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TESTING STABILITY WITHOUT PENDULUMS: A FEASIBILITY ANALYSIS

Frain, Patrick B. Jr.

Monterey, CA; Naval Postgraduate School

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NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

**TESTING STABILITY WITHOUT PENDULUMS:
A FEASIBILITY ANALYSIS**

by

Patrick B. Frain Jr.

June 2018

Thesis Advisor:	Fotis A. Papoulias
Second Reader:	Matthew G. Boensel

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Current International Maritime Organization (IMO) and U.S. Coast Guard regulations require inclining tests of vessels to use three heel-measuring devices, one of which must be a pendulum. This is a problem since pendulums are required to be at least 10 feet in height and newer vessel designs are constrained by overhead clearance and deck space. To investigate this problem, this thesis examines five different stability test results that were submitted to the U.S. Coast Guard Marine Safety Center (MSC). The author identified and inputted random error into the independent variables used to calculate each vessel’s metacentric height (GM). The independent variables were then used in a Design of Experiment (DOE) to examine which factors had the strongest effect on GM. Of the factors analyzed, the device used to measure heel angle proved to be the most significant. The author then constructed three different miniature models to conduct inclining experiments in a controlled environment. The heel-measuring devices used during these experiments were a smartphone and pendulum. In all three miniature model experiments, the smartphone demonstrated better precision over the pendulum. This thesis recommends keeping current standards and regulations intact until further data and research are gathered.

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TESTING STABILITY WITHOUT PENDULUMS: A FEASIBILITY ANALYSIS

Patrick B. Frain Jr.
Lieutenant, United States Coast Guard
BS, U.S. Merchant Marine Academy, 2008

Submitted in partial fulfillment of the
requirements for the degree of

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from the

NAVAL POSTGRADUATE SCHOOL
June 2018

Approved by: Fotis A. Papoulias
Advisor

Matthew G. Boensel
Second Reader

Ronald E. Giachetti
Chair, Department of Systems Engineering

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ABSTRACT

Current International Maritime Organization (IMO) and U.S. Coast Guard regulations require inclining tests of vessels to use three heel-measuring devices, one of which must be a pendulum. This is a problem since pendulums are required to be at least 10 feet in height and newer vessel designs are constrained by overhead clearance and deck space. To investigate this problem, this thesis examines five different stability test results that were submitted to the U.S. Coast Guard Marine Safety Center (MSC). The author identified and inputted random error into the independent variables used to calculate each vessel's metacentric height (GM). The independent variables were then used in a Design of Experiment (DOE) to examine which factors had the strongest effect on GM. Of the factors analyzed, the device used to measure heel angle proved to be the most significant. The author then constructed three different miniature models to conduct inclining experiments in a controlled environment. The heel-measuring devices used during these experiments were a smartphone and pendulum. In all three miniature model experiments, the smartphone demonstrated better precision over the pendulum. This thesis recommends keeping current standards and regulations intact until further data and research are gathered.

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LIST OF ACRONYMS AND ABBREVIATIONS

ASTM	American Society of Testing and Materials
BRSA	British Ship Research Association
CFR	Code of Federal Regulations
D	test weight shift distance
DOE	design of experiment
G	center of gravity
GM	metacentric height
IE	inclining experiment
IMO	International Maritime Organization
INCOSE	International Council of Systems Engineering
ISO	International Organization for Standards
ITTC	International Towing Tank Conference
KB	center of buoyancy
KG	vertical center of gravity
KM	height of metacenter
M	metacenter
SE	Systems Engineering
SPV	small passenger vessel
UN	United Nations
USCG	United States Coast Guard
W	test weight
WL	waterline

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EXECUTIVE SUMMARY

The United States Coast Guard (USCG) is the primary regulatory authority for U.S. flagged commercial vessels. The USCG dictates and oversees regulations pertaining to commercial vessel operations that include but is not limited to stability, machinery, electrical, lifesaving, and fire protection systems. The regulations that govern these systems are defined in the Code of Federal Regulations (CFR). The focus of this study is the stability requirements found in 46 CFR Subchapter S. Currently, vessels that are newly constructed or have undergone major modifications are required to verify intact stability with a test known as the incline experiment (IE). This experiment verifies the location of the vertical center of gravity (KG) which is the basis for determining positive, neutral, or negative stability. Current regulations stipulate that three measuring devices be used to measure the incline of the vessel during the experiment. Devices authorized are: pendulums, manometers, digital inclinometers, and laser pendulums. However, of the three devices required, one must be a pendulum. Since newer vessel designs make it difficult to mount pendulums, required to be at least 10 feet in height, owners are requesting to conduct stability tests without pendulums. A feasibility analysis was conducted to determine whether performing stability tests without pendulums provides an equivalent level of safety to other authorized alternate measuring devices.

Two separate experiments were set-up to analyze and draw conclusions regarding the feasibility of not using pendulums during an IE. The first experiment analyzed raw data collected from five separate stability tests that were verified and approved by the USCG. The author developed an Excel-based model to detect factors that had the greatest impact on the calculation of GM. Of the four factors analyzed, the analysis revealed that the type of device used was the most significant. However, no conclusive evidence proved that one measuring device was superior to another. To improve the results of the model, additional factors influencing the outcome of GM need to be collected. It is recommended that witnessing live stability tests be carried out to gather additional data not found in submittals to the USCG. Such data would include prevailing weather conditions during each weight

shift, identifying additional sources of error during set-up, and measuring the exact locations of each measuring device relative to the centerline of the vessel.

The second experiment performed was an analysis of three separate stability tests conducted on three miniature vessel models. An IE was performed on each model to observe how different factors affect the resultant GM in a controlled environment. Furthermore, each hull had a different design as an additional factor for analysis. The heel measuring devices used for each experiment were a pendulum and smartphone. The experiment found that smartphones consistently provided better precision in the calculation of GM. However, determining which device provided better accuracy could not be found since the theoretical GM of each model was unknown. Furthermore, the heel angles produced by each hull design were notably different according to the corresponding moment-tangent plots. It is unclear whether this was a result of external factors such as water fluctuations during the experiment or due to the hull design. It is recommended to replicate the experiments with longer periods of time between weight shifts to minimize error due to water disturbances. In addition, adjusting factors on a single model, such as height of the pendulum, could be carried out to examine its overall effect on GM.

Prior to setting up the experiments, finding relevant research that pertained to IEs was needed. Two different articles were found that investigated primary factors that contributed to IE systematic error and the use of smartphone technology to measure heel angles in lieu of pendulums. The first article, titled “Uncertainty Analysis Procedure for the Ship Inclining Experiment” (Woodward et al. 2016), found that systematic errors for IEs were similar to those identified for hydrodynamic testing on ship models. Research into errors found in ship model testing procedures prescribed by the International Towing Tank Conference (ITTC) was carried out. The ITTC is the organization that has the “responsibility for the prediction of the hydrodynamic performance of ships and marine installations based on the results of physical and numerical experiments” (International Towing Tank Conference 2018). The article described how the errors found in the ITTC standards could be applied to actual IE data. After applying errors found in the ITTC standards, the authors conducted a sensitivity analysis via partial derivatives to calculate which factors had the greatest impact on KG. The article examined nine separate factors affecting KG for five different vessel types. In the end, the article concluded that "no one parameter can be identified in all cases as problematic from the studies." (Woodward et al. 2016, 86). Next, the second article researched was "The Application of Smartphone in Ship Stability Experiment" (Djebli et al. 2015). The article examined existing procedures that govern the conduct of IEs, identified as the classical method that require pendulums. It investigated whether a new device could be adopted by the International Maritime Organization (IMO) during an IE. The IMO is the organization under the United Nations (UN) that prescribes international shipping standards for all countries signatory to its conventions. The authors of the article conducted an experiment using a miniature ship model to conduct an IE using only a pendulum and smartphone to measure heel angles. The article concluded that "the accuracy of the obtained measurements using this new method is similar to the classical method based on pendulum measurements and is even better regarding simplicity, bulk, accuracy, readout, and robustness" (Djebli et al. 2015, 6). The article concluded that the IMO consider smartphone devices as an authorized alternative device.

Based on the relevant research, a process was needed for finding feasible solutions to the problem statement. The author developed a general methodology that followed sound systems engineering practices to accomplish this. The process included defining the overall objectives, developing a process or architecture to follow, and finally collecting and entering data into the architecture to derive results. For the first experiment, the author contacted the Marine Safety Center (MSC), a division within the USCG, which is tasked with reviewing and approving all plan review documents pertaining to stability calculations. By law, the owners of newly constructed vessels are required to submit IE results to this office for review prior to beginning commercial operations. The MSC sent the author five IE submissions from small passenger vessels (SPV) that used a variety of heel measuring devices during their respective experiments. The submissions were studied and modeled to replicate the results. Factors focused on were: GM, test weights and their shift distances to create different moments, lightweight displacement, and recorded heel angles. To predict which factor had the greatest influence on stability, a designed experiment was developed to measure the change in GM as the remaining four factors were adjusted to three different error levels. The factors included in the design of experiment (DOE) were test weights used, test weight shift distances, heel angle accuracy, and the type of device used. Lightweight displacement was not included for the analysis due to the wide subjectivity of estimating weights to add or remove during the lightweight survey. This DOE was applied to five different IE submissions that each had six weight shifts to calculate GM. The DOE was set-up with four factors, three error levels that followed a normal distribution, and was replicated ten times for each weight shift and produced over 24,000 data points for analysis. The error levels that were applied to the DOE were based on current standards governing IEs and reasonable estimation by the author. The DOE analysis concluded that the type of device used had the greatest level of significance for all five vessels. To explore why the type of device used provided the highest level of significance, the raw, non-parametric, data from the IE submissions was analyzed without applied error. This identified any outliers or skewness within the data and provided insight if any device disproportionately shifted the GM which would account for the strong level of significance in each DOE. Three out of the five vessels each had one device that had a wide range of GM calculations, but the median values were mostly consistent across all three vessels. There was no clear indication that one device was superior to the other.

For the second experiment, three separate IEs were conducted on three miniature hull models constructed by the author. The purpose of the experiment was to provide insight to the systematic errors during IEs in a controlled environment. The three different hull types used were V-hull, pontoon, and barge designs and were all constructed of Styrofoam boards. The models were outfitted with a pendulum, test weights, and a smartphone as the alternate measuring device. The same procedure found in the CFR and IMO standards was used during the experiment. The V-hull model produced the best results during the experiment due to the higher degree of precision between measuring devices. As the experiment was carried out using the remaining two hull models, the precision became progressively worst. It was unclear whether this was a product of the hull design or other external factors that were acting on the models. Although all attempts were made to minimize water fluctuations during the experiment, further experimentation is needed to produce better results. In all three models, a two-sample t-test between measuring devices was used to detect statistical differences. In all three experiments, the level of significance was 90% indicating strong differences between devices.

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Djebli, Abdelkader, Benameur Hamoudi, Omar Imine, and Lahouari Adjout. 2015. “The Application of Smartphone in Ship Stability Experiment.” *Journal of Marine Science and Application* 14, no. 4 (December): 406-12. DOI: 10.1007/s11804-015-1331-9.

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I. INTRODUCTION

The introduction chapter provides an overview of the purpose and general guidelines for conducting an inclining experiment (IE). The author examines current regulations that govern the conduct of IEs and challenges if such regulations can be updated to incorporate newer technologies. This led to the identity of the problem statement: Do alternative devices that measure heel angles during the IE offer an equivalent level of safety to pendulums? Next, a systems engineering (SE) process was developed for finding solutions to the problem statement. Finally, this section provides an overview of the thesis organization.

A. BACKGROUND

Conducting an IE is the primary method for verifying intact stability for new and modified vessels. The test is used in the commercial and military sectors to ensure vessel designs meet the specifications for positive stability by locating the vertical center of gravity (KG). The American Society for Testing and Materials (ASTM) defines the inclining experiment as “moving a series of known weights, normally in the transverse direction, and then measuring the resulting change in the equilibrium heel angle of the vessel. By using this information and applying basic naval architecture principles, the vessel’s KG is determined” (American Society for Testing and Materials [ASTM] 2014, 777). By performing an IE, the stability of the vessel in different loading conditions, sea-states, or following major repairs can be predicted accurately.

The general theory of how an IE measures KG is based on geometry and some basic naval architecture principles. The factors influencing the calculation of KG are the center of buoyancy above the keel (KB) and the height of the metacenter above the keel (KM). First, the KB of a vessel is the centroid of where all underwater buoyant forces are focused above the keel. The KB is determined by the shape of the underwater hull. As vessels pitch and roll, the portion of the underwater hull that is submerged changes resulting in the KB shifting. When the KB shifts at small angles, namely zero to four degrees, the lines of action drawn through the different points of KB that intersect at a single point above the keel is known as the metacenter (M), as seen in Figure 1.

