C35=filename(21:trigg:lambda_size,5);
C53=filename(23:trigg:lambda_size,3);
C55=filename(23:trigg:lambda_size,5);
%
% Total exciting forces
%
F3_t_amp=filename(f3loc:trigg:lambda_size,5);
F5_t_amp=filename(f5loc:trigg:lambda_size,5);
F3_t_pha=filename(f3loc:trigg:lambda_size,6);
F5_t_pha=filename(f5loc:trigg:lambda_size,6);
F3_t    =F3_t_amp.*exp(i*F3_t_pha.*pi/180.0);
F5_t    =F5_t_amp.*exp(i*F5_t_pha.*pi/180.0);
%
% Froude/Krylov exciting forces
%
F3_f_amp=filename(f3loc:trigg:lambda_size,1);
F5_f_amp=filename(f5loc:trigg:lambda_size,1);
F3_f_pha=filename(f3loc:trigg:lambda_size,2);
F5_f_pha=filename(f5loc:trigg:lambda_size,2);
F3_f    =F3_f_amp.*exp(i*F3_f_pha.*pi/180.0);
F5_f    =F5_f_amp.*exp(i*F5_f_pha.*pi/180.0);
%
% Diffraction exciting forces
%
F3_d_amp=filename(f3loc:trigg:lambda_size,3);
F5_d_amp=filename(f5loc:trigg:lambda_size,3);
F3_d_pha=filename(f3loc:trigg:lambda_size,4);
F5_d_pha=filename(f5loc:trigg:lambda_size,4);