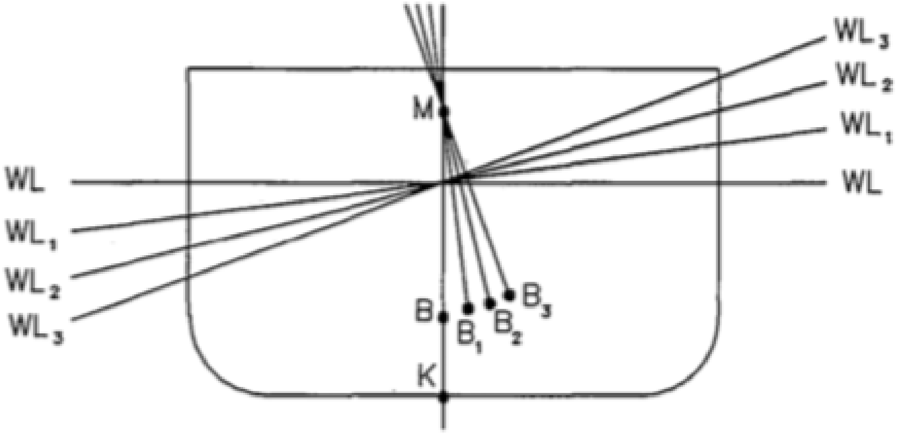

Figure 1. Illustration of the Metacenter as the Center of Buoyancy Shifts.
Source: ASTM (2014).

Examining Figure 1, as the center of buoyancy (B) changes, the metacenter (M) remains stationary above the keel and the distance between the two points is known as height of the metacenter or KM. This value is calculated during an IE or taken from the vessel hydrostatic table, which is derived in the detailed design phase by the naval architect. The metacenter is used as the reference point for determining the vessel stability condition prior to adding personnel, fuel, and cargo during its operational life-cycle. The initial stability condition is based on the relative distances between the metacenter and center of gravity, which are fixed points during an IE. The distance between these points is known as the metacentric height (GM). The general equation for calculating GM is

$$GM = KM - KG.$$

Observing the above equation, when GM is positive, the center of gravity is located below the metacenter and the vessel is said to have positive stability. However, if the GM is non-positive, the center of gravity is at or above the metacenter and the vessel is in a neutral or unstable condition, respectively. Figure 2 illustrates the relationship among GM, KM, and KG.

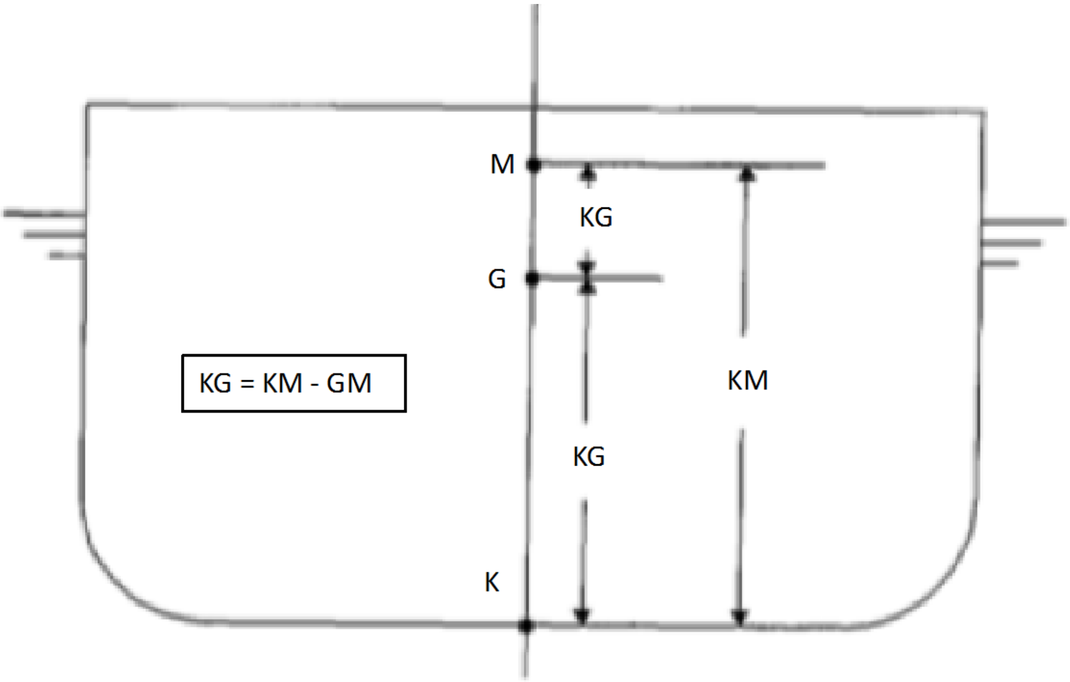

Figure 2. Illustration of the Relationship of GM, KM, and KG. Adapted from ASTM (2014).

To evaluate where the center of gravity (G) is focused in relation to the keel, the vessel is prepared in the *lightship condition* and surveyed prior to beginning the IE. The lightship condition means that the "vessel is complete in all respects, but without consumables, stores, cargo, crew and effects, and without any liquids on board except that machinery fluids, such as lubricants and hydraulics, are at operating levels" (ASTM 2014, 777). The surveys performed during the IE include taking draft readings, measuring the salinity of the water in which the vessel is floating, freeboard readings on each side of the vessel to measure the lightship displacement, and a complete inspection of the vessel to determine items that should be added or removed to meet the definition of lightship.

When surveys are completed, external weights are added to the vessel to induce a port or starboard heel. The amount and size of test weights is dependent on the lightship displacement and the amount of heel required to reach a maximum of four degrees. The four-degree limit is to ensure the metacenter remains in a fixed position for the duration of the IE. According to international and domestic regulations, the test weights are required to be certified or validated to limit the error of the calculated moments. In some circumstances, if the use of test weights is prohibitive due to lack of open deck space, the moments can be created by filling ballast tanks and exchanging water between the port and starboard side. However, this method is not preferred since ullage readings are required to measure the amount of water shifted for each heel angle recorded. Taking manual ullage readings will generally not be as accurate as certified weights when performing the test. Figure 3 is an illustration of shifting an external test weight in the transverse direction resulting in a heel angle.

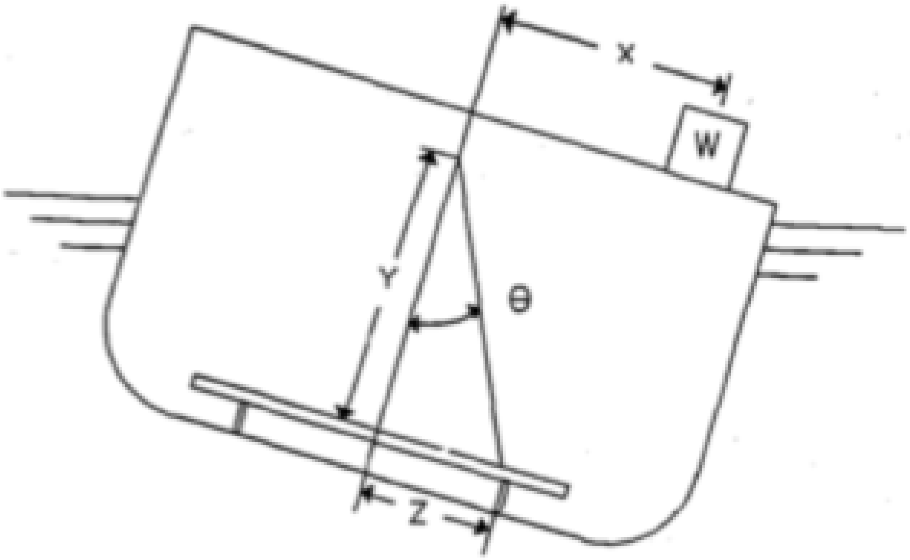

Figure 3. Illustration of Shifting a Test Weight in the Transverse Direction with a Resulting Heel Angle. Source: ASTM (2014).

As test weights are being shifted creating different moments, the resulting heel angle is being recorded by a minimum of three different measuring devices. Currently, devices that are authorized per domestic regulations are: pendulums, digital inclinometers, manometers, and laser pendulums.

Since the test weight, test weight shift distance, lightship displacement, and resulting heel angle are all known, the GM can be calculated for each test weight shift using the following equation.

$$GM = \frac{test\ weight\ (w) * test\ weight\ shift\ distance(d)}{displacement\ (\Delta) * \tan(heel\ angle\ (\theta))}$$

By observing the above equation, “since GM and Δ remain constant values for the duration of the IE the ratio between *(w)(d) / tan θ* will be constant” (ASTM 2014, 778) This equation will be the basis for all modeling results that will be produced in the proceeding chapters. To confirm the accuracy of the test, the moments are plotted against the tangents of the heel angles which should result in a straight line as seen in Figure 4. The grouping of vertical dots represents each weight shift with each individual dot representing each heel angle measuring device.

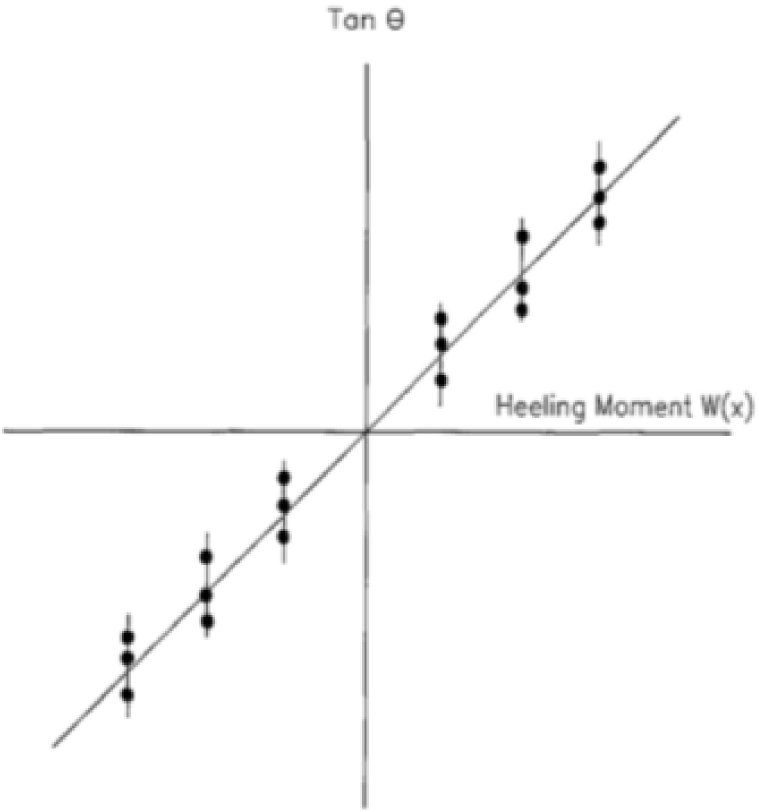

Figure 4. A Depiction of a Typical Moment-Tangent following an IE.
Source: ASTM (2014).

If the moment-tangent plot does not result in a straight line for all weight shifts, this could indicate that unwanted moments occurred or error was introduced during the experiment. If this does occur, an investigation should be conducted to find the root cause of why the moments and tangents do not plot as a straight line. Depending on the findings, measurements or the entire experiment may need to be redone.

B. PROBLEM DEFINITION

Current regulations prescribed by the IMO and USCG require three separate heel measuring devices during the IE, of which, one must be a pendulum. Recently, owners of commercial small passenger vessels (SPV) have been inquiring on the feasibility of conducting IEs without pendulums. SPVs are generally no more than 65 feet in length and carry passengers for hire. Much of the space along the centerline of these vessels is covered by permanent structures with fixed seating. As newer SPV designs are developed, less space is being allocated for mounting pendulums, which typically span 10–12 feet, during the IE. Weather conditions are another factor that may have a large effect on pendulum use. With the exception of perfect calm conditions, tiny movements of the vessel “make a typical three-meter (9.8′) pendulum swing 0.80 to 2.40 inches in a haphazard pattern” (Dalrymple-Smith 2016, 32). A 2.40-inch oscillation would result in a 1.15-degree error, which is significant. This is approximately equivalent to adding a 150-pound weight 10 feet off the centerline to a vessel with a displacement of 10,000 pounds with a GM of 7.5 feet. To combat oscillations, a large tub may be placed at the bottom of the pendulum, as seen in Figure 5. The tub would be filled with a heavy viscous liquid, such as motor oil, to stabilize oscillations and would need to be properly disposed of after the test.