F3_d=F3_d_amp.*exp(i*F3_d_pha.*pi/180.0);
F5_d=F5_d_amp.*exp(i*F5_d_pha.*pi/180.0);
%
% Calculate Ship Motions
%
```

```
        A33bar=-(omegae.^2).*(M33+A33)+i*omegae.*B33+C33;
        A35bar=-(omegae.^2).*(M35+A35)+i*omegae.*B35+C35;
        A53bar=-(omegae.^2).*(M53+A53)+i*omegae.*B53+C53;
        A55bar=-(omegae.^2).*(M55+A55)+i*omegae.*B55+C55;
        %
        eta3=(A55bar.*F3_t-A35bar.*F5_t)./(A33bar.*A55bar-A35bar.*A53bar);
        eta5=(A53bar.*F3_t-A33bar.*F5_t)./(A53bar.*A35bar-A33bar.*A55bar);
        xi=eta3-eta5*xarm;
        %
        % Random wave calculations
        %
        A=(1.25/4)*(omega_m^4)*(HS^2);
        B=1.25*omega_m^4;
        S     =(A./omega.^5).*exp(-B./omega.^4);
        Se    =S./abs((1-(2.0/g)*omega*V*cos(beta*pi/180)));          % Convert S(w) to S(we)
        %
        % Define response spectra
        %
        Sxi  =((abs(xi)).^2).*Se';
        Seta3=((abs(eta3)).^2).*Se';
        Seta5=((abs(eta5)).^2).*Se';
        %
        % Initializations
        %
        Sxi_i=0;
        Seta3_i=0;
        Seta5_i=0;
        %
        % Integral S(w)*|RAO|^2
        %
        for I=2:1:filesize(2),
            Sxi_i  = Sxi_i  + 0.5*(Sxi(I)  + Sxi(I-1))  * abs((omegae(I-1)-omegae(I)));
            Seta3_i= Seta3_i+ 0.5*(Seta3(I)+ Seta3(I-1))* abs((omegae(I-1)-omegae(I)));
            Seta5_i= Seta5_i+ 0.5*(Seta5(I)+ Seta5(I-1))* abs((omegae(I-1)-omegae(I)));
        end
        %
        % RMS values
        %
        RMS_xi(ibeta,iSpeed)  = sqrt(Sxi_i);
        RMS_eta3(ibeta,iSpeed)= sqrt(Seta3_i);
        RMS_eta5(ibeta,iSpeed)= sqrt(Seta5_i);
        %
    end
end
%
% Contour plots
%
conv=1.6878;
Vp_min=V_min/conv;
Vp_max=V_max/conv;
delta_Vp=delta_V/conv;
%
figure(1)
[th,r]=meshgrid((0:beta_incr:360)*pi/180,Vp_min:delta_Vp:Vp_max);
[X,Y]=pol2cart(th,r);
h=polar(th,r);delete(h);
hold on
contour(X',Y',RMS_eta5/HS,c_p),caxis([0 10]),colorbar