Figure 5. An Illustration of a Tub that would Hold Viscous Liquid to Dampen Pendulum Oscillations. Source: Dalrymple-Smith (2016).

Finally, constructing and mounting pendulums is a time-consuming task compared with using the other authorized measuring devices. This would incur additional time needed for construction and set-up.

As technology matures and new innovations are developed, alternate devices may offer the same level of precision and accuracy as pendulums which have been the primary IE device for hundreds of years. Currently, there is limited research being conducted to analyze if alternate measuring devices offer an equivalent level of safety to pendulums. Developing a model that could analyze the factors having the greatest effect on GM would be useful to study this problem. By studying which factors have the greatest effect, it can be evaluated whether heel measuring devices have a significant impact on GM results. This in turn could lead to recommendations to promulgate new policy to allow vessel owners the option of using pendulums during an IE.

C. SYSTEMS ENGINEERING PROCESS

To evaluate the problem definition, the systems engineering (SE) process was used to study the feasibility of not using pendulums during an IE. The SE process is “a predefined set of activities selectively used to accomplish Systems Engineering tasks" (International Council on Systems Engineering [INCOSE] 2004, 12). The SE task for this thesis was to decompose the problem definition and study its different constituent parts. By studying the individual parts that make up the IE, the different functions and their connectivity to the IE as a whole could be examined to understand the problem and how to model it. To model the problem, a process that was objective, repeatable, and traceable needed to be developed. This would include defining the objectives, developing architectures, designing a model, and verifying those elements to form viable solutions to the problem. The process followed was adopted from the International Council on Systems Engineering (INCOSE) handbook that is illustrated in Figure 6.

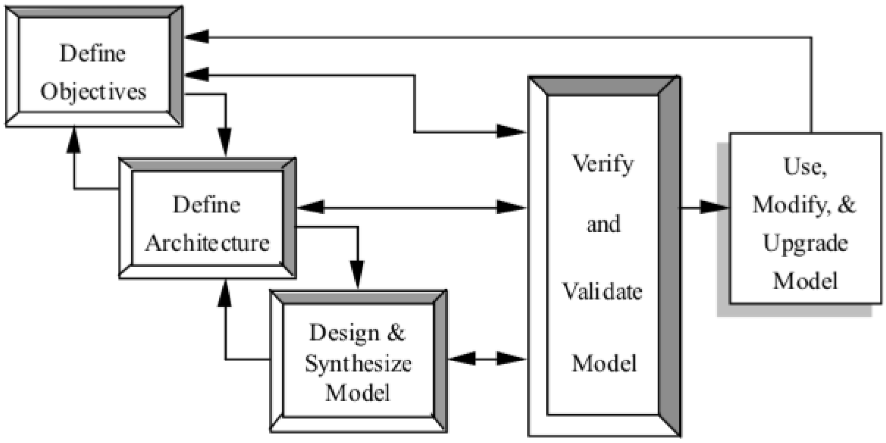

Figure 6: Iterative Model Engineering Approach. Source: INCOSE (2014).

This approach will be used as the basis for two different models used to form solutions for the defined problem. The objective for each model was to determine the feasibility of not using pendulums during an IE while still achieving the same level of accuracy and precision. Furthermore, after formulating the objective, a system *architecture* was defined. A system architecture is "a fundamental and unifying structure defined in terms of elements, information, interfaces, processes, constraints, and behaviors" (Maier and Rechtin 2002, 287). By organizing the different IE components into a process, the constraints and connectivity of the different variables that affect metacentric height (GM) could be evaluated. The components specifically examined were the size of the test weights and their shift distances that formed various moments, heel angles generated as a result of the moments, and the type of instrument used to measure the heel angle. Two different architectures were generated using a Microsoft Excel-based data analysis tool developed by the author and evaluated miniature vessel models. The architectures developed would serve as the means for meeting the stated objective. Next, the design and synthesis portion of the process was gathering and producing data from the architectures developed. Finally, the different models were verified against the original objectives, architecture, and design to ensure it met the needs of producing feasible solutions to the problem definition. This process will be the basis for determining the feasibility of not using pendulums during an IE.

D. THESIS ORGANIZATION

The remaining chapters of this thesis are organized as follows: Chapter II introduces similar research and current regulations pertaining to the IE. Chapter III covers the raw data collected for the DOE analysis and performs an initial overview of the data. Chapter IV details the different sources of random error that were inputted to the DOE analysis. Chapter V details the analysis for the Microsoft Excel-based DOE model. Chapter VI provides the set-up, procedure, and analysis of the IEs performed on three different miniature models constructed by the author. Finally, Chapter VII provides the conclusions, recommendations, and future work for this study.

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II. LITERATURE REVIEW AND CURRENT REGULATIONS

This chapter gives a relevant literature review for on-going research for methods of reducing systematic error in the IE as well as new technologies being considered as alternate measuring devices. In addition, an overview of domestic and international regulations pertaining to the IE for commercial vessels will be covered.

A. LITERATURE REVIEW

Limited research exists for investigating IE systematic error or comparing authorized alternate measuring devices. This section reviews published articles that analyze error and uncertainty for calculating KG during the IE and examines the feasibility of using smartphones as an authorized device.

In the article “Uncertainty Analysis Procedure for the Ship Inclining Experiment,” the authors developed a procedure to identify “experimental uncertainty in the estimate of KG obtained by the IE” (Woodward et al. 2016, 86). The authors noted that uncertainty applied to ship model hydrodynamic testing, which is governed by procedures found in International Towing Tank Conference (ITTC) standards, could also be applied to the IE. By applying the methodology in the ITTC standards, the paper examined uncertainty for all independent variables and conducted a sensitivity analysis via partial derivatives. The paper concluded that none of the variables could be identified as “problematic” but provided guidelines for estimating the confidence interval for KG and recommendations on removing uncertainty. Figure 6 provides a graphic of the papers findings for each independent variable that contributed to KG.

Examining Figure 6, the factors that had the most frequent component uncertainty were heel angle and draught. A similar analysis will be performed by examining the metacentric height in lieu of the center of gravity as the response variable for the DOE analysis and miniature model experiment.

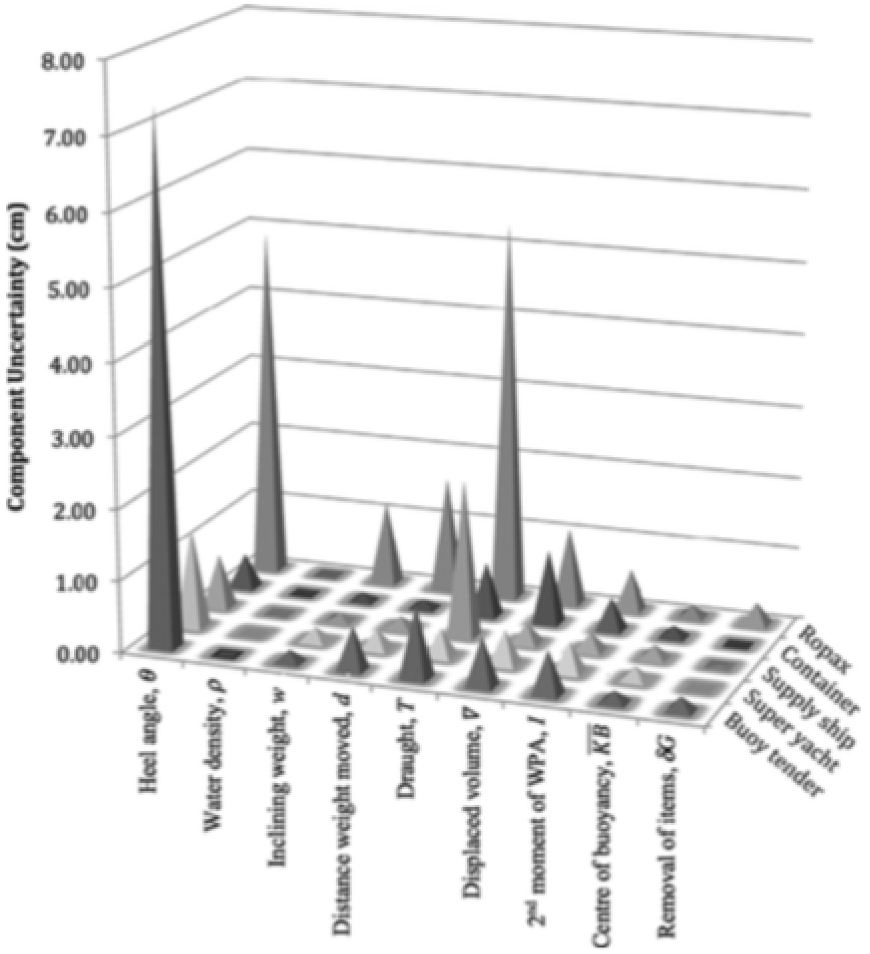

Figure 6. Results from the “Uncertainty Analysis Procedure for the Ship Inclining Experiment” Article for Component Uncertainty in KG. Source: Woodward et al. (2016).

Next, a journal article titled, “The Application of Smartphone in Ship Stability Experiment” looked at the feasibility of conducting IEs using smartphones to measure the heel angle (Djebli et al. 2015, 1). The paper described an experiment that utilized a miniature vessel model and conducted an IE with a smartphone and pendulum to measure heel angles. The experimental set-up can be seen in Figure 7 that depicts a six-foot-long, one-foot wide miniature British Ship Research Association (BRSA) trawler.

Figure 7. Experimental Set-up of BRSA Trawler for the Experiment.
Source: Djebli et al. (2015).

The results of the experiment were that there was no significant difference between the pendulum and the smartphone. In addition, the smartphone provided a much lower standard deviation for the obtained measurements and was much easier to set-up. The article concluded that using the smartphone technology should be recommended to the IMO and other regulatory agencies that oversee ship stability tests. The same experiment will be performed on three miniature models that will be described in the proceeding chapters to examine the differences between a smartphone and pendulum.

B. INTERNATIONAL STANDARDS

The IMO is an agency of the United Nations (UN) that collectively brings together countries with maritime borders to set international standards for safe shipping. In 2008, the IMO published Resolution MSC.267(85) which is the Adoption of the International Code on Intact Stability (IMO 2008). The code covers the international requirements for intact stability for vessels conducting international trade. Since the IE is a critical procedure for ensuring positive stability but has high potential for introducing systematic error, the code provides detailed instructions for the test procedure. The code recommended the use of three pendulums that are four to six meters in length but required at least two in order “to allow identification of bad readings at any one station” (International Maritime Organization [IMO] 2008, 71). It further states that alternate devices that have the same accuracy as pendulums can only be used in conjunction with at least one pendulum. Alternate devices that the IMO currently authorizes are digital inclinometers and u-tube manometers. There was no mention of laser pendulums. However, the code does allow for flag-state administrations, such as the USCG, to waive the pendulum requirement if mounting pendulums is determined to be impractical due to vessel constraints.

C. DOMESTIC REGULATIONS

The USCG is the regulatory agency that governs commercial vessel regulations for U.S. flagged vessels. Regulations for vessel stability requirements are generally found in Title 46 of the Code of Federal Regulations Subchapter S as well as USCG published guidelines that clarify regulations. Currently, USCG requirements are in sync with IMO standards and require three measuring devices with at least one pendulum to be used during the IE. Alternate devices used during the IE need an equivalent level of accuracy to the pendulum. The only noticeable difference between international standards and the USCG guidelines is the USCG authorization of laser pendulums if they have the same level of accuracy as traditional pendulums. In addition, there is no allowance for vessel owners not to use at least one pendulum during an IE or for the allowance of smartphone technology.

III. RAW DATA FOR DESIGN OF EXPERIMENT ANALYSIS

This chapter will discuss the raw data gathered for the Excel-based model that will be produced for the analysis and results chapter. In addition, moment-tangent plots will be generated based on the raw data submitted to the USCG in order to draw expectations of what the DOE analysis may reveal.