%
figure(2)
[th,r]=meshgrid((0:beta_incr:360)*pi/180,Vp_min:delta_Vp:Vp_max);
[X,Y]=pol2cart(th,r);
h=polar(th,r);delete(h);
hold on
c_p=[0:0.2:10];
contour(X',Y',RMS_eta3/HS,c_p),caxis([0 10]),colorbar
```

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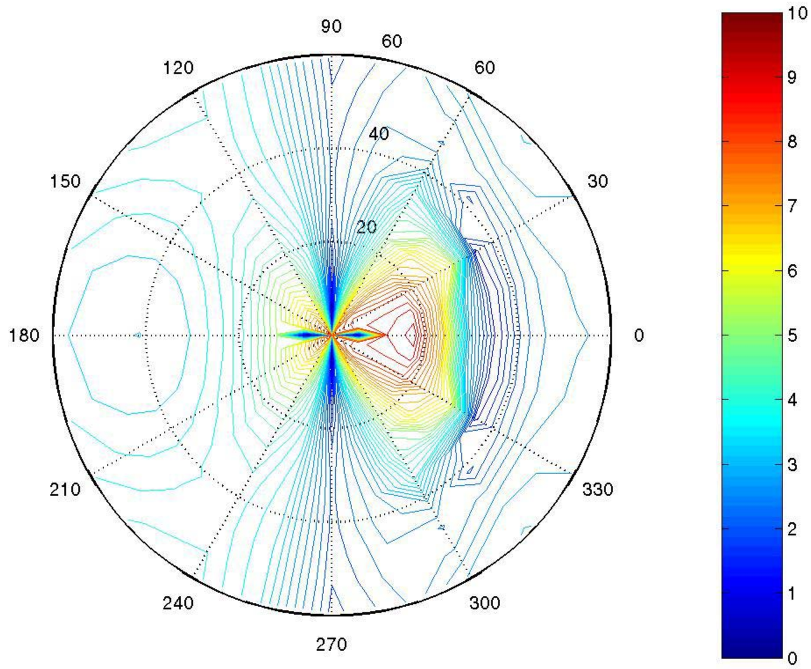
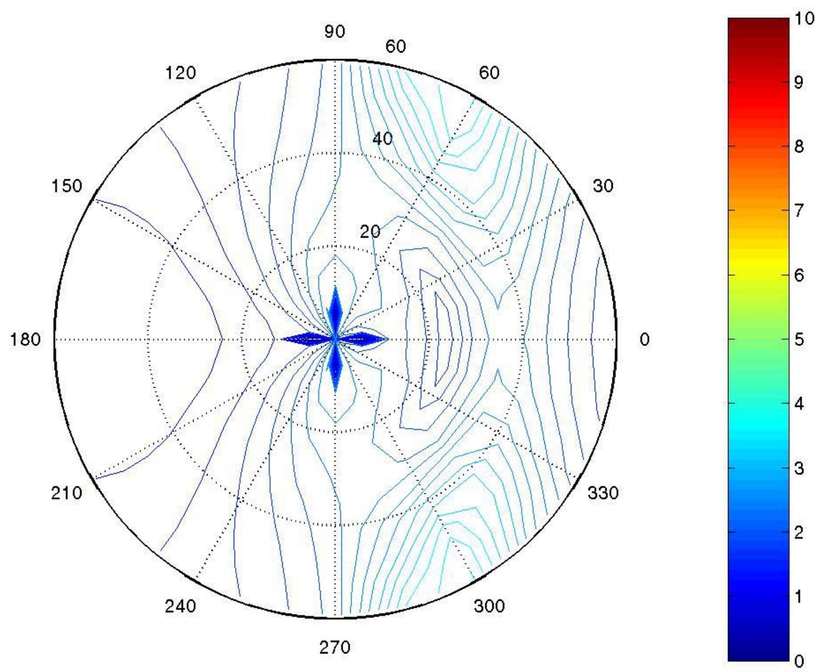
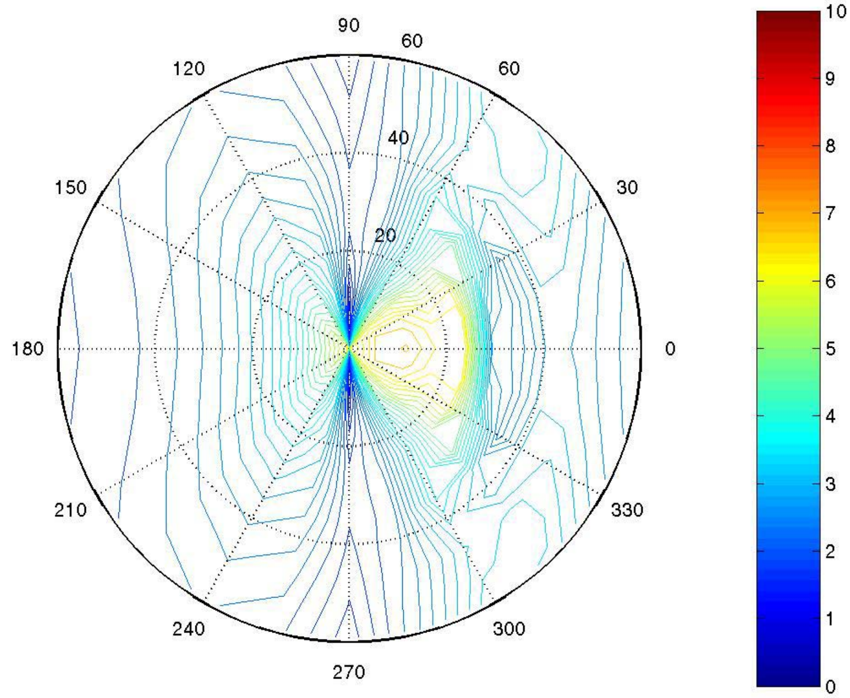
APPENDIX E PIERSON – MOSKOWITZ CONTOUR PLOTS



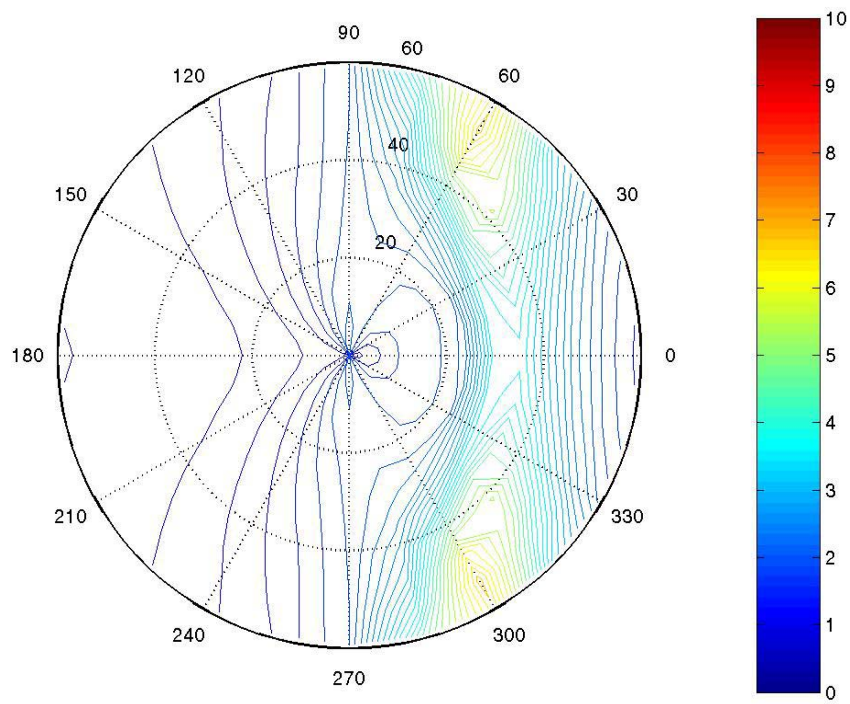
Model 4787 (PM) Pitch Response



Model 4787 (PM) Heave Response



Model 4794 (PM) Pitch Response



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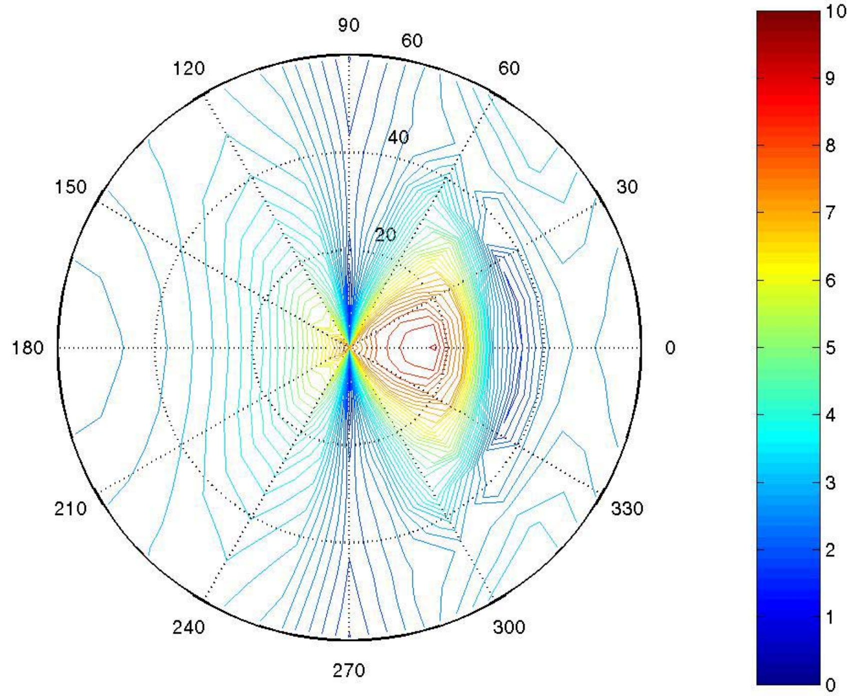

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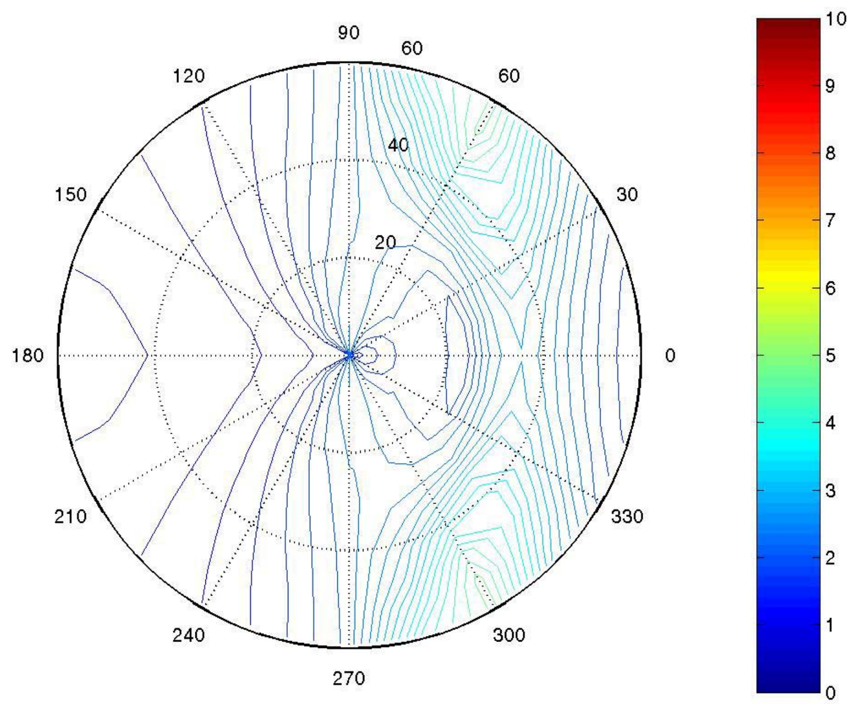

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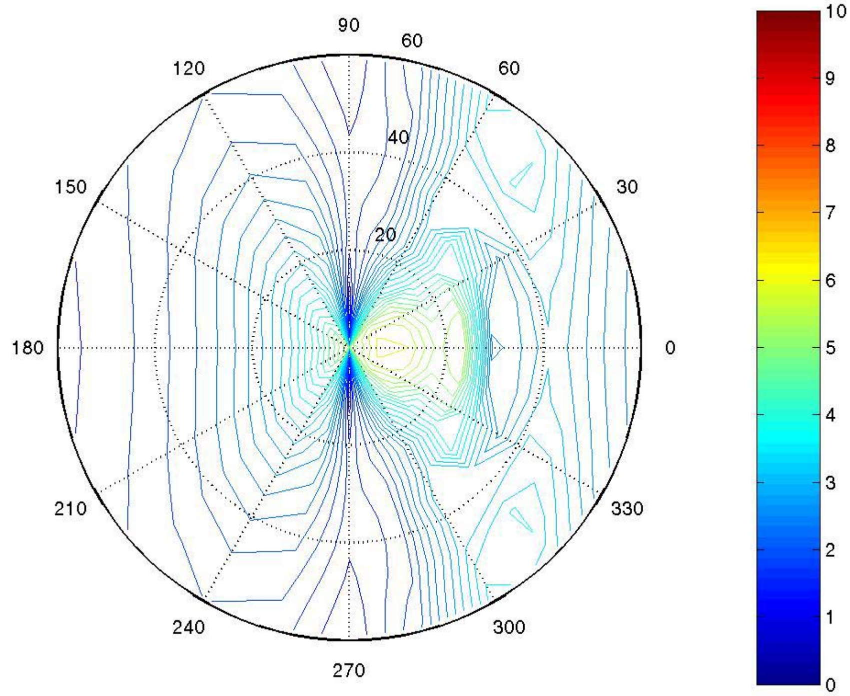
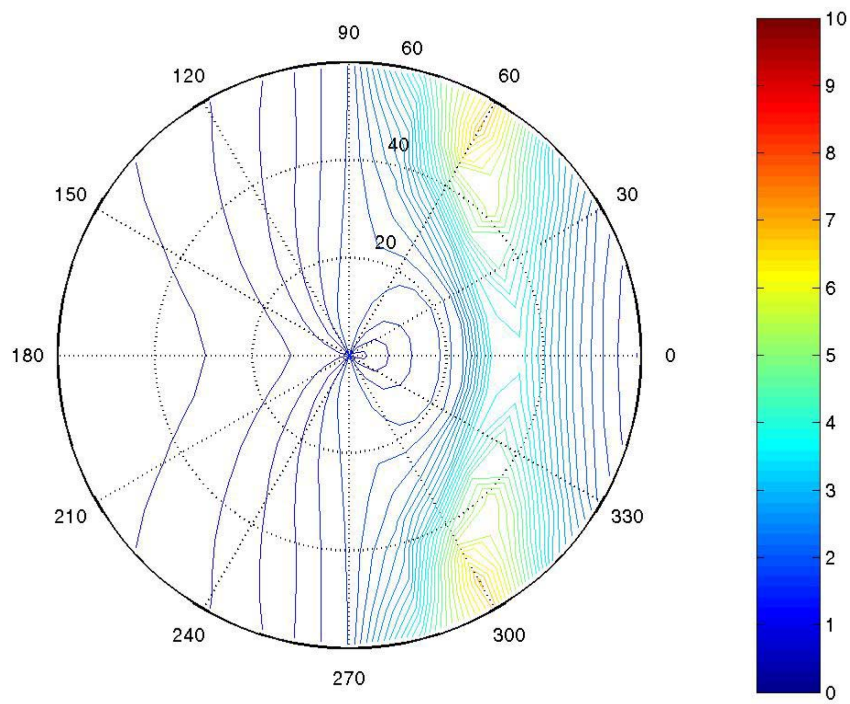


Model 4802 (PM) Pitch Response