A. RAW DATA

To provide an analysis on whether alternate measuring devices offer an equivalent level of accuracy to pendulums, raw data from IEs that had been conducted on existing vessels was needed. Per 46 United States Code of Federal Regulations (CFR) Subchapter S Subpart 170.075(a) states that owners of commercial vessels are required to submit plans to the USCG Marine Safety Center (MSC) for plan review pertaining to vessel stability. This is to ensure commercial vessels meet minimum safety standards when carrying crew, passengers, or cargo. Part of the required submittal package to MSC includes a plan that shows the location of KG, which is generally done when an IE is performed. Since plans are reviewed and stored at MSC, the author contacted that office and requested IE submittals to analyze. Specifically requested were data from vessels that used alternate devices along with pendulums during IEs. The MSC was able to furnish the author with five separate IE submittals from commercial SPVs regulated under 46 CFR Subchapter T. These five vessels were all regulated under the same rules but vastly differed in their size, shape, and configuration. Due to the different hull shape dimensions, the test weight to displacement ratios will be noticeably different for each vessel. For vessels with narrower beams, additional test weights were needed to create the necessary moments for heeling the vessel to four degrees. For vessels with wider beams, test weights could be extended further off centerline requiring less overall test weights to be used for the necessary moments. Furthermore, the details regarding each vessel IE procedure will be discussed in the sections below; however, identifiable information such as vessel name or its general characteristics will not be disclosed to protect the privacy of vessel owners who submitted these plans to the USCG.

1. Vessel One Raw Data Analysis

Vessel one was one of the smaller vessels used for the analysis and had a displacement of approximately 12,000 pounds. For the IE conducted, the vessel owners used two pendulums and one digital inclinometer to measure the heel angle during the experiment. Over 1,400 pounds of external test weights were used for six separate weight shifts that produced moments for the calculation of GM. Figure 8 is a moment-tangent plot from the raw data of the IE.

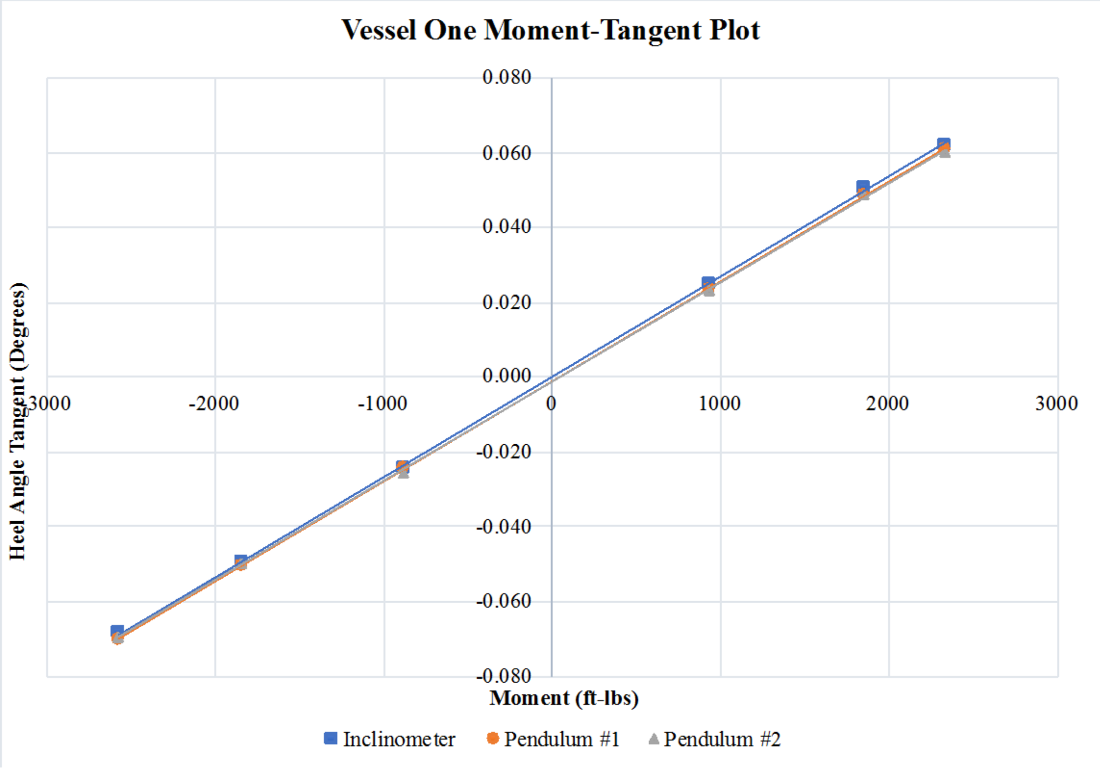

Figure 8. Moment-Tangent Plot of Vessel One Raw Data

Examining Figure 8, all data points for the moment tangent plot are along straight lines indicating there were no unwanted moments or faulty angle readings during the entire experiment. It is expected that significant statistical differences will not be detected between the measuring devices during the DOE analysis. This is due to the plotted points being nearly stacked on top of one another that indicates strong agreement among all the devices used.

2. Vessel Two Raw Data Analysis

Vessel two was the smallest platform analyzed for the DOE with a displacement of approximately 6,500 pounds. The owners elected to use two digital inclinometers and one pendulum for the IE. Approximately 1,390 pounds of test weights were used to create the different moments needed for the experiment. Figure 9 is an illustration of the moment-tangent plot submitted to the USCG for approval.

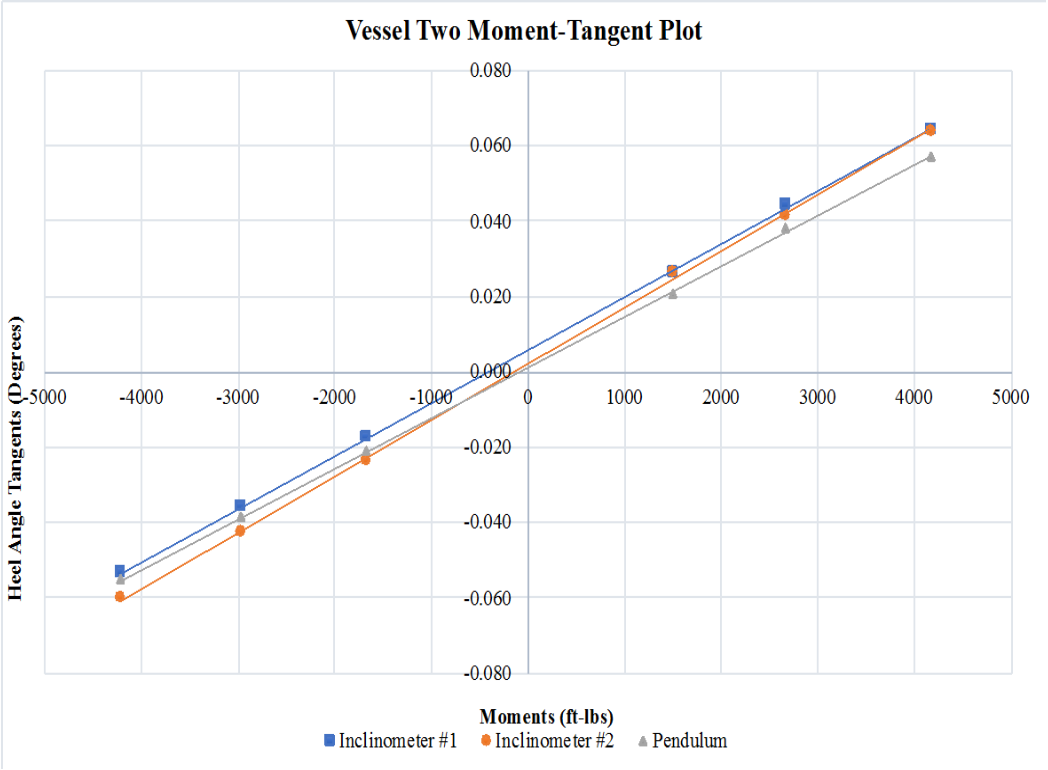

Figure 9. Moment-Tangent Plot of Vessel One Raw Data

Examining Figure 9, the individual devices appear to plot in a straight line and have a strong correlation. However, there are slight differences among devices at each weight shift. This is illustrated by the space among plotted points at each moment along the x-axis.

It is expected that there may be significant statistical differences among devices since the plotted points do not consistently overlap with one another. This would mean that there was not consistent agreement among devices for the duration of the IE.

3. Vessel Three Raw Data Analysis

Vessel three was the largest vessel used during the analysis with a displacement of approximately 1,000,000 pounds or 416.7 long tons. The owners used two digital inclinometers and one pendulum during the IE. Over 350,000 pounds of test weights were used to create the different moments needed to induce the necessary heel angles. Figure 10 is an illustration of the moment-tangent plot submitted to the USCG for approval.

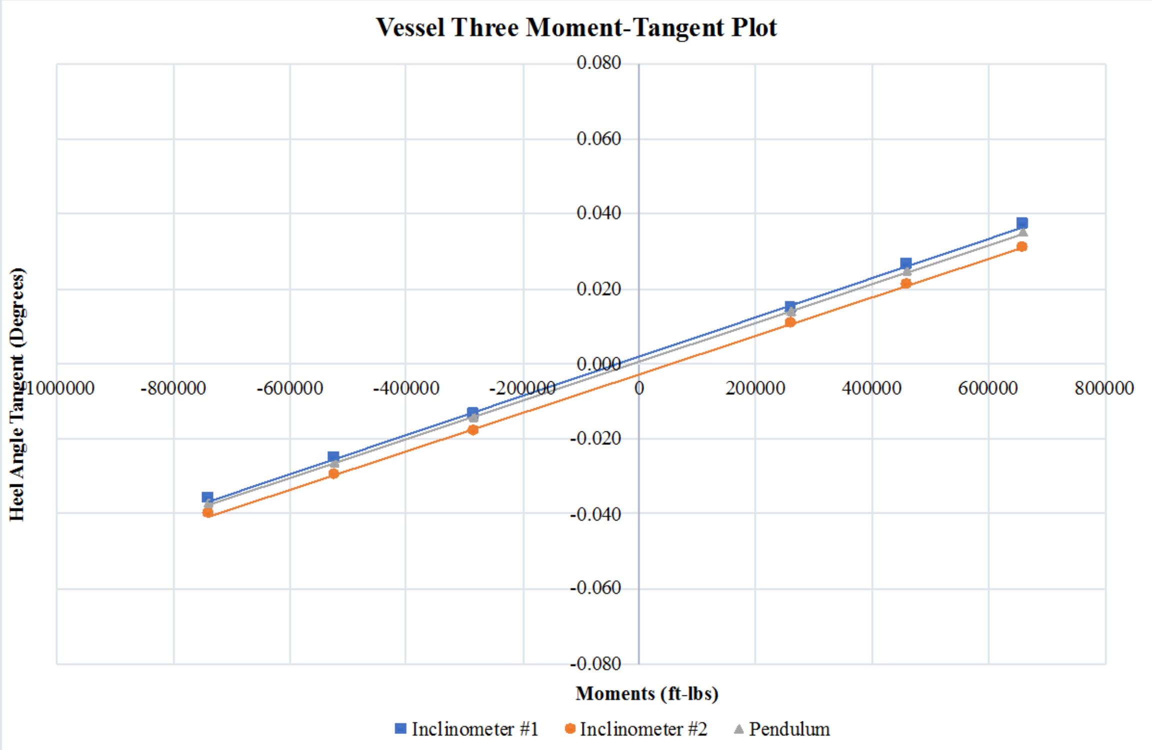

Figure 10. Moment-Tangent Plot of Vessel Three Raw Data

According to Figure 10, the data points for each individual device plotted as a straight line and appear to be strongly correlated. Inclinometer two does not appear to consistently agree with the heel angles of inclinometer one or the pendulum. Due to this inconsistency, significant statistical differences among devices is expected during the DOE analysis. This does not mean that inclinometer two produced faulty readings during the IE. It means that there was a consistent bias that was introduced or that the other two devices are producing bias readings. The bias could be due to where the device was placed along the centerline or human error with regards to operating the device. Unfortunately, these details were not provided in the submittal to perform a more detailed analysis.

4. Vessel Four Raw Data Analysis

Vessel four was the second largest platform used for this analysis and had a displacement of approximately 29,000 pounds. The owners used two pendulums and one digital inclinometer during the IE. The vessel used approximately 500 pounds in test weights to induce the different moments necessary to heel the vessel. Figure 11 is an illustration of the moment-tangent plot for vessel four.