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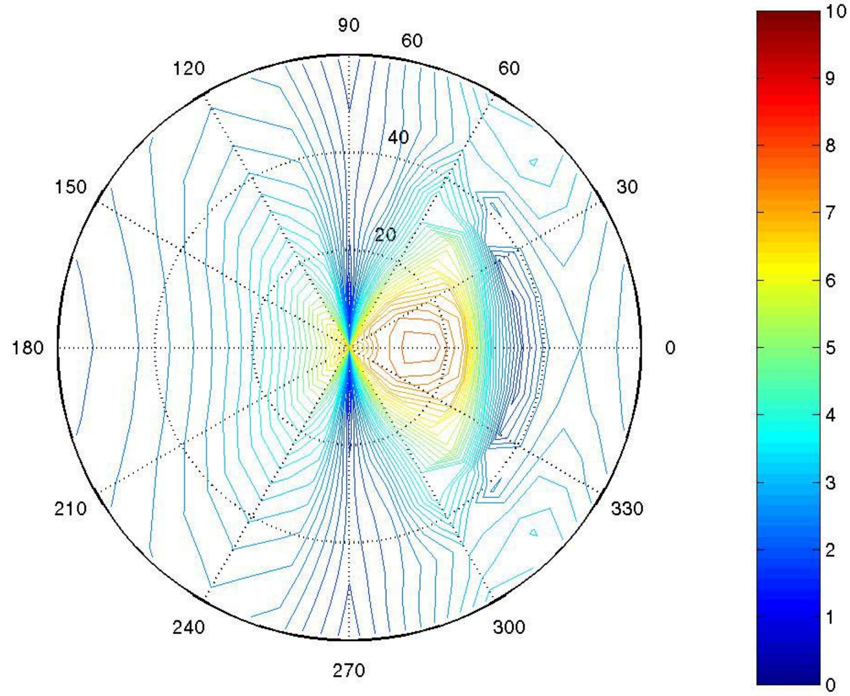
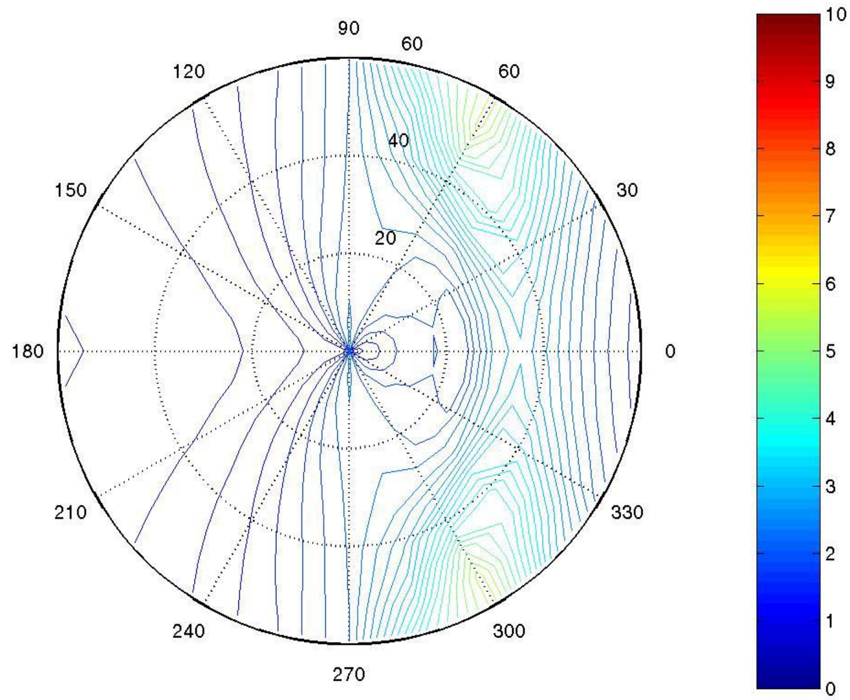
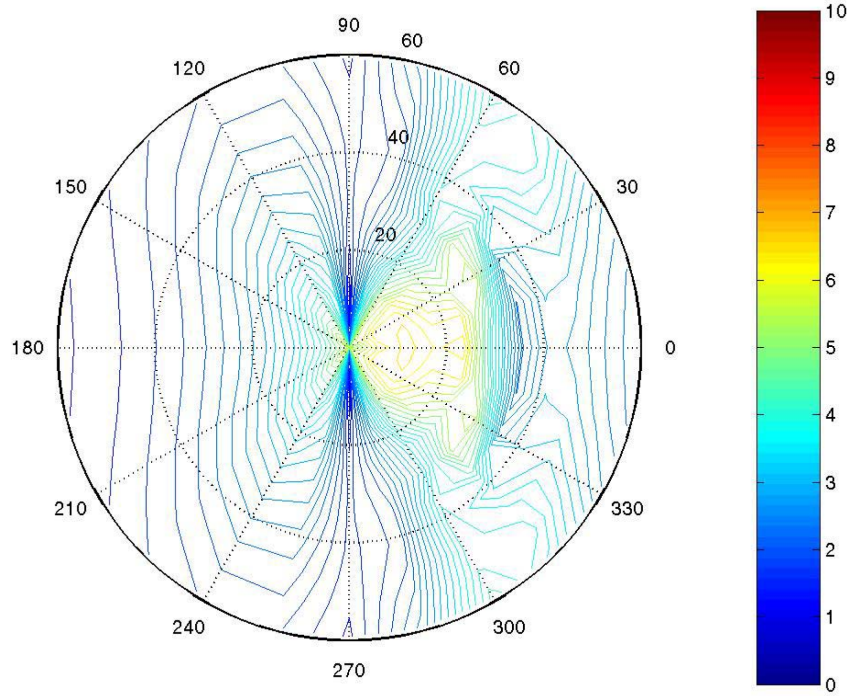


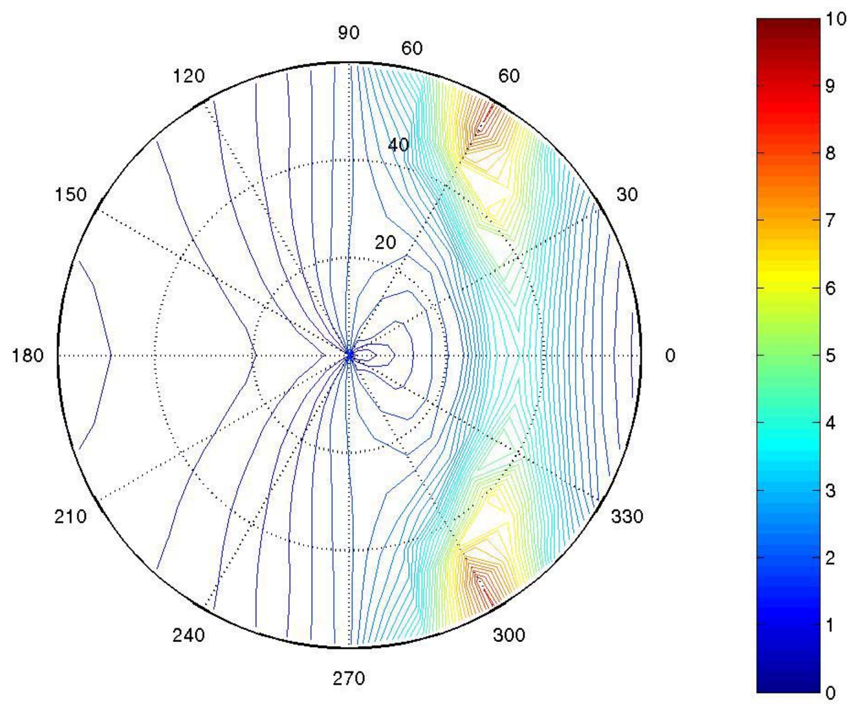
Model 4805 (PM) Pitch Response



Model 4805 (PM) Heave Response

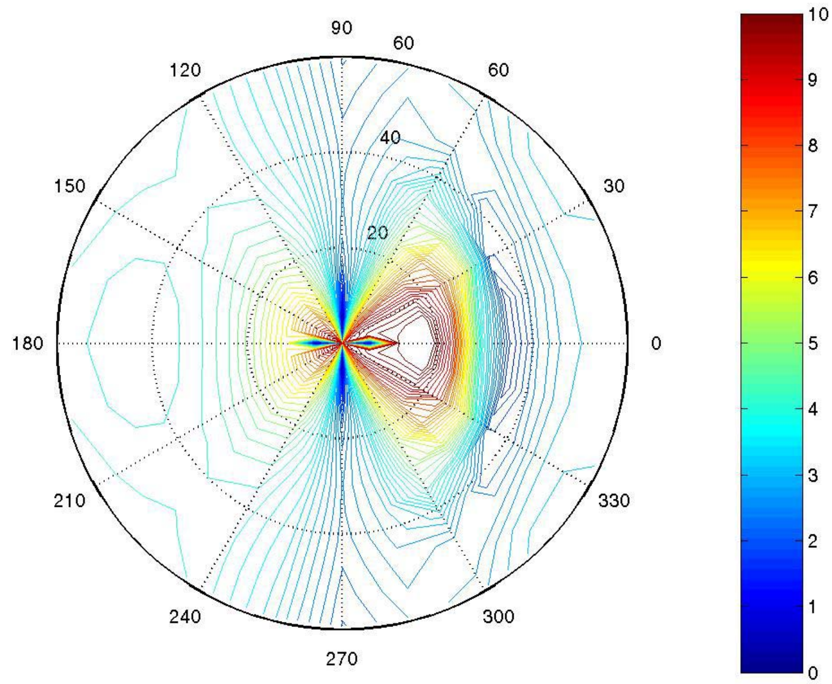


Model 4812 (PM) Pitch Response



Model 4812 (PM) Heave Response

APPENDIX F BRETSCHNEIDER CONTOUR PLOTS



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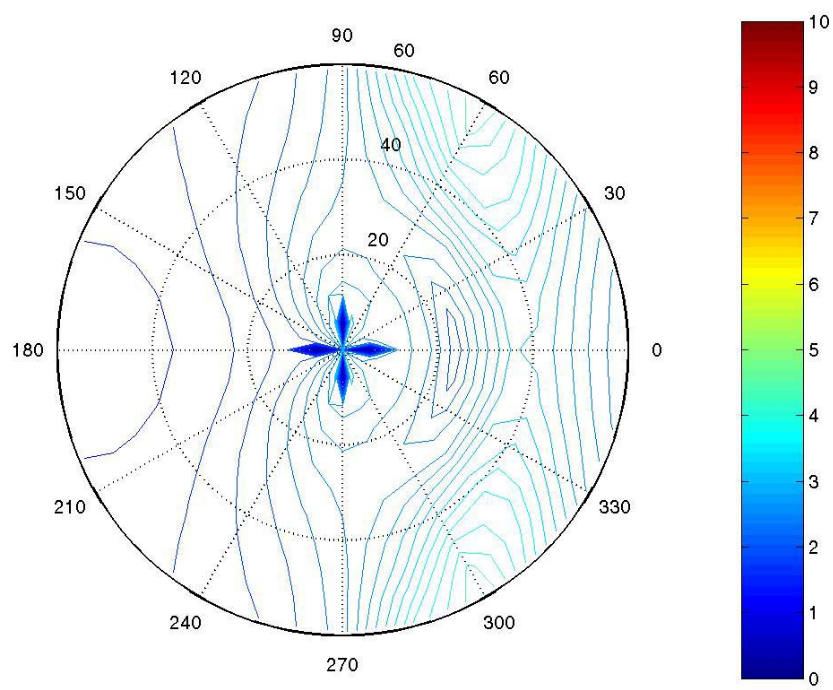

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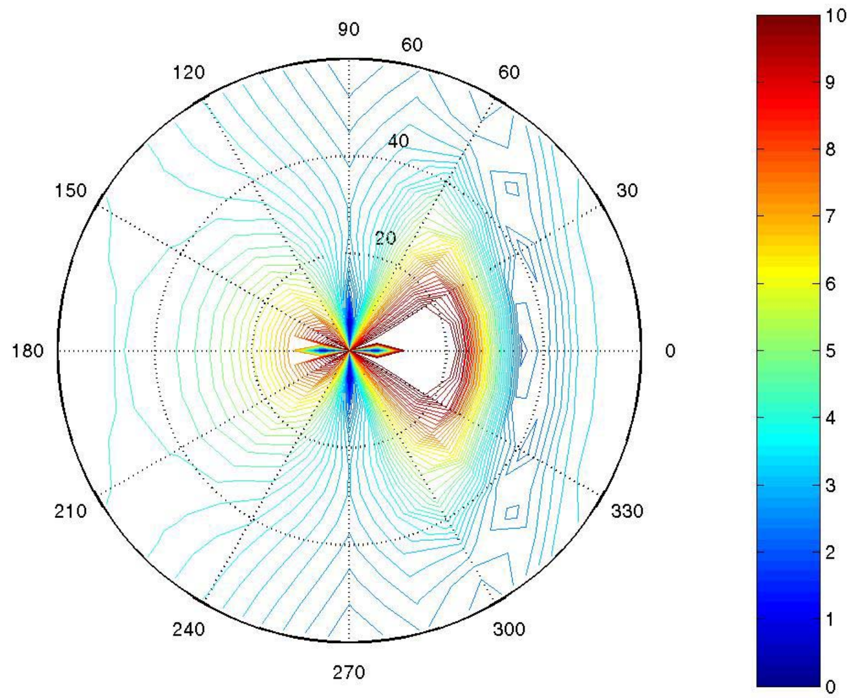

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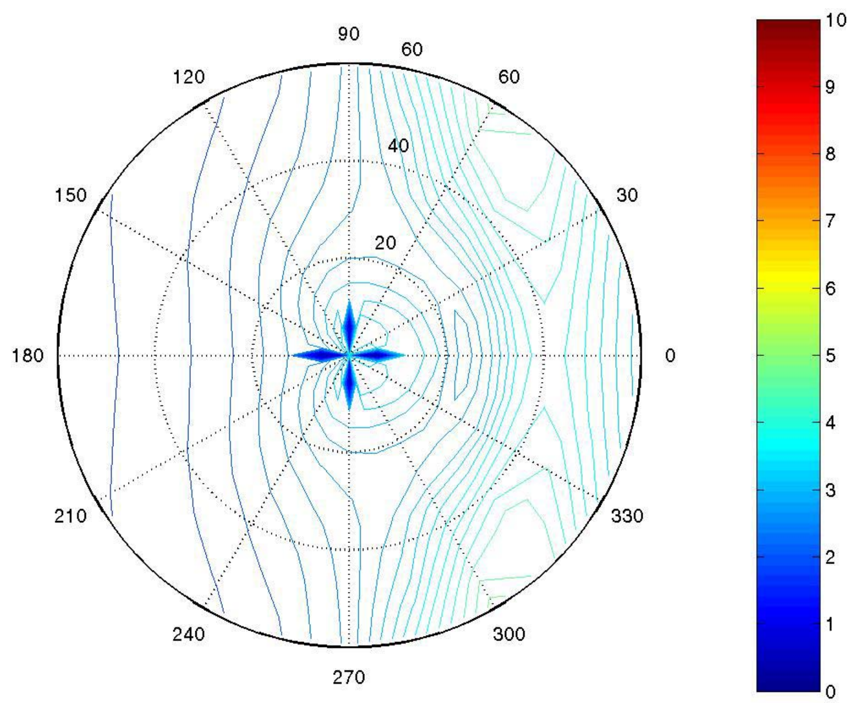

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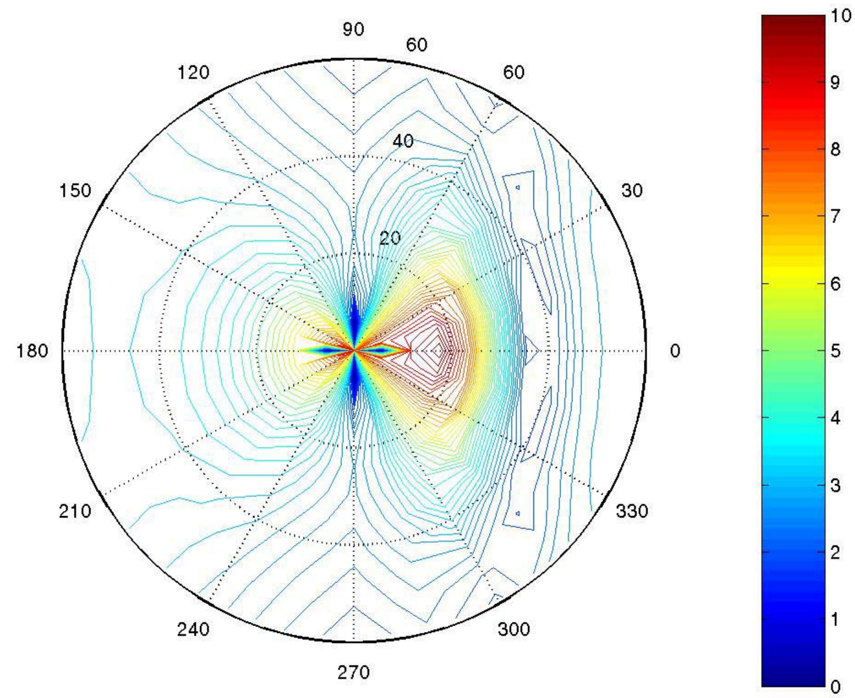

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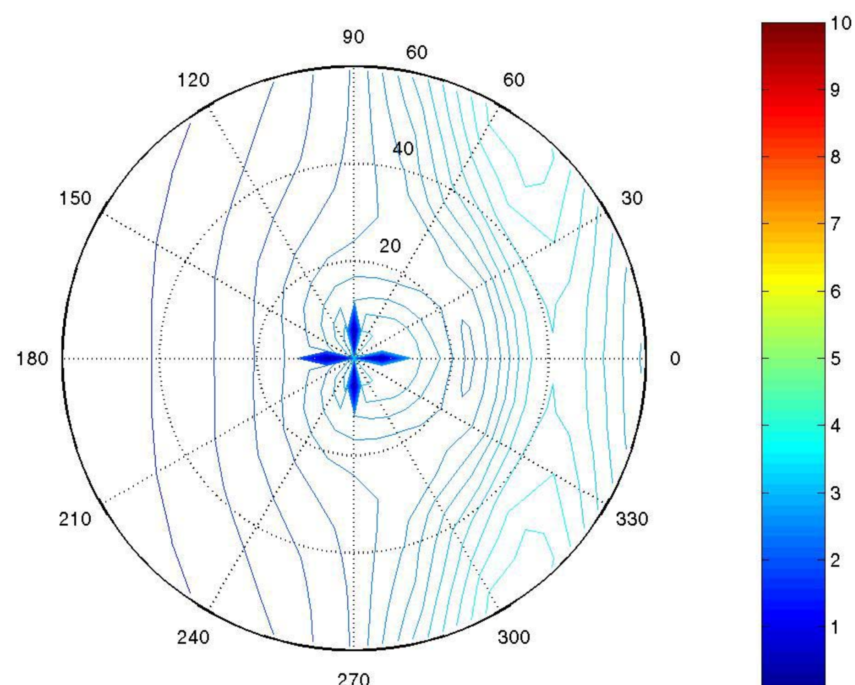
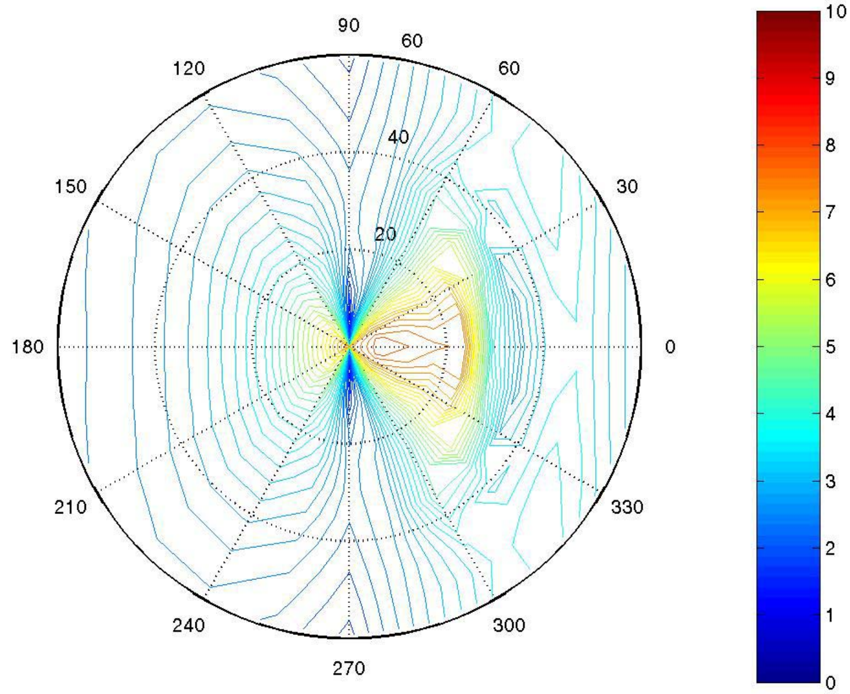