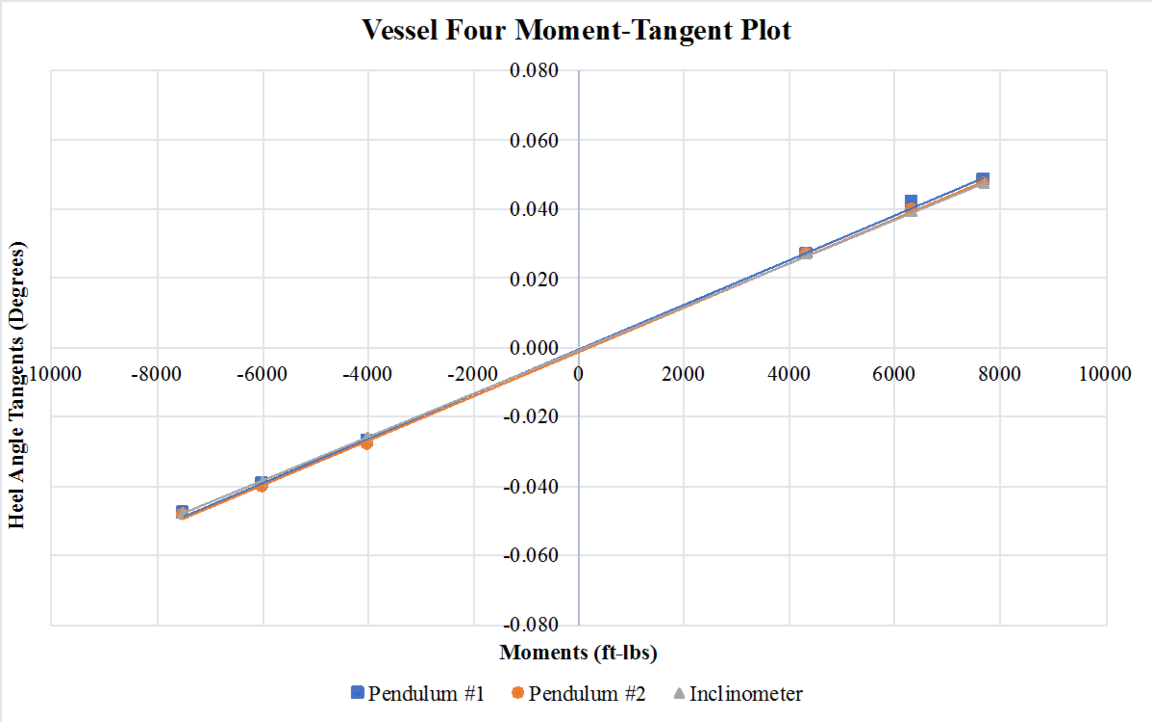

Figure 11. Moment-Tangent Plot of Vessel Four Raw Data

Examining Figure 11, all devices during each weight shift appear to plot as a straight line and are strongly correlated. There is very little space among the plotted points at each moment indicating that all devices are in agreement. Based on this graph, it is expected that there should be no significant differences among devices used.

5. Vessel Five Raw Data Analysis

Vessel five was the third-largest platform used for this analysis with a displacement of approximately 15,000 pounds. The owners used two digital inclinometers and one pendulum for the IE. Over 2,000 pounds of test weights were used to create the different moments. Figure 12 is an illustration of the moment-tangent plot submitted to the USCG for approval.

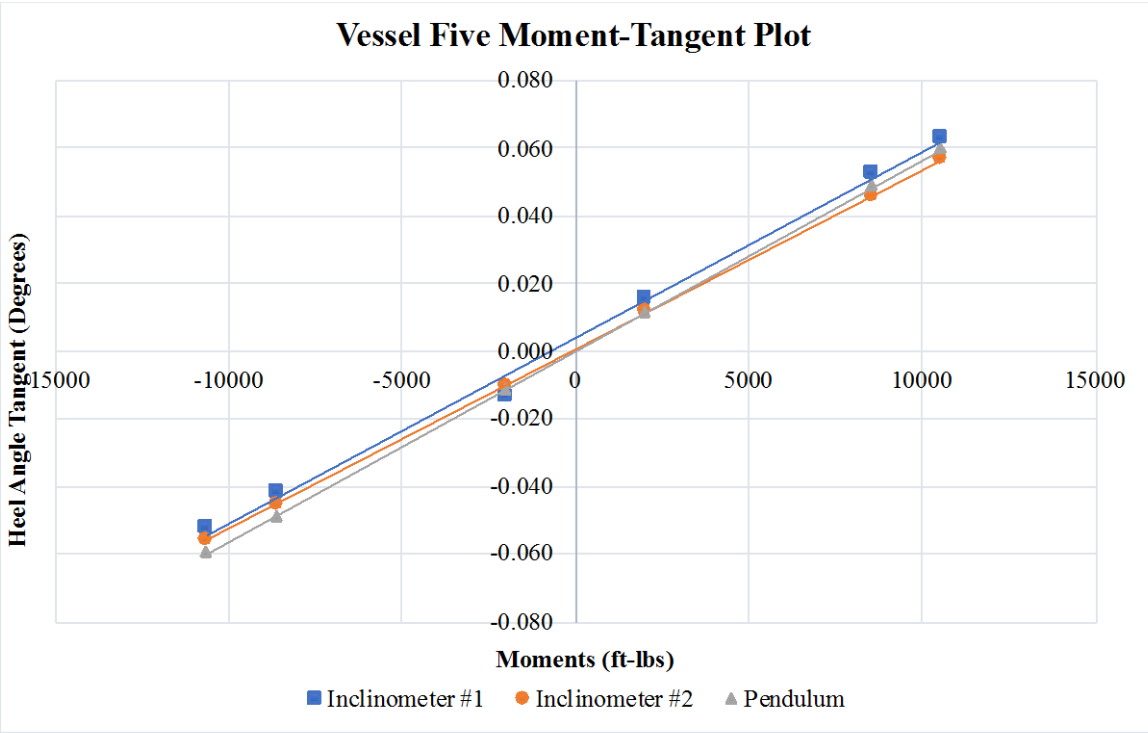

Figure 12. Moment-Tangent Plot of Vessel Four Raw Data

Examining Figure 12, all devices and their respective moment-tangent data points plotted as a straight line and appear to have a strong correlation. The individual data points in Figure 12 do not overlap with one another indicating there was no consistent agreement among devices during the IE. Therefore, it is expected that there will be significant statistical differences among devices when the DOE analysis is conducted.

B. RAW DATA CONCLUSION

Based on the raw data provided by the USCG, there was no consistent bias that could be identified that would skew the results. In addition, it could not be concluded that one measuring device was superior to the others. Examining all the moment-tangent plots in the previous sections, it is not anticipated that the test weight or test weight shift distance will be significant factors for the DOE analysis. Most plotted values do not have statistically significant differences for any given moment value when vertically aligned with the x-axis which represents the different moments. This means that the test weights and shift distance measurements were consistent throughout the experiment. The observed differences among the plotted values were more frequent when horizontally aligned with the y-axis. This axis plots the tangent of the heel angles produced by each measuring device during the IE. Due to the numerous vertical gaps observed among the plotted points, it is expected that the type of device used or the accuracy of the device used will produce the most significant differences in the results.

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IV. INCLINING EXPERIMENT UNCERTAINTY

This chapter discusses uncertainty regarding the independent variables used to calculate the metacentric height, GM. The uncertainty identified will be quantitatively estimated and used as input for the design of experiment (DOE) analysis in the proceeding chapter.

A. TEST WEIGHT ERROR

The test weight is the mass that is shifted to create different moments for the heel angles. Prior to the experiment beginning, test weights are required to be certified or validated by the person performing the IE (United States Coast Guard [USCG] 2016, 5). The devices used to verify test weight accuracy (i.e., scale or dynamometer) have error that is inherent to the device. After analyzing different certificates that accompanied the certified test weights, there was a wide range of accuracies that were noted based on the scale used and size of the test weight. The most reasonable error the author could deduce was to use three different error level settings for the DOE which were 0.50, 2.50, and 5.00 pounds. Unfortunately, applying a consistent percentage error for all test weights was not feasible. Each IE submitted to MSC used different amounts of test weights to create the moments necessary to heel the vessel. For instance, vessel three used 20 different test weights during the IE opposed to vessel two which used six different test weights. Each of the weights ranged in size and each vessel used different scales which had different error associated with them. Since modern scales have rated accuracy levels of no more than five pounds, this was the maximum error level used for the DOE analysis. The five-pound maximum limit is less than one percent error from the total test weights used in each submittal analyzed.

B. TEST WEIGHT SHIFT DISTANCE ERROR

After the test weight is placed on board and shifted off the centerline, the naval architect performing the IE measures the exact distance to accurately calculate the moment. There are several sources of error with measuring this shift distance that include: accuracy of the measuring device used (i.e., engineering scale or tape measure), using the exact reference point on the test weight after the shift, or human error of the observer recording the distance. Since all experiments used different devices and had different personnel observing the shift distance, error was adjusted to three different levels that included 0.25, 0.50, and 1.00 inches. These values are representative of the probable error for the test weight shift distance and would account for all sources of error previously mentioned for shifting test weights.

C. LIGHTWEIGHT DISPLACEMENT ERROR

During the IE, vessels are generally in the lightship condition. The lightship displacement is calculated prior to the experiment beginning by taking draft and freeboard readings on each side of the vessel. After recording the salinity of the surrounding water, the displacement can be calculated by referring back to the hydrostatic tables or it is manually calculated. After calculating the lightship displacement, a lightship survey is conducted to add or subtract weight that is not considered part of lightship. During the survey, if additional items were identified that needed to be added or removed, the naval architect would either estimate the approximate weight of the item or physically remove or add it to the vessel. These items, along with other sources of weight (e.g., bilge water, fuel in tanks), create unnecessary moments which could invalidate the test. The items to be added or removed are at the discretion of the person-in-charge (PIC) or flag-state or classification society to make the determination if the vessel is in the lightship condition (IMO 2008). For these reasons, this factor likely has the greatest source of error.

For the analysis conducted, no sources of error were applied to the lightship displacement. Each test that was analyzed had a wide range of items that needed to be added, removed, or estimated prior to the test beginning. If the weight was estimated, the item would be added or removed after the completion of the test. Since all vessels had different personnel overseeing the test effort, there was a wide range of subjectivity of how much error to add for each vessel during the lightship survey which would introduce a large bias in the data. Therefore, lightship displacement values were kept constant throughout each analysis.

D. HEEL ANGLE ERROR

Each IE examined for this analysis employed only pendulums and digital inclinometers to measure heel angles. Therefore, laser pendulums and manometers could not be observed. The different errors associated with pendulums and digital inclinometers are explained further in the following paragraphs.

1. Pendulum Error

The pendulum is the primary device required in all IEs and has two main sources of error when calculating heel angles. These sources of error include measuring the height of the pendulum and measuring the deflection after the vessel heels as seen in Figure 8.

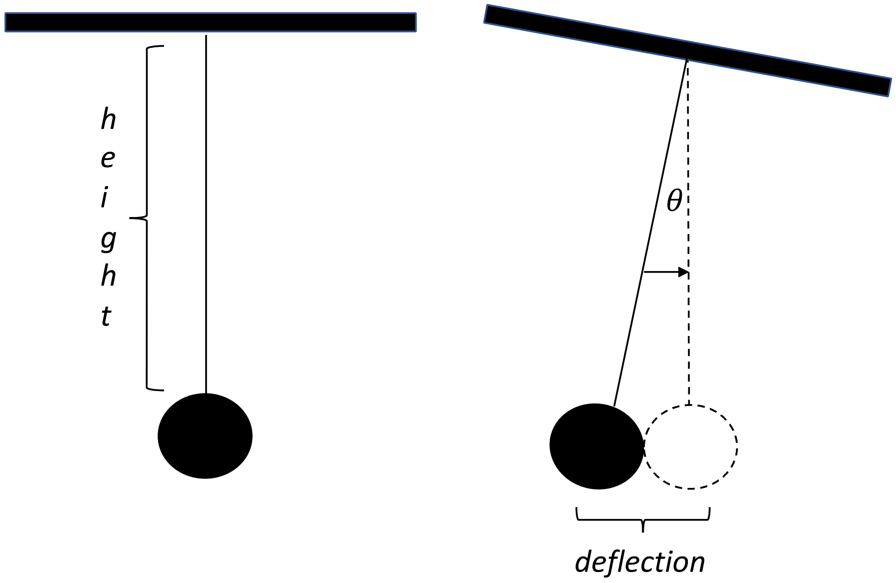

Figure 13. Illustration of a Pendulum Used during IE.

By measuring the total deflection of the pendulum at a known height, the angle of inclination (θ) can be calculated using the following equation.

$$\theta = tan^{-1}\left(\frac{deflection}{height}\right)$$

For both height and deflection measurements, there is human error involved. For the set-up of the analysis, error was only applied to the deflection of the pendulum and not the height. This was done to have an even comparison and produce a balanced DOE since digital inclinometers only had one source of error applied to them. This is not to say pendulums and digital inclinometers only have one or two sources of error, but those were errors that could reasonably be estimated. Other sources of error affecting the pendulum deflection include: oscillations due to weather, workmanship during construction of the pendulum, and the distance off centerline the pendulum was placed. To develop error levels for the DOE, an examination of different commercial engineering scales were researched. In general, engineering scale tick marks had gaps of 1/32nd, 1/16th, and 1/8th of an inch. If using a 10-foot pendulum, these markings would correspond to approximately 0.02, 0.03, and 0.06 degrees of heel, respectively.

2. Digital Inclinometer Error

The digital inclinometer is a mature technology that has been around for many years. This device is placed along the centerline of the vessel and records the heel angle via internal components. Depending on the specifications of the device, it can take up to 10 sample readings and return the mean and standard deviation for each weight shift. This significantly reduces device error relative to pendulums that generally oscillate during the IE. The USCG has set the specifications that all digital inclinometers shall meet which is "when employed as a substitute for up to two of the required pendulums, digital inclinometers must have a precision of at least ± 0.01 degrees with an accuracy of ± 0.05 degree." (USCG 2016, 6). The inherent accuracy of the digital inclinometer was the only error applied for this analysis. Other errors for the digital inclinometer that were omitted were precision of the angular deflections and the transverse position of the device off centerline. It was assumed that the location error would nearly match the pendulum location error and, therefore, would have little impact during the analysis. The range of error levels used were 0.01, 0.03, and 0.05 degrees for the device accuracy. These values were chosen based on the above USCG specifications with 0.05 degrees being the maximum permissible error. It should be noted that a 0.05-degree digital inclinometer reading is approximately equal to a 1/10th inch deflection for a 10-foot pendulum. This means that the error levels applied to both devices are relatively similar and ideal for comparison.

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V. DESIGN OF EXPERIMENT ANALYSIS AND RESULTS

This chapter will discuss how the analysis was set-up to examine five separate IEs that were conducted on U.S. flagged Small Passenger Vessel (SPVs). In addition, the design of experiment (DOE) results will be analyzed to look at which factors had the greatest impact on GM. In addition, a non-parametric analysis from the factors with the greatest level of significance will be evaluated to determine why the DOE produced the results that it did.

A. ANALYSIS SETUP

The MSC provided the author with five separate IE submittals from commercial SPVs. The raw data from the submittals was used as the baseline for the analysis. The information that was extracted from the submittals were: pendulum heights and deflections, inclinometer heel angles, test weights with shift distances, lightweight displacements, and final GM calculations. These factors were duplicated in the Microsoft Excel analysis tool to generate the same results. After verifying the spreadsheet accuracy with the MSC submittals, the author wanted to explore if there were any statistical differences between pendulums and the authorized alternate measuring devices used for each vessel. The only alternate devices that were used from submitted IEs were digital inclinometers. Therefore, an initial null and alternate hypothesis was formed and used as the objective for the DOE seen below.

$$H_O: Measured\ Heel\ Angles\ for\ Pendulums = Measured\ Heel\ Angles\ for\ Digital\ Inclinometers$$

vs.

$$H_A: Measured\ Heel\ Angles\ for\ Pendulums \neq Measured\ Heel\ Angles\ for\ Digital\ Inclinometers$$

With the spreadsheet model prepared and an objective null hypothesis formed, random error was applied to the test weight, test weight shift distance, and heel angle. The random error applied followed a normal distribution since that was what the data most likely followed and would be verified during the non-parametric analysis of the GM results.

A random number generator that followed a normal distribution was used for the model. To generate the random numbers, the raw data provided in the submittals was inputted as the mean value and the standard deviation was the three different error levels discussed in the previous chapter. A GM calculation with the applied error was generated for each weight shift and compared against the baseline GM calculation.

To analyze whether the random error applied had any meaningful influence on the model, a DOE was set-up to measure which factors had the highest level of significance. In addition, the type of device used for the calculation of GM was added as the fourth factor. All four factors had three levels and were all replicated 10 times. Therefore, there were 810 data points generated per weight shift, as seen in the below calculation.

$$Data\ Points\ per\ Weight\ Shift = 3\ Levels^{4\ Factors} * 10\ Replicates$$

$$Data\ Points\ per\ Weight\ Shift = 810\ Data\ Points$$

The five IEs each had six weight shifts. Therefore, there were 24,300 GM calculations for the analysis for all vessels. The DOE was set-up in Minitab statistical software. The software provided five separate balanced full factorial designs with the previously mentioned factors, levels, and replicates. After generating different full factorial designs, all were inserted into the spreadsheet model to produce GM calculations based on the combination of factors and levels. After running all the combinations in the model, the generated GM calculations were placed back in the Minitab software for analysis. Minitab generated five separate Analysis of the Variance (ANOVA) tables that provided key insights to each IE.

B. DOE ANALYSIS

After running Monte Carlo simulations with random errors inputted into each of the three factors previously mentioned, a GM was calculated for each trial. The resulting GM was analyzed in Minitab via ANOVA tables. All factors and their contribution to the overall IE error were plotted as Pareto charts as seen in Figures 14, 15, 16, 17, and 18 where factor “A” represents the device used, factor “B” is the test weight error, factor “C” is the test weight shift distance error, and factor “D” represents the accuracy of the device being used. The combination of factors, such as “AB,” represent interactions among factors. The chart is plotted with all factors on the vertical axis and the *level of significance* on the horizontal axis. The level of significance is the probability of rejecting the null hypothesis which, in this scenario, is that there is no difference between pendulums and digital inclinometers with respect to their measured heel angles. A red dashed line is drawn at the 90% level of significance value since this is a common threshold for rejecting null hypotheses.