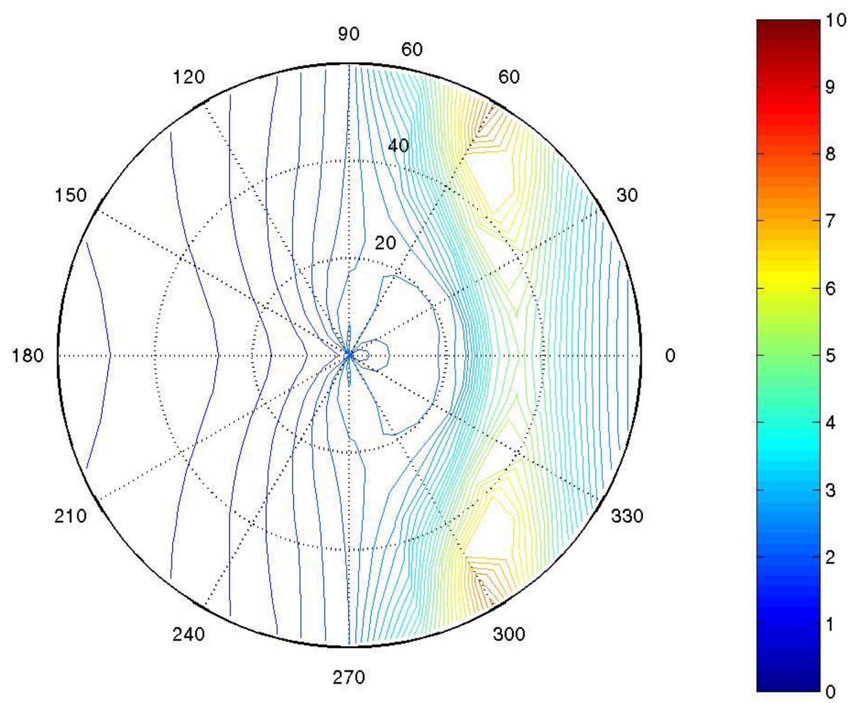


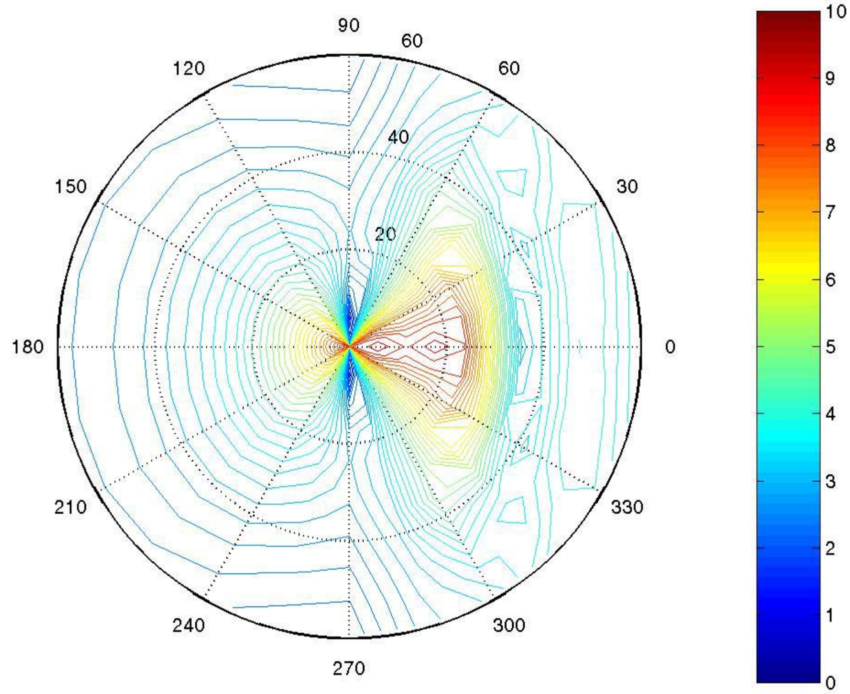
Model 4787 (B: 16.2 sec) Heave Response



Model 4794 (B: 9.8 sec) Pitch Response



Model 4794 (B: 9.8 sec) Heave Response



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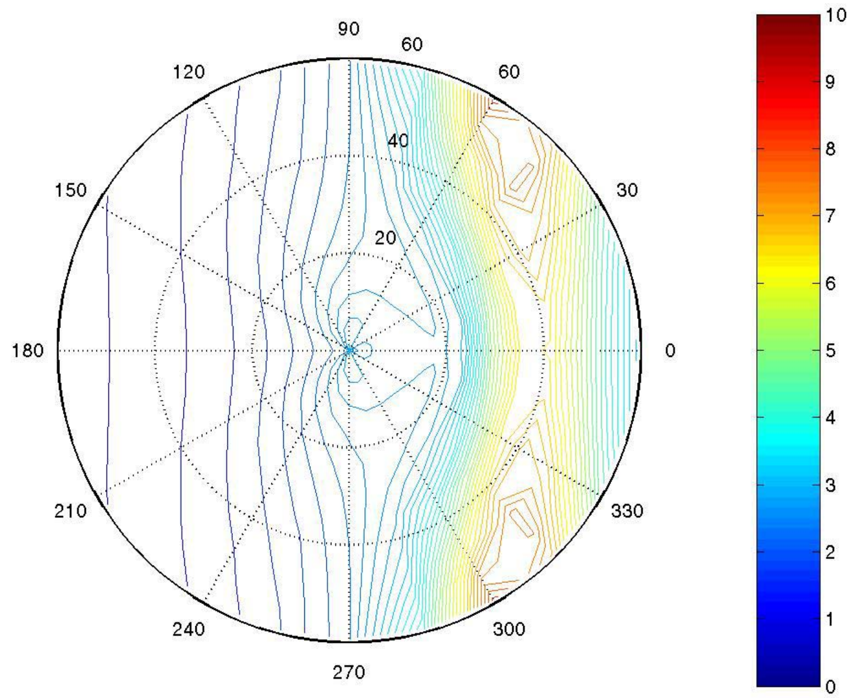

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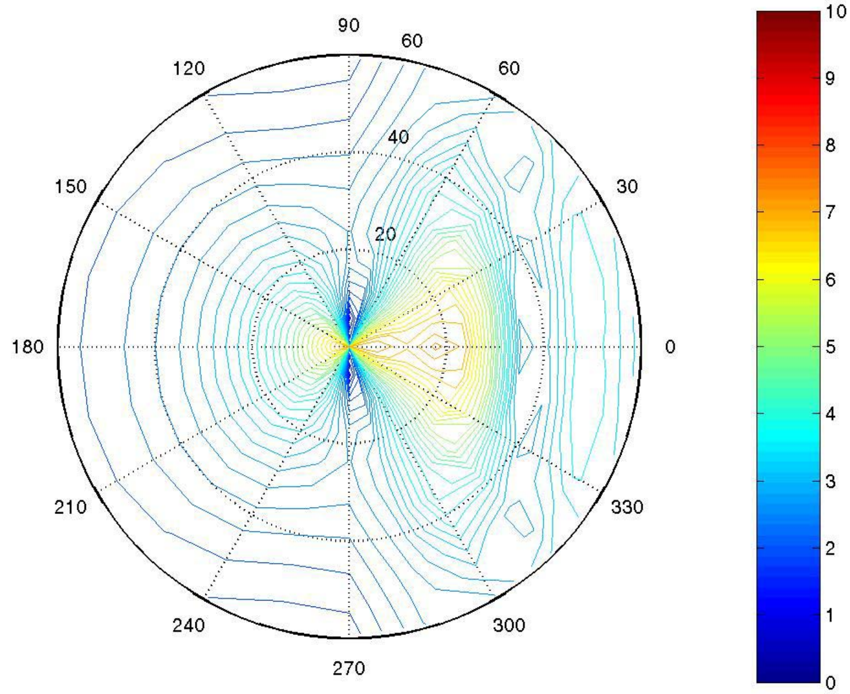

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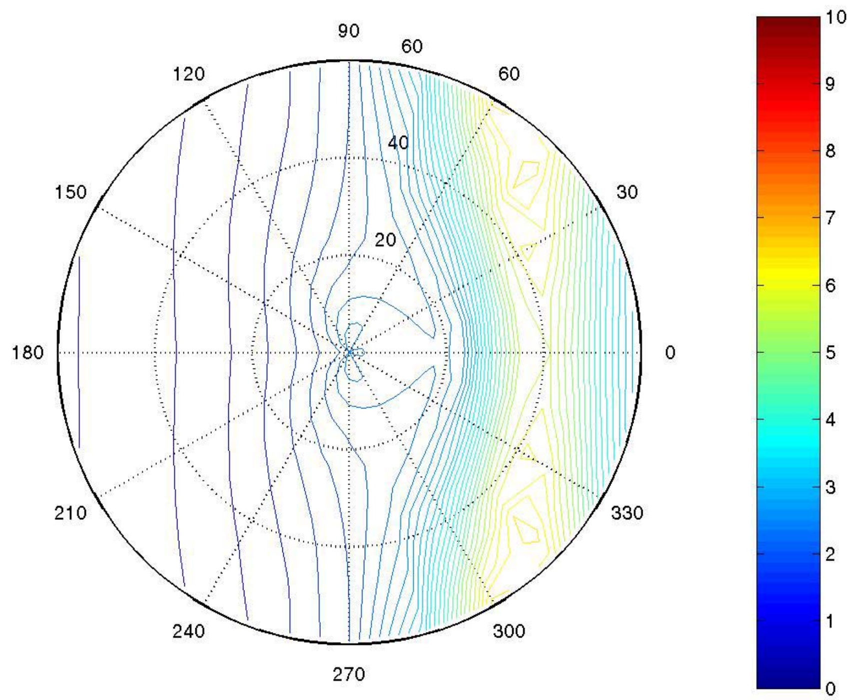

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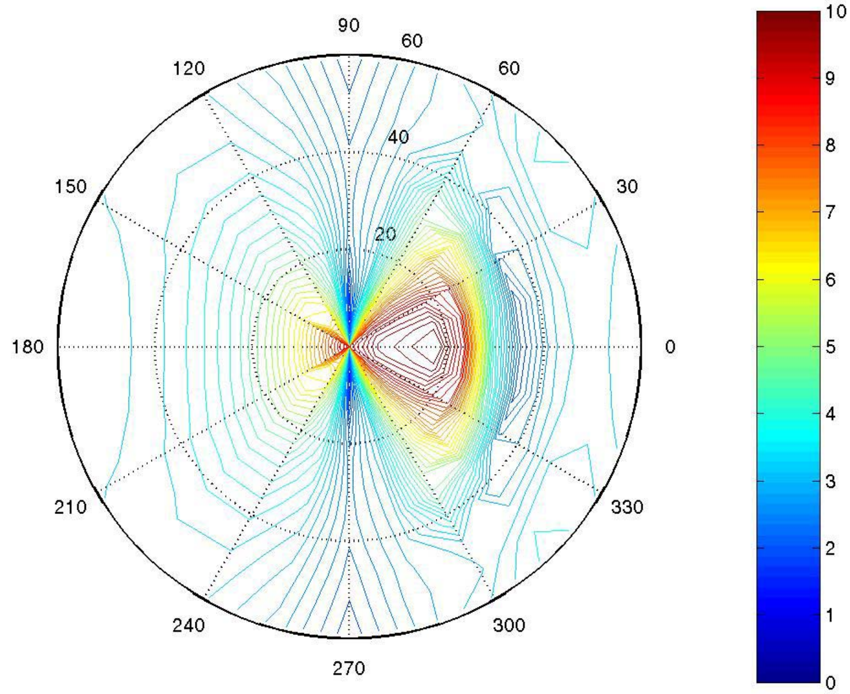

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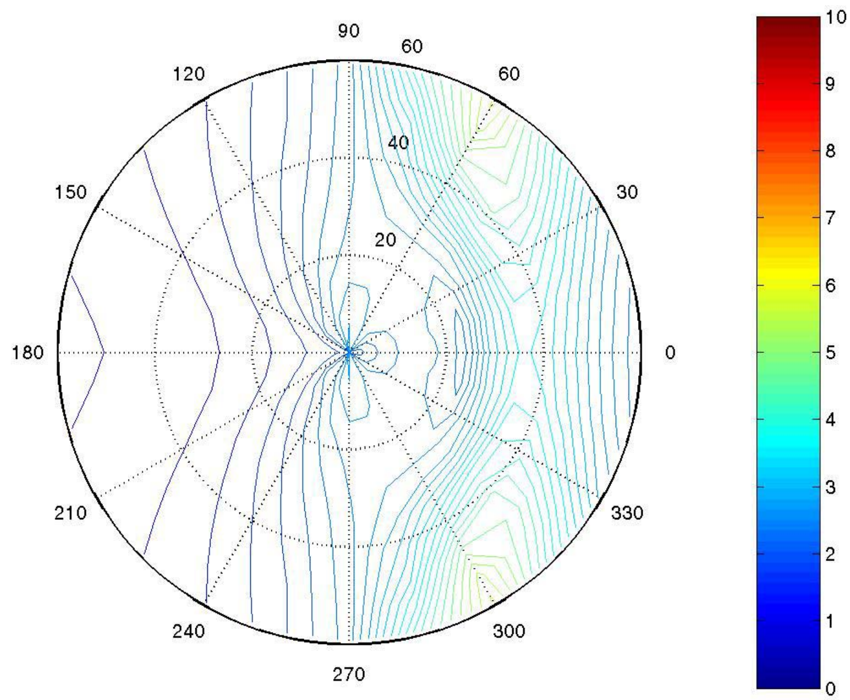

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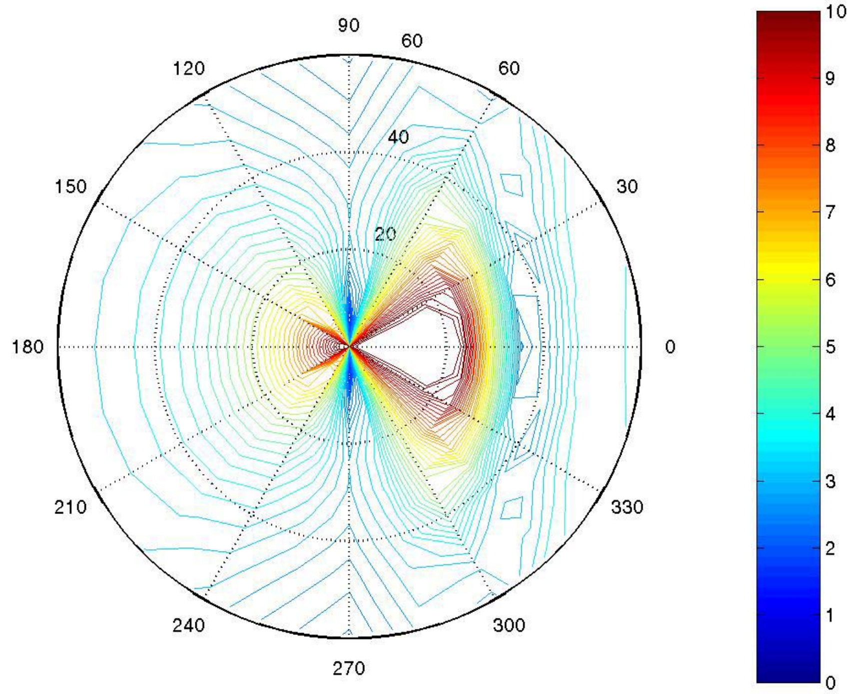

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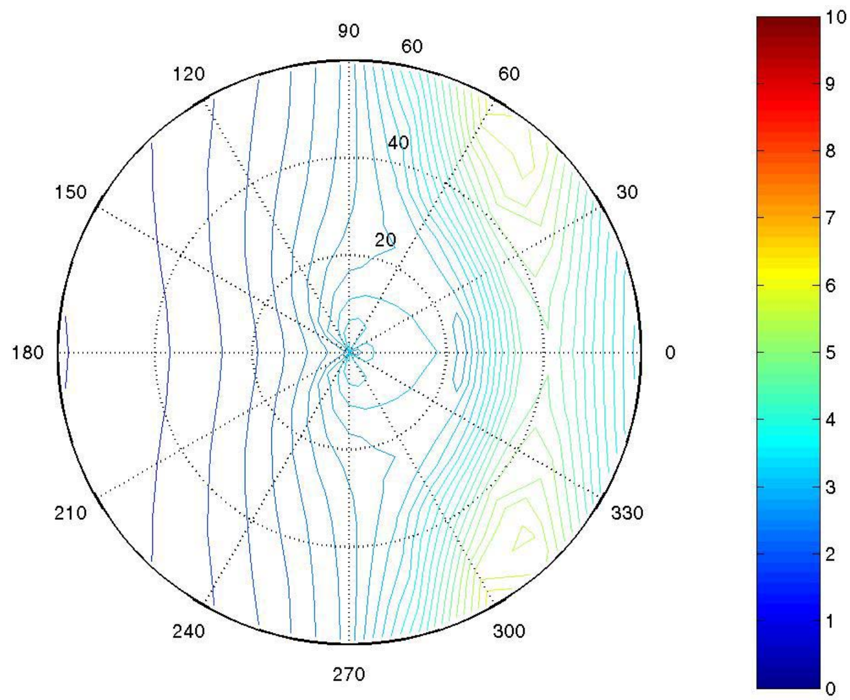

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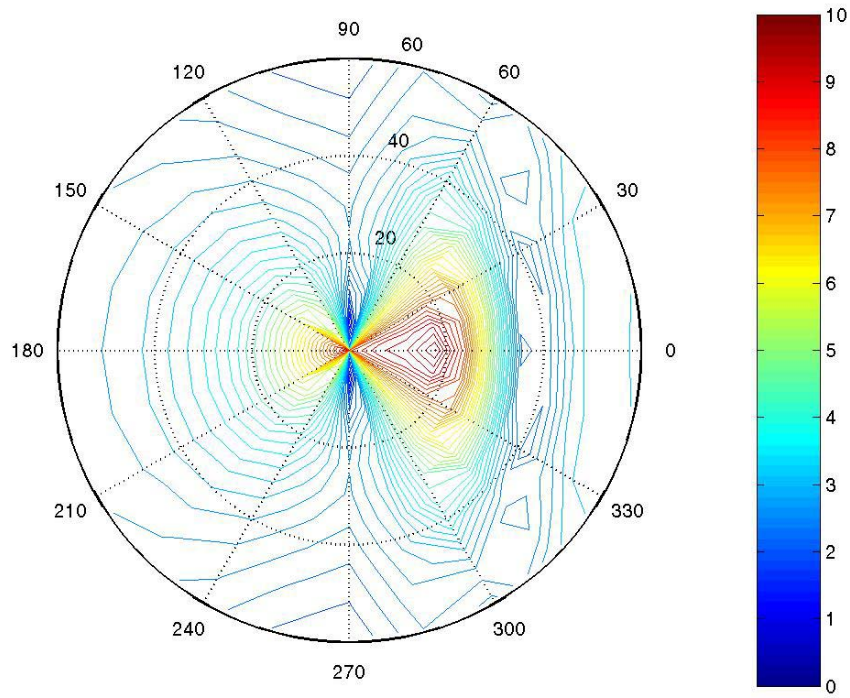