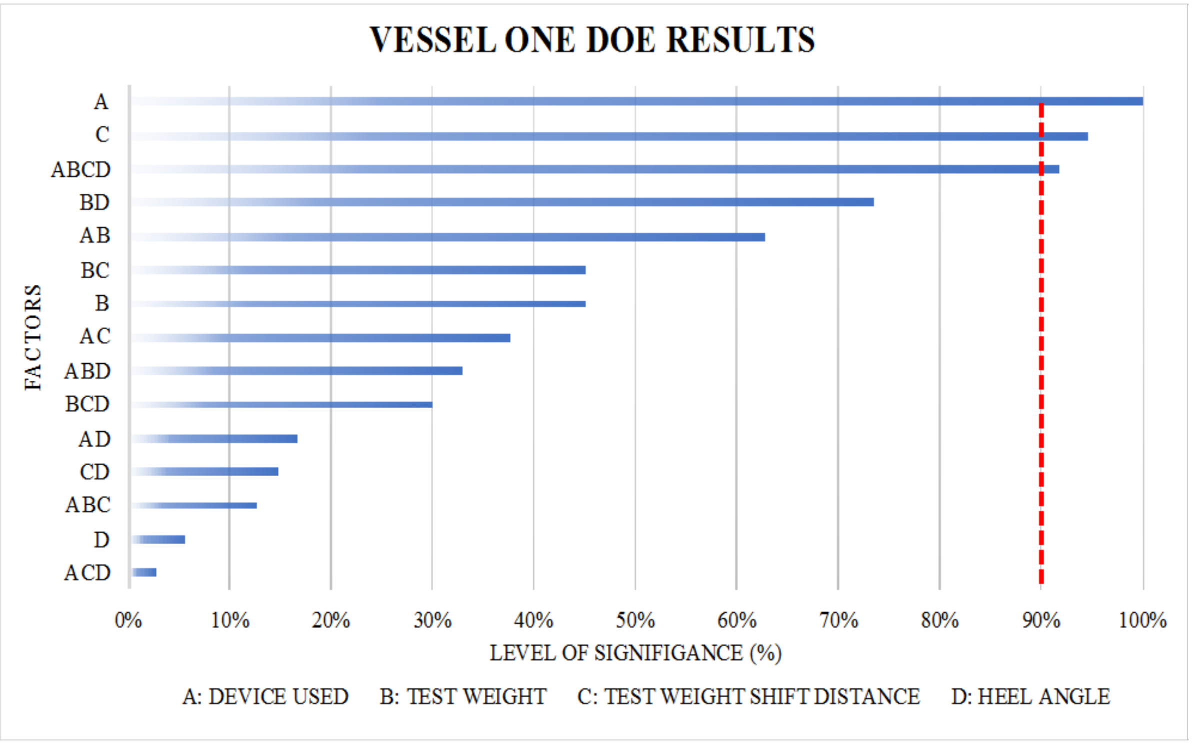

Figure 14. DOE Results from Vessel One Analysis

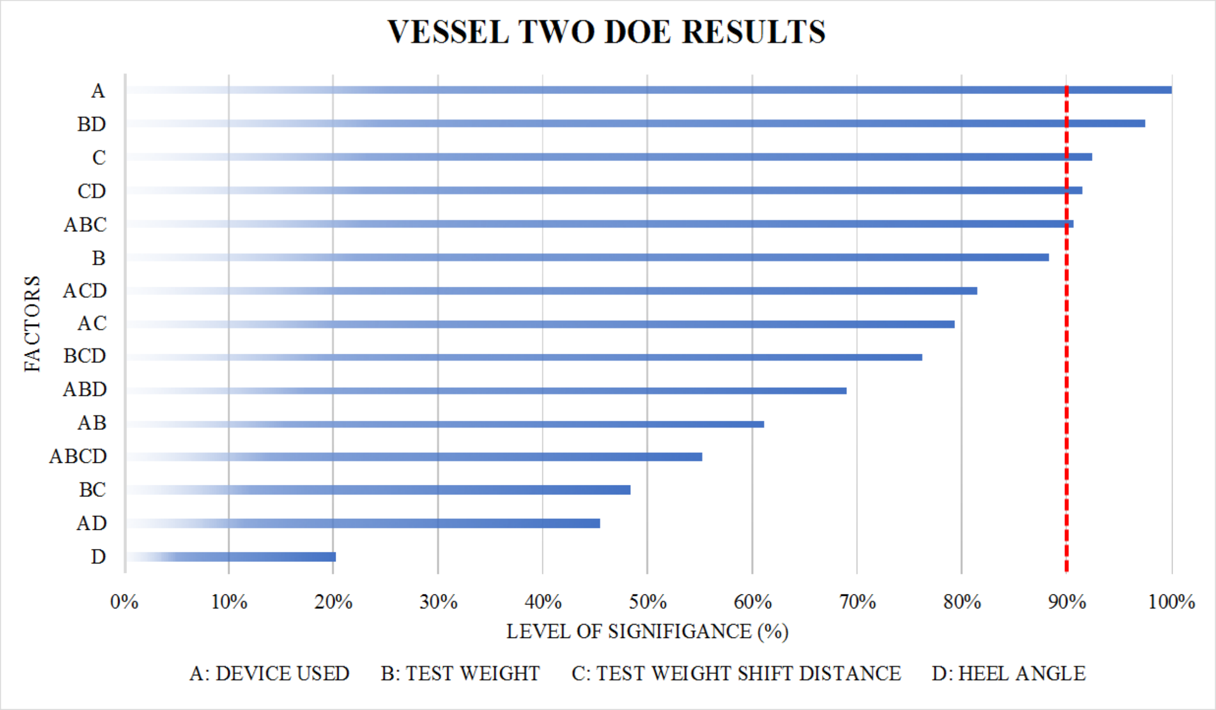

Figure 15. DOE Results from Vessel Two Analysis

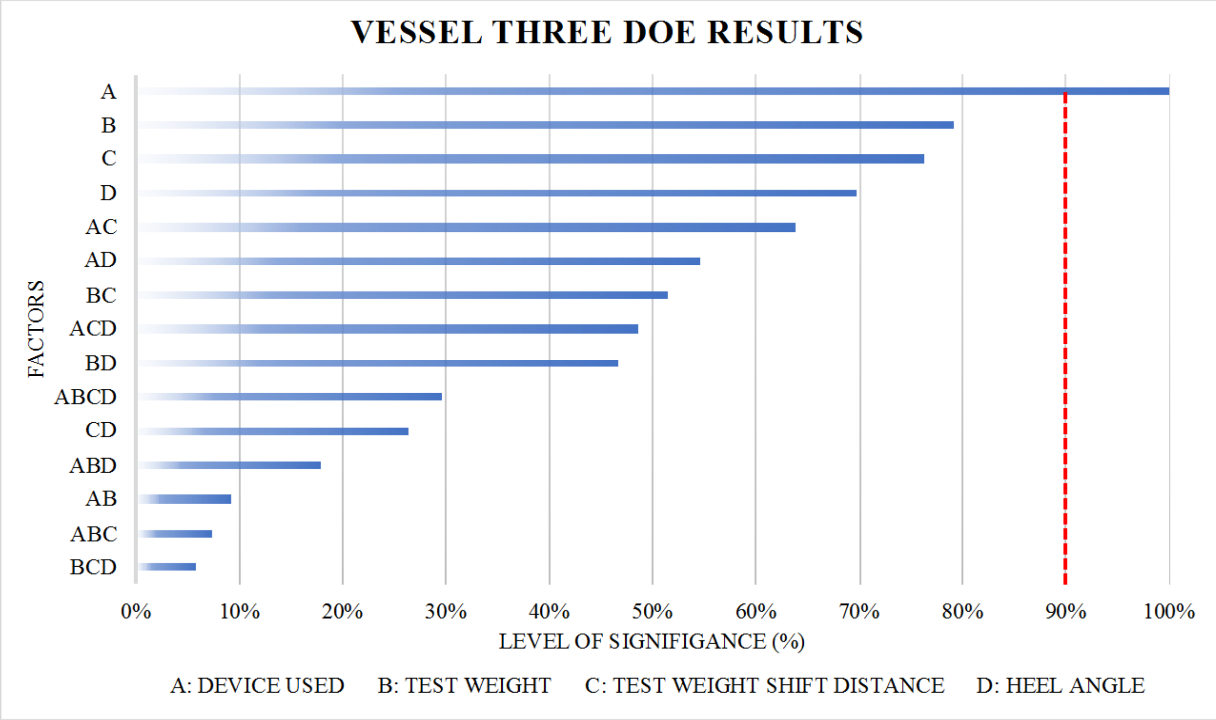

Figure 16. DOE Results from Vessel Three Analysis

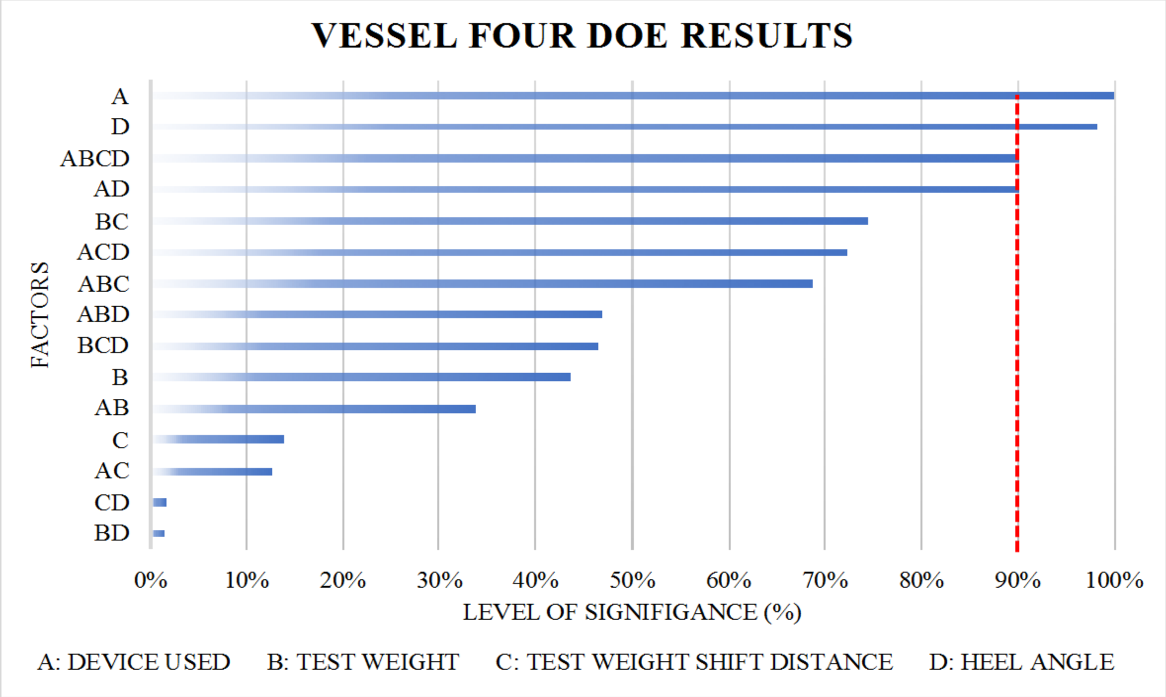

Figure 17. DOE Results from Vessel Four Analysis

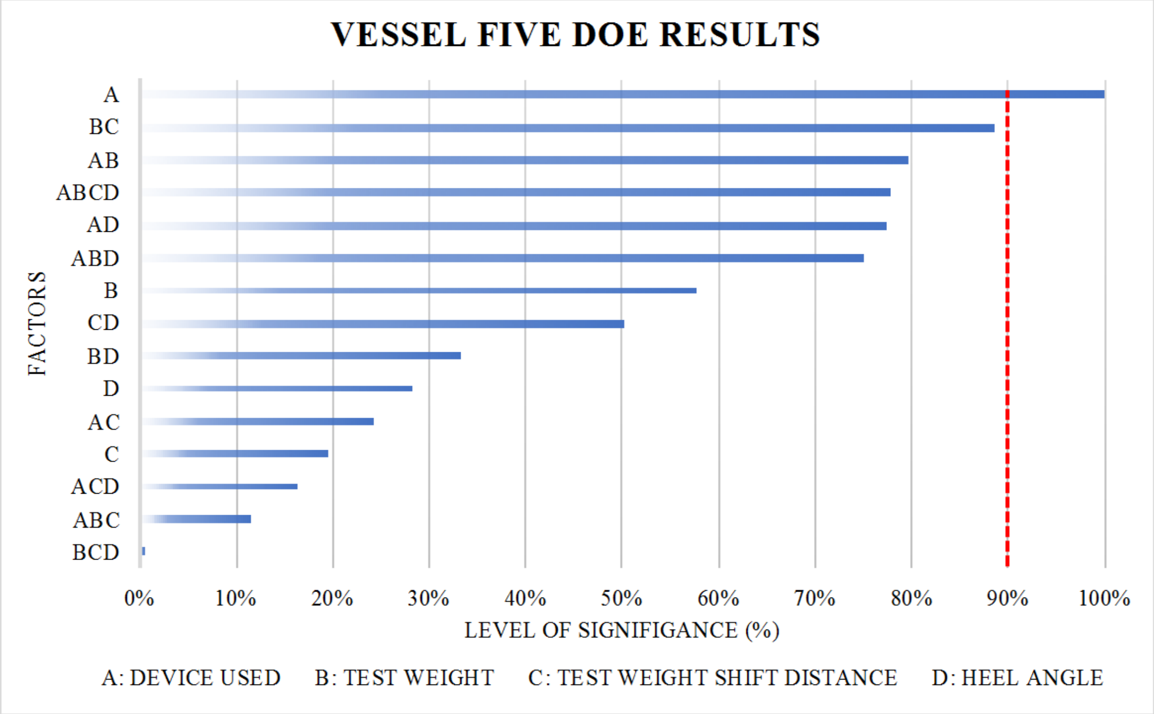

Figure 18. DOE Results from Vessel 5 Analysis

In all the results presented in the previous figures, the type of device used for measuring heel angle was the most significant factor for each vessel. This means that there is high confidence that if the model were run 100 times, it would be expected that there would be statistical differences among all devices for all trials. The DOE was set-up with the null hypothesis that there was no difference among heel measuring devices for calculating GM. According to the previous figures, the null hypothesis of assuming there is no difference among measuring devices can be rejected. To explore further why the type of device used was significant in all five vessels, an analysis of each devices' raw data as it contributed to GM will be examined in the next section.

C. NON-PARAMETRIC DEVICE DATA

Since all DOEs concluded that the type of device used during the experiment had the greatest impact on calculating GM, examining the non-parametric data may explain why. This section will display and plot the GM calculations from the raw data without random error applied. It will show the mean, standard deviation, median, minimum, maximum, and range for all GM calculations. In addition, the GM calculations will be transformed into dot plots to visualize the data for skewness and outliers.

For the data provided in each dot plot, a standardized method was developed to evaluate each vessel objectively. First, the data was evaluated for *outliers*. Outliers are values that are significantly higher or lower than the mean value of the sample set. These values can add bias to the data leading to a misinterpretation during the analysis. Next, the data was evaluated for *skewness*. Skewness is the degree to which the data set is non-symmetric about the mean. Skewness or the symmetry of the data set could indicate if the raw data was normally or nonnormally distributed. This would validate the assumption of using a normal distribution for the DOE error inputs. Finally, a comparison of the median values and range of the GM calculations were examined for each vessel indicating accuracy and precision.

1. Vessel One Non-parametric Analysis

The GM calculations for each device used on vessel one can be seen in Table 1 and Figure 19. The red dashed line represents the mean value among all devices—approximately 3.1 feet.

Table1. Non-parametric GM Calculations for Vessel One (in feet)

	Digital Inclinometer	**Pendulum #1**	**Pendulum #2**
Mean	3.08	3.12	3.11
Standard Deviation	0.05	0.10	0.16
Median	3.10	3.11	3.08
Minimum	3.01	3.01	2.84
Maximum	3.13	3.26	3.35
Range	0.12	0.25	0.51

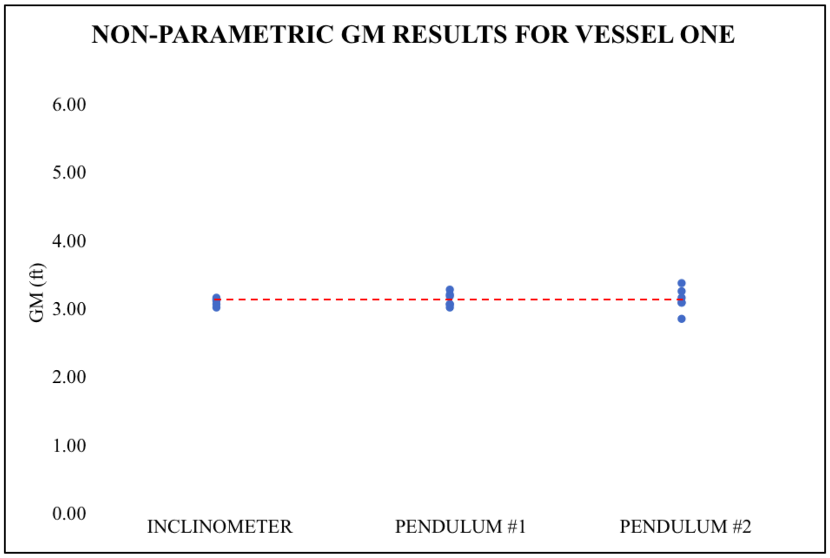

Figure 19. Non-parametric Dot Plot of GM Results for Vessel One

Reviewing the calculations for each device, there were no outliers in the data. In addition, there did not appear to be skewness and therefore it was reasonably assumed the data was normally distributed. The median values among devices is within 0.03 feet from one another, and the range of values appears consistent. Overall, the digital inclinometer provided the best precision.

2. Vessel Two Non-parametric Analysis

Next, the non-parametric data from vessel two was examined as seen in Table 2 and Figure 20. The red dashed line represents that mean value among all devices—approximately 11.1 feet.

Table 2. Non-parametric GM Calculations for Vessel Two (in feet)

	Digital Inclinometer #1	**Digital Inclinometer #2**	**Pendulum**
Mean	11.42	10.31	11.62
Standard Deviation	2.32	0.80	0.44
Median	11.21	10.49	11.67
Minimum	8.91	8.91	10.99
Maximum	14.89	11.03	12.15
Range	5.99	2.13	1.16

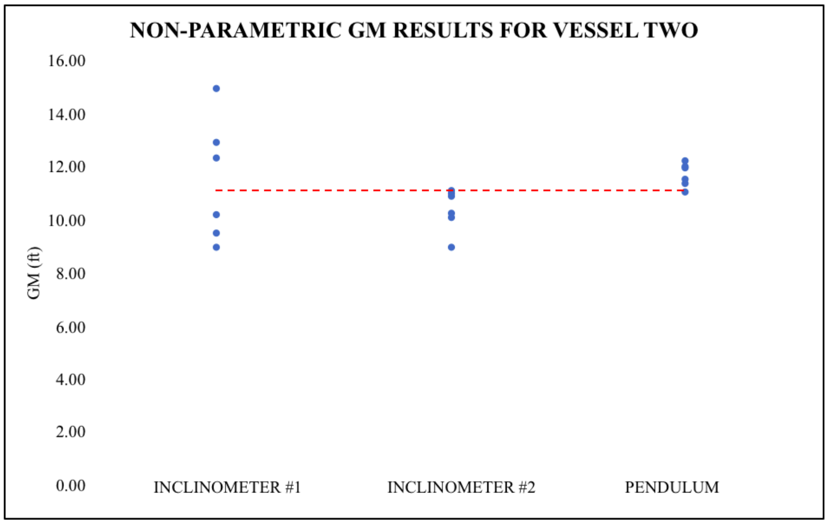

Figure 20. Non-parametric Dot Plot of GM Results for Vessel Two

After evaluating the data, it is clear that GM calculations for digital inclinometer #1 were more variable than the other two devices. There were no outliers for each of the devices and there does not appear to be skewness. The span of GM calculations for digital inclinometer #1 had almost a six-foot range between the minimum and maximum values. Although digital inclinometer #1 had the lowest precision, the median values were approximately one-foot from each other, indicating consistency among devices since vessel two had an approximate GM of 11 feet. Overall, the pendulum provided the best precision.