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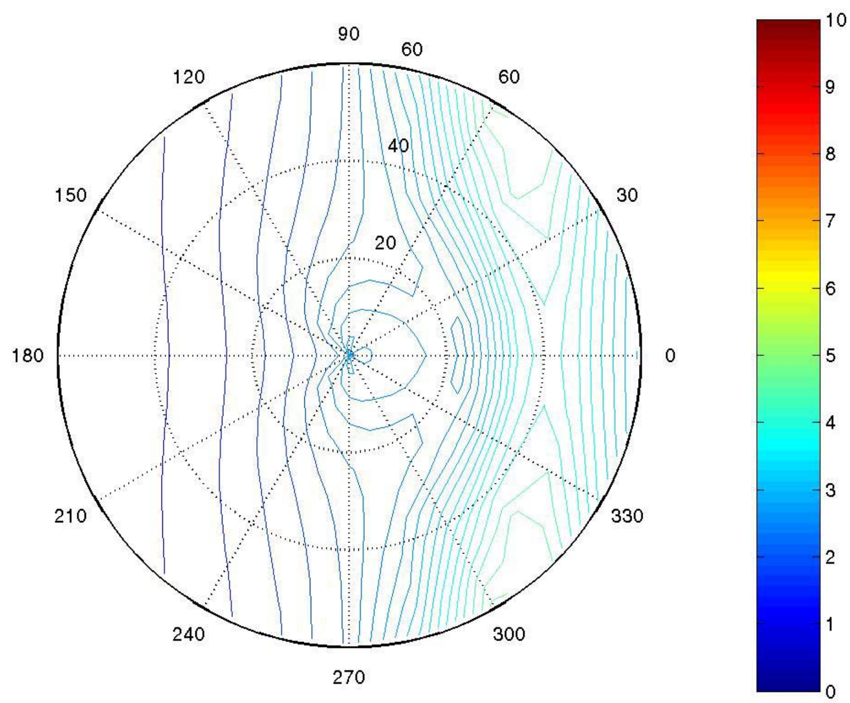

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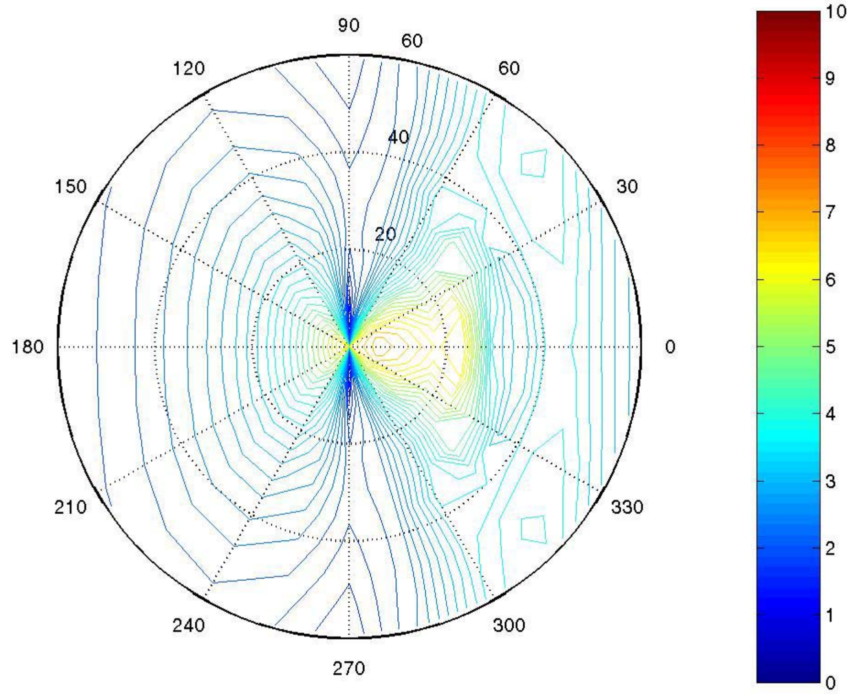

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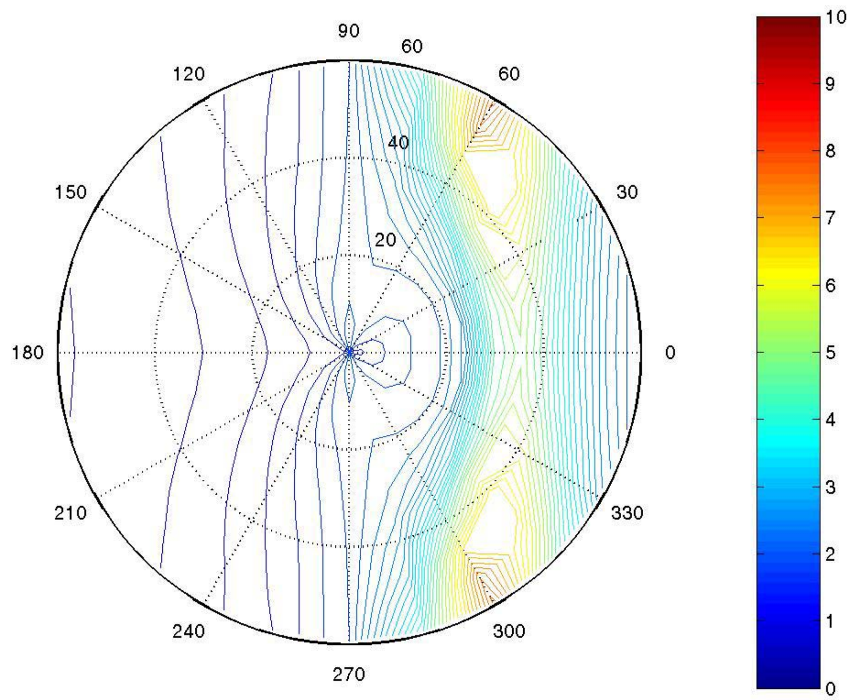

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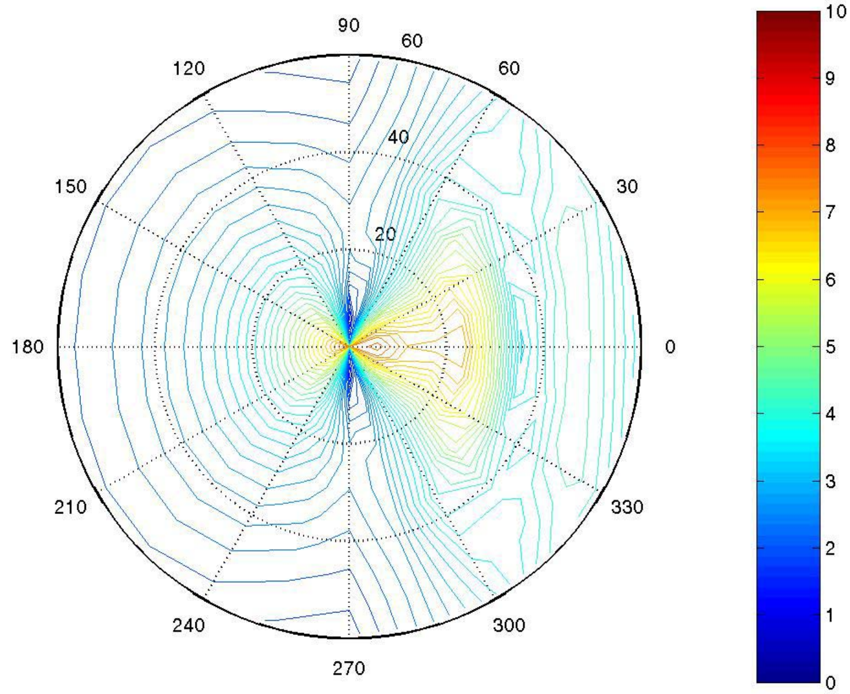

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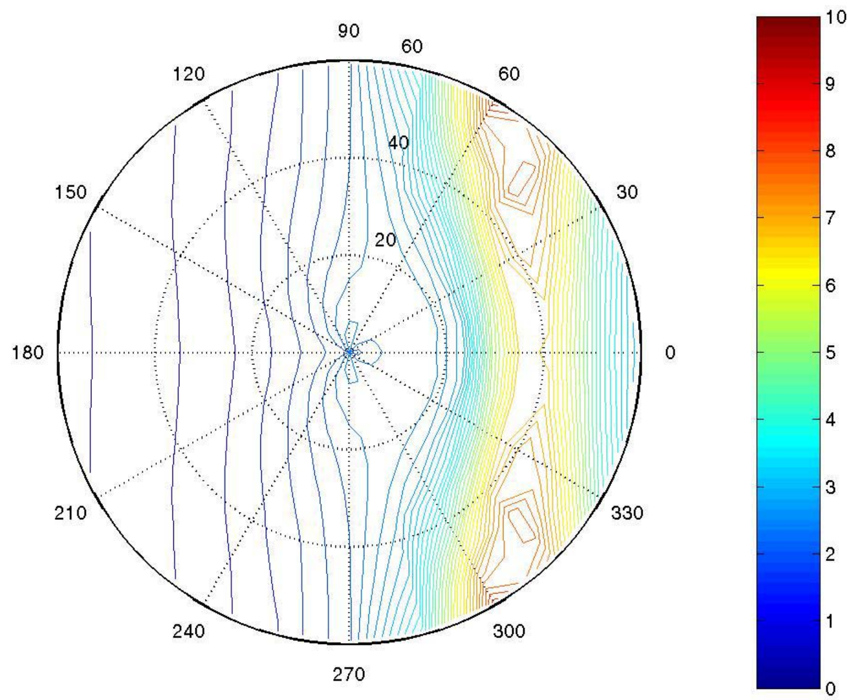

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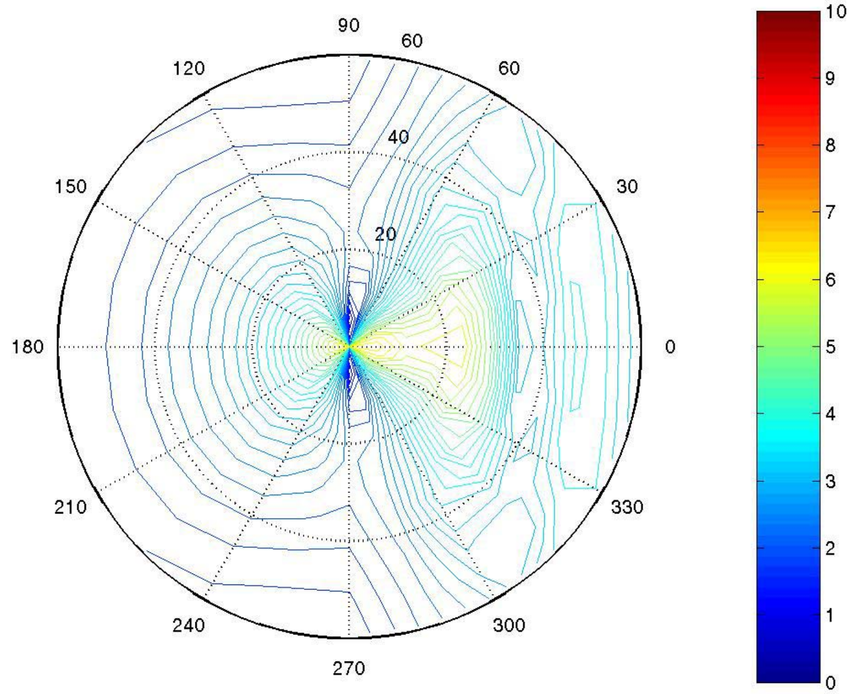

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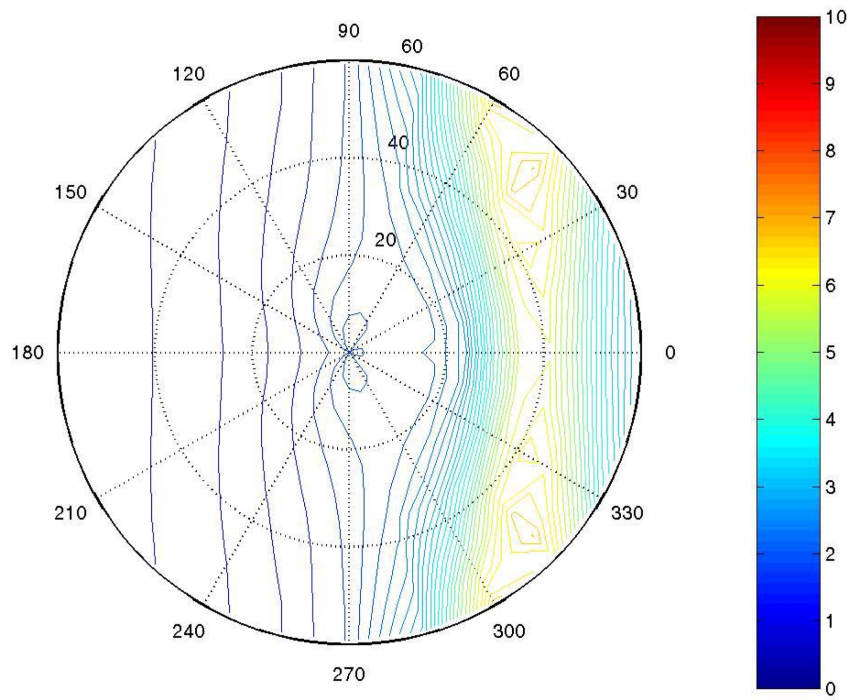

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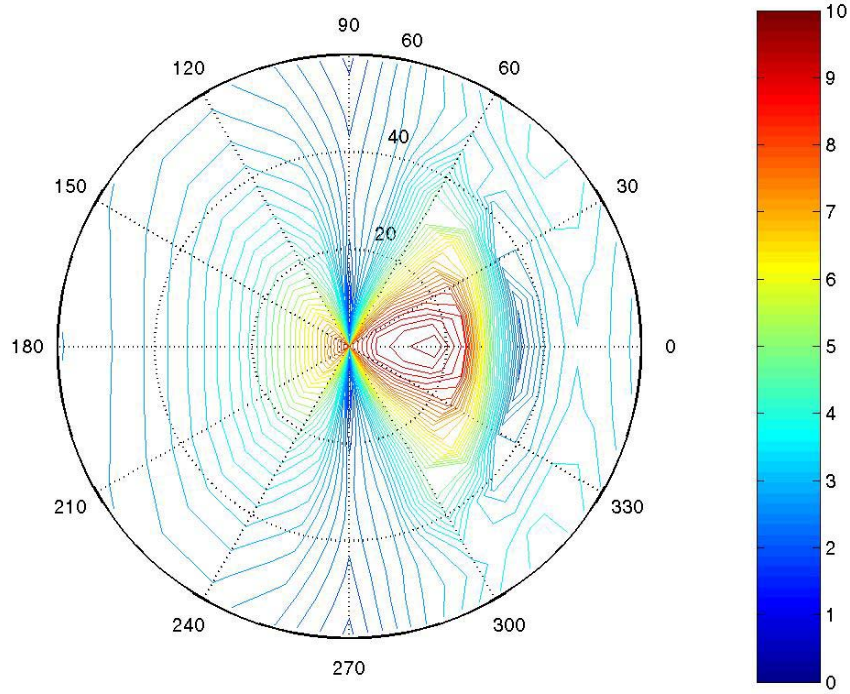

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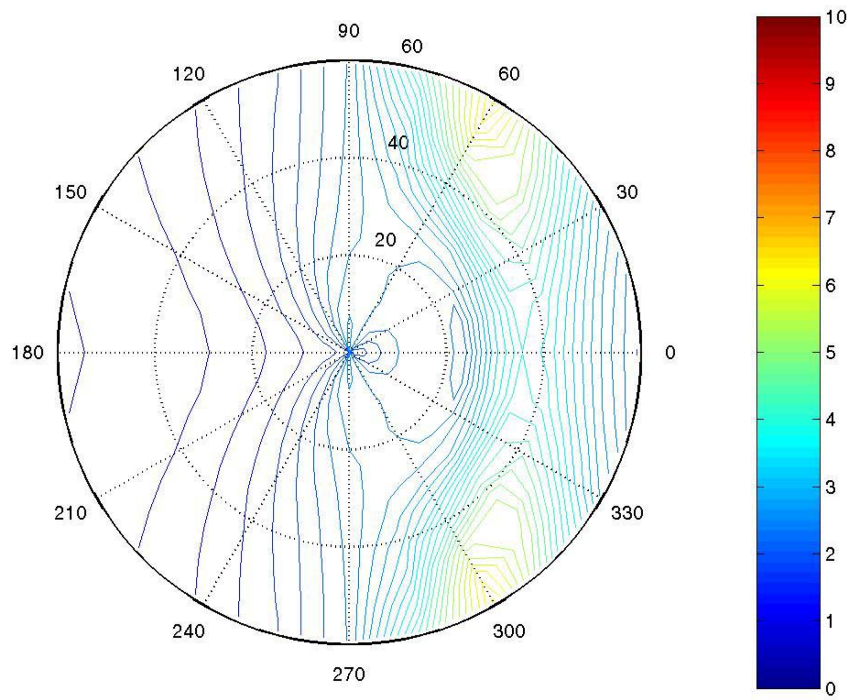

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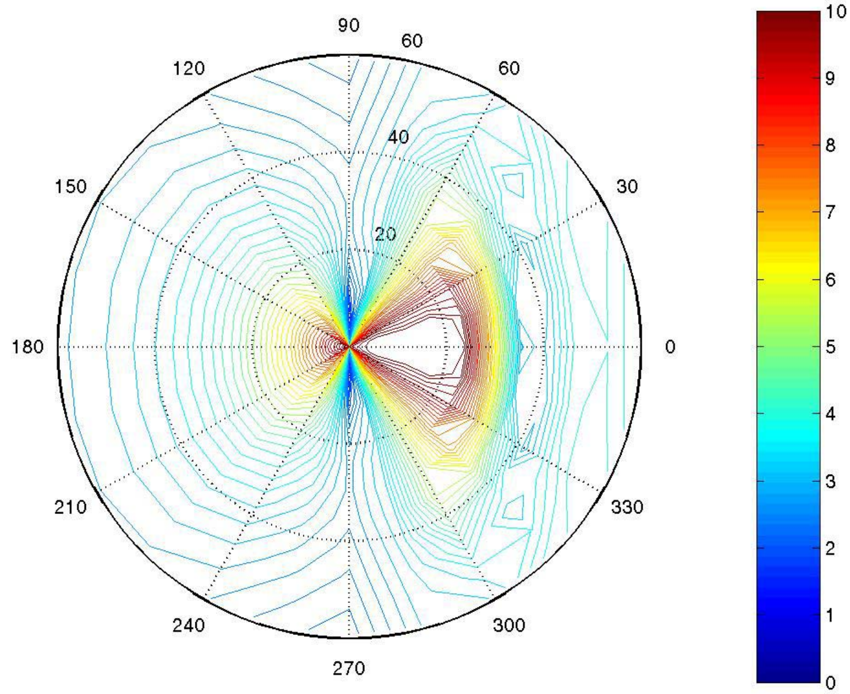

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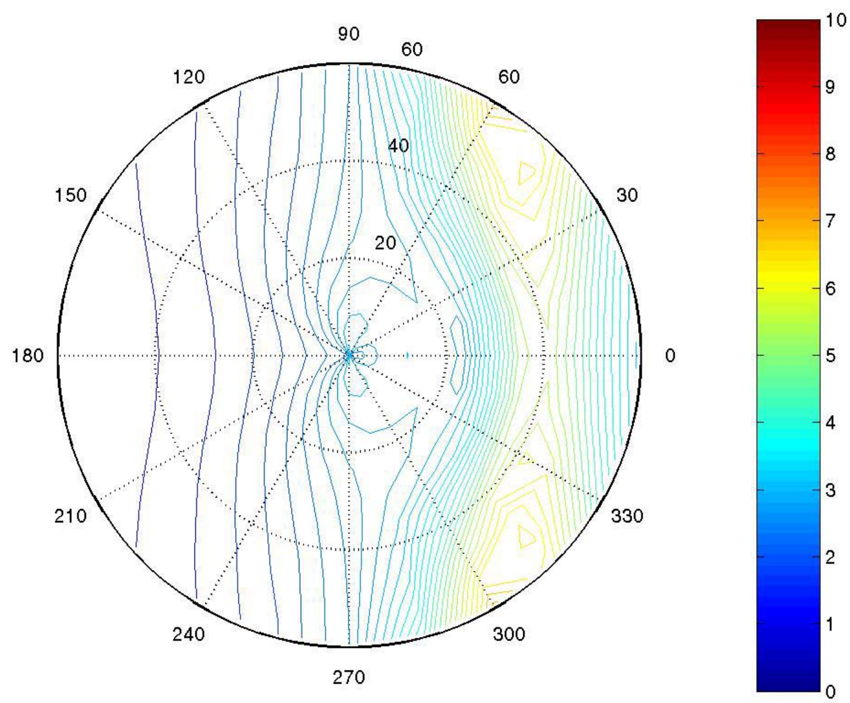

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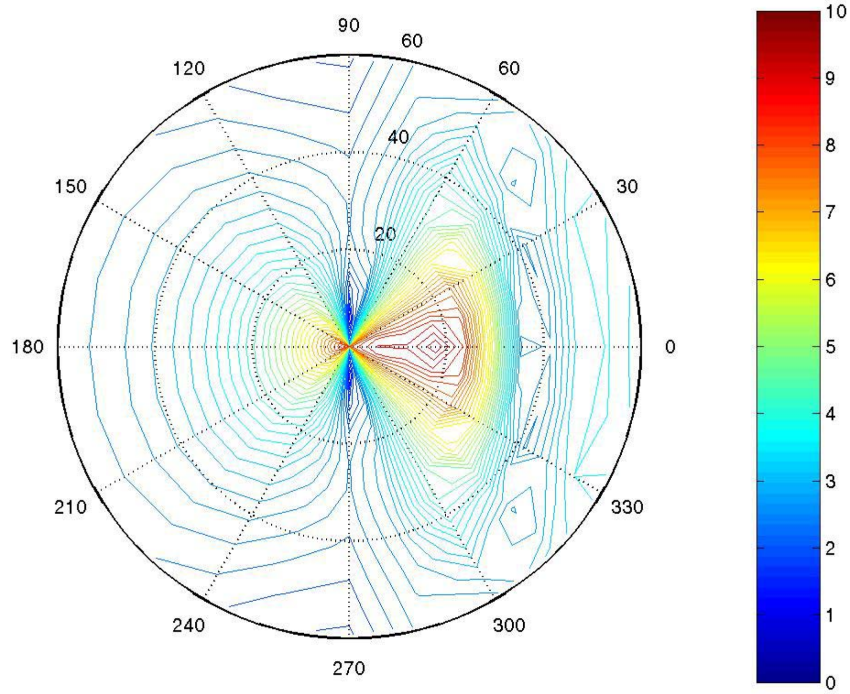

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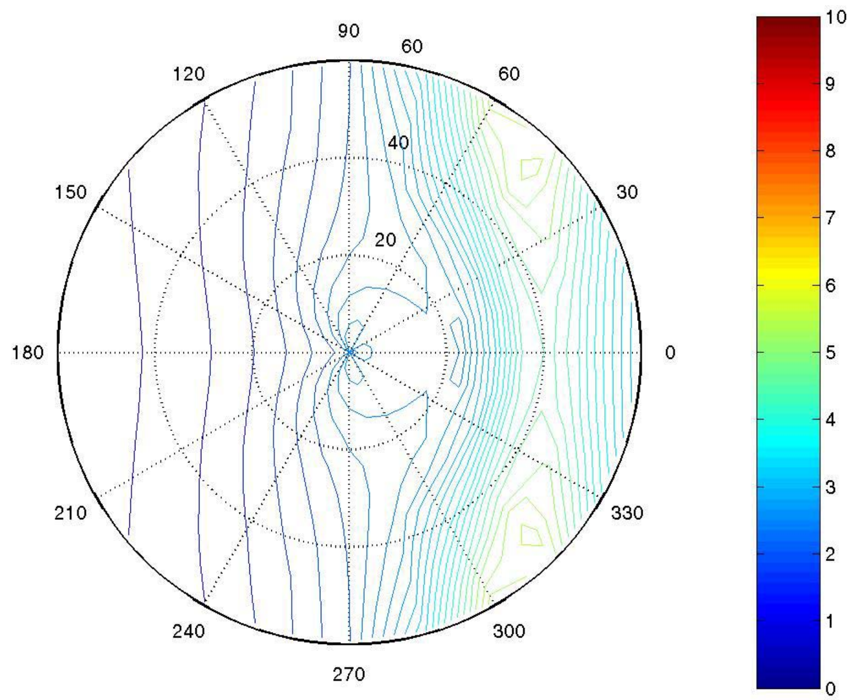

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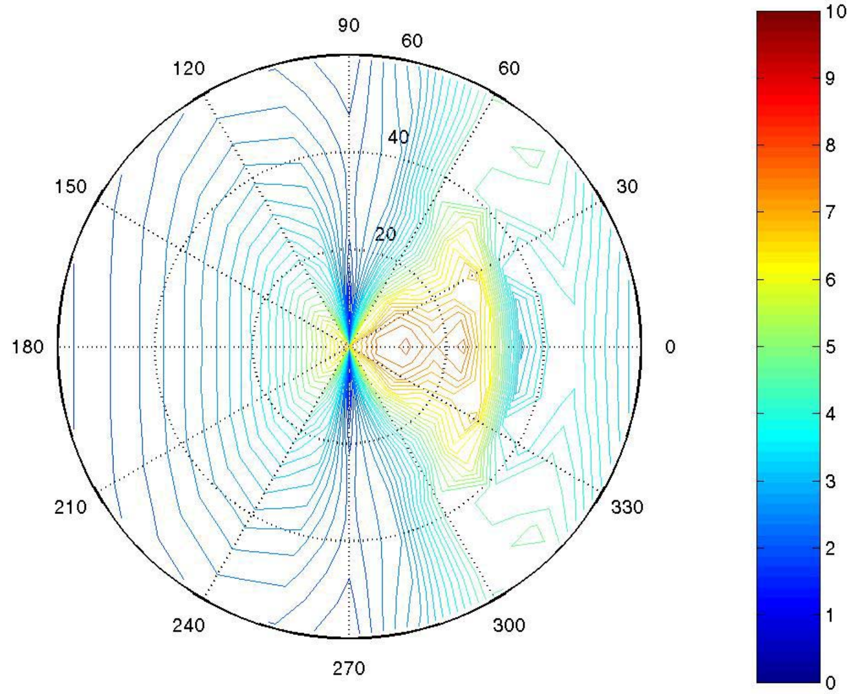

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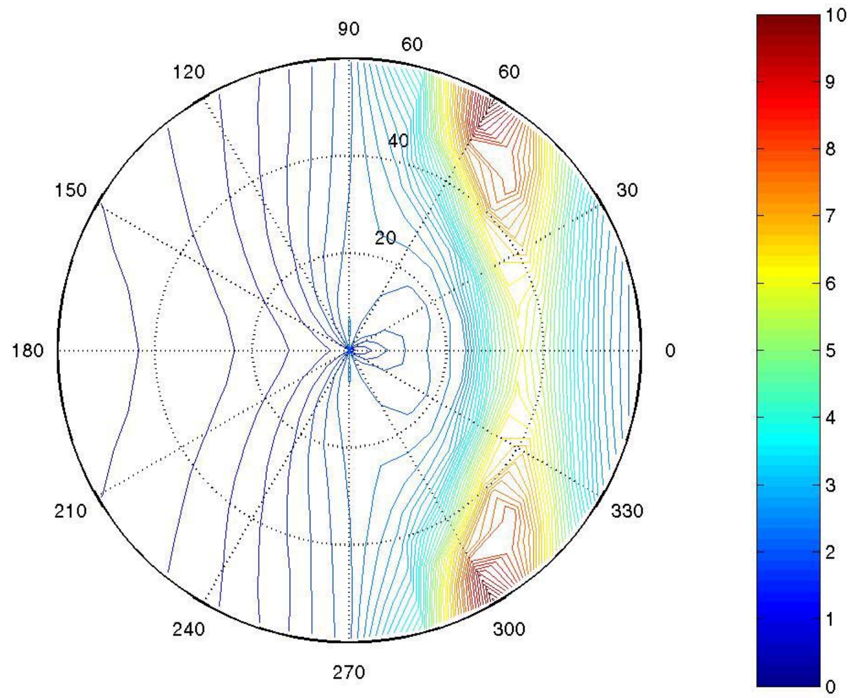

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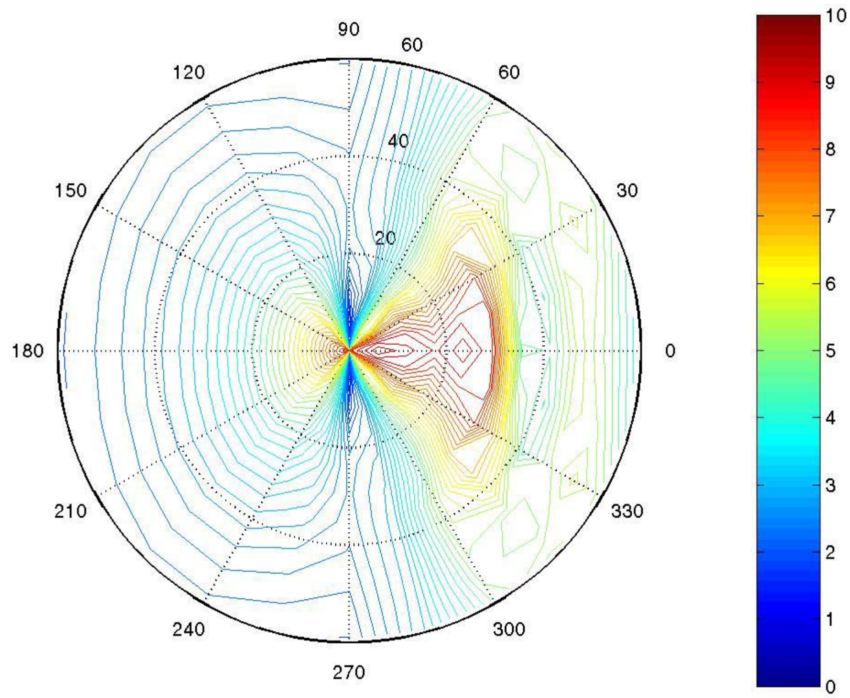

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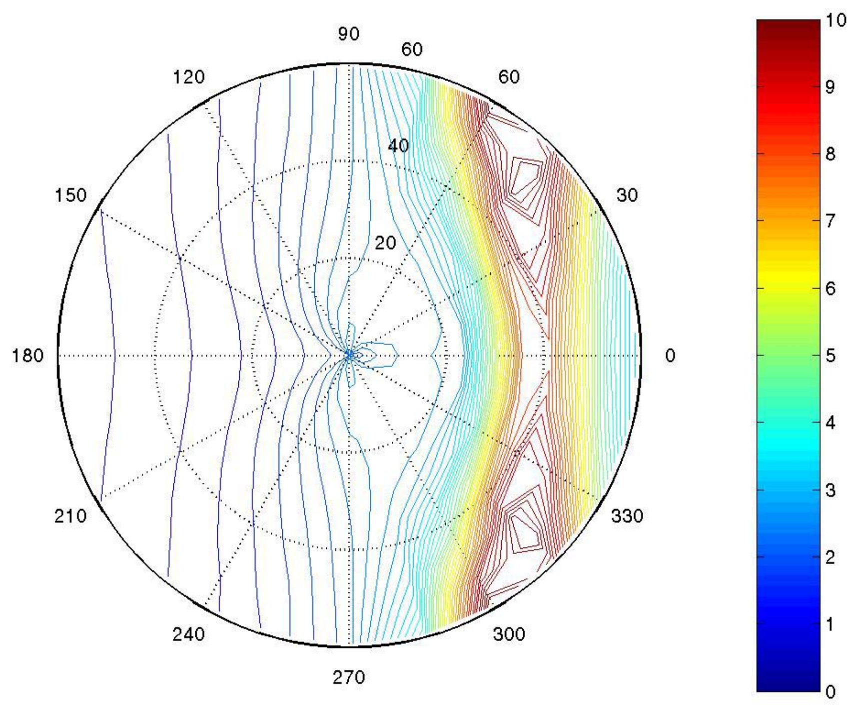

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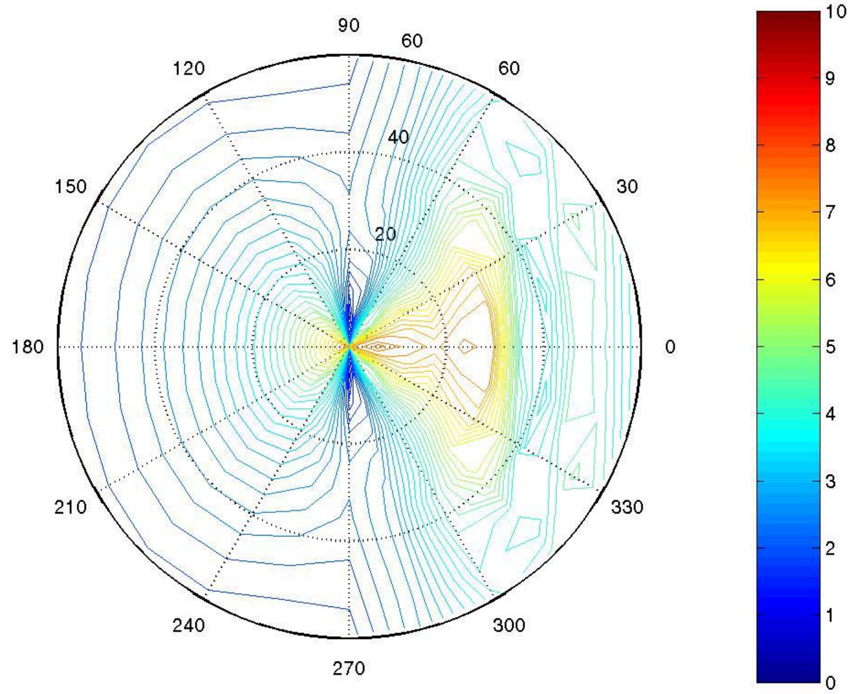

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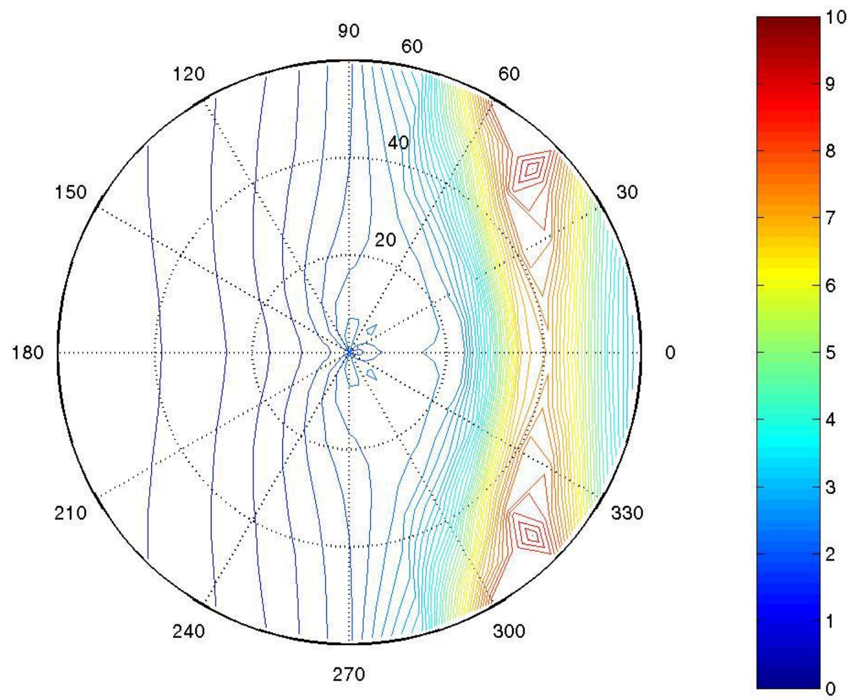

Model 4812 (B: 16.2 sec) Heave Response

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