3. Vessel Three Non-parametric Analysis

Furthermore, the non-parametric data from vessel three was examined and can be seen in Table 3 and Figure 21. The red dashed line represents that mean value among all devices—approximately 18.6 feet.

Table 3. Non-parametric GM Calculations for Vessel Three (in feet)

	Digital Inclinometer #1	Digital Inclinometer #2	Pendulum
Mean	18.29	19.08	18.47
Standard Deviation	1.63	3.17	0.43
Median	18.35	18.94	18.48
Minimum	16.67	15.07	17.99
Maximum	19.90	23.77	18.95
Range	3.23	8.70	0.97

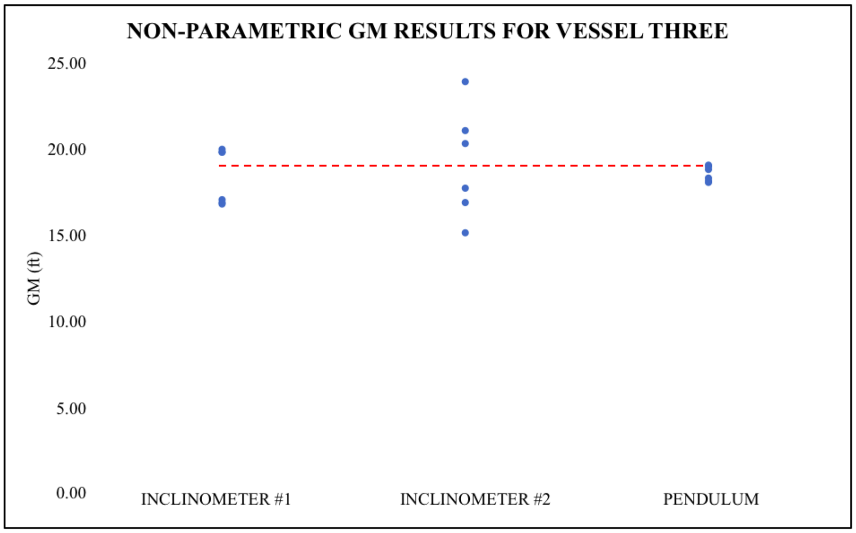

Figure 21. Non-parametric GM Results from Vessel Three (in feet)

There were no outliers in the data and no apparent skewness. In addition, the median values were consistent at less than 0.6 feet. However, the range in data for both digital inclinometers were significantly higher than the pendulum. For digital inclinometer #2, there was nearly an 8.5-foot range in GM calculations which is a significant fluctuation between weight shifts. The pendulum had the overall best precision with slightly under one-foot.

4. Vessel Four Non-parametric Analysis

Next, the data for vessel four was analyzed and can be seen in Table 4 and Figure 22. The red dashed line represents the mean values among all devices at approximately 5.4 feet.

Table 4. Non-parametric GM Calculations for Vessel Four (in feet)

	Pendulum #1	Pendulum #2	Digital Inclinometer
Mean	5.36	5.39	5.50
Standard Deviation	0.18	0.27	0.12
Median	5.35	5.45	5.51
Minimum	5.14	4.99	5.36
Maximum	5.58	5.64	5.64
Range	0.44	0.65	0.28

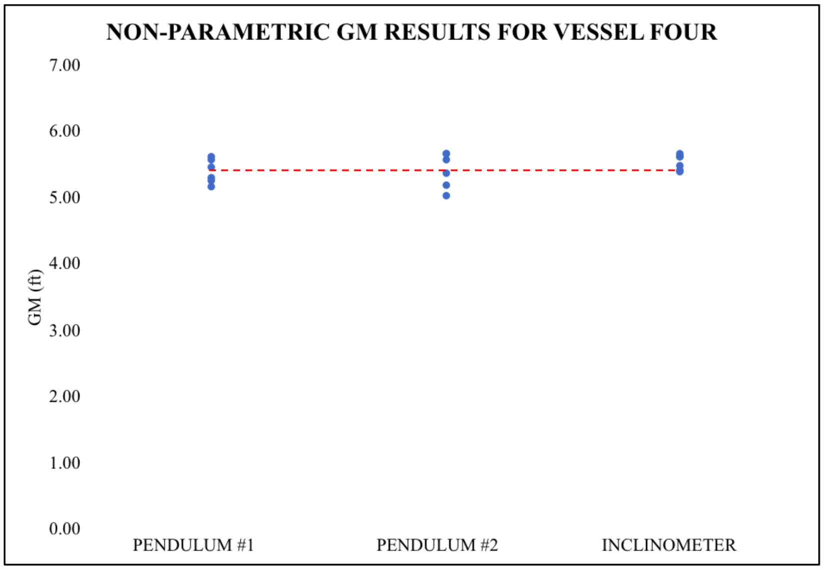

Figure 22. Non-parametric GM Results from Vessel Four (in feet)

There was no outliers and no apparent skewness in the data. In addition, the median and range of values appear to be consistent as well. The device that provided the overall best precision was the digital inclinometer.

5. Vessel Five Non-parametric Analysis

Finally, the data for vessel five can be seen in Table 5 and Figure 23. The red dashed line represents the mean value among all devices at approximately 12.5 feet.

Table 5. Non-parametric GM Calculations for Vessel Five (in feet)

	Digital Inclinometer #1	**Digital Inclinometer #2**	**Pendulum**
Mean	11.89	13.10	12.45
Standard Deviation	2.19	0.57	0.18
Median	11.63	13.25	12.39
Minimum	8.85	12.01	12.29
Maximum	14.54	13.62	12.78
Range	5.69	1.61	0.49

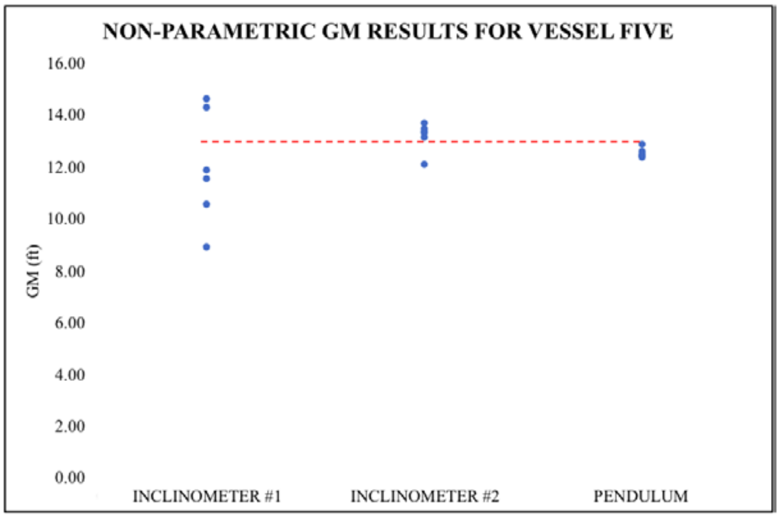

Figure 23. Non-parametric GM Results from Vessel Five (in feet)

There appears to be some skewness in both digital inclinometers, and the median values are not consistent across all devices. The median value between digital inclinometer #1 and the other two devices is approximately two feet. Furthermore, there were no outliers recorded for each device that would disproportionately affect the data. Also, the range in GM calculations were almost seven feet for digital inclinometer #1 with digital inclinometer #2 having a two-foot range. Overall, the pendulum provided the best precision.

D. OVERALL NON-PARAMETRIC ANALYSIS

The GM calculations for each vessel had variable results among each device. For three out of the five vessels, the pendulum provided a higher level of precision compared to the digital inclinometer. It should be noted that these same three vessels had significantly higher GM values and all used two digital inclinometers and one pendulum. It is unclear whether the higher GM values or the combination of devices used were the cause of the pendulums having more precision. In addition, at least one digital inclinometer for each of the three vessels had large deviations in comparison to the other two devices used during the IE. Reasons that may explain the various deviations for each device include the transverse and longitudinal position of the measuring device along the centerline, human or inherent device error in the measurements, weather conditions during the IE, or the design of the vessel. There was no data to support these theories since the submittals did not provide details on exact device placement relative to the vessel, prevailing weather conditions for each weight shift, how many personnel were recording measurements, or the overall design of the vessel and how weather interacts with the hull (i.e., sail area). Since these variables could not be further explored, a more detailed analysis could not be conducted.

The key insights that were drawn from this analysis were that all experiments had at least one device that did not correspond with the other two. There are several factors that can account for these discrepancies, as was explained in the previous paragraph. The data could not provide which device had better precision in each analysis since there was no device that was consistently producing better results over the other devices used. Further information would need to be gathered from each of these IEs to identify the other external factors not accounted for in the data. This could lead to a clearer recommendation whether pendulums could be excluded from IEs.

VI. PHYSICAL EXPERIMENTATION

This chapter examines IEs conducted on three separate physical models that were constructed by the author. The intent of the experiment was to perform IEs on miniature vessel models with different hull configurations and observe the impact to the GM calculations. The following paragraphs will cover the initial set-up, materials used, and configuration of the models. Finally, the analysis results of the experiment will enable conclusions to be drawn.

A. INITIAL SET-UP AND PROCEDURE

The primary purpose for this experiment was to explore how different hull configurations affected IE results among different heel measuring devices. By performing this experiment on a miniature level, the author could control external factors that were unknown in the MSC submittals. By limiting the external forces to the model, the impact to GM results could be observed. The systems engineering approach was applied to the experiment in order to develop, design, and fabricate three separate hull models and analyze the results of the two-different heel measuring devices used. A smartphone that measures heel angles via internal accelerometer and a pendulum were used for comparison. The equipment utilized for this experiment is summarized in Table 6.

Table 6. List of Equipment Used for Inclining Experiment for Physical Models

Item Nomenclature	Use
Styrofoam Block	Three of these rectangular Styrofoam boards that measured 30.4 cm x 15.1 cm x 2.5 cm were procured and used as the foundation for all hull configurations.
Cylindrical Styrofoam Rods	Styrofoam cylinder rods that measured approximately 30.4 cm by 2.5 cm were used as pontoons for one of the hull models. Two pieces were cut in half, lengthwise, and glued to the bottom of the rectangular Styrofoam boards.
Pendulum Mast	A 27 cm wooden mast was inserted into the stern portion of all models to suspend the pendulum.
Wooden Spool	A wooden spool was attached to the top of the pendulum mast to separate the mast from pendulum string. This enabled the pendulum to swing freely unobstructed.
Paper Clip	A paper clip was attached to the end of the spool to minimize the friction between the pendulum string and wooden spool.
Pendulum String	A monofilament string was attached to the top of the pendulum that measured approximately 25 cm in length and was attached to each wooden spool via paper clip.
Plumb Bob	A small lead plumb bob was attached to the bottom of the pendulum string to ensure it remained straight and not fluctuations due to air movement in the laboratory.
Engineering Scale	A small engineering scale that measured 15 cm in length was used to record the pendulum deflections.
Test Weights	A series of 20-gram test weights were used to create moments that induced different heel angles needed for the IE.
Rubber Mat	A rubber mat was placed on top of the Styrofoam block to create a friction barrier for the test weights and smartphone. This was to prevent slippage that would create unnecessary moments and to avoid risk of the smartphone dropping in the water.
Smartphone	A smartphone, specifically an iPhone 6 model MG632LL/A, was the other primary device used to measure the heel angle of the model. The specific application used was the Small Craft Motion Program, or SCraMP. SCramP was developed Leigh McCue, a professor within the Aerospace and Ocean Engineering department at Virginia Tech University.

Figure 24 is a picture of the complete set-up for one of the three models and includes all equipment except the cylindrical rods from Table 6.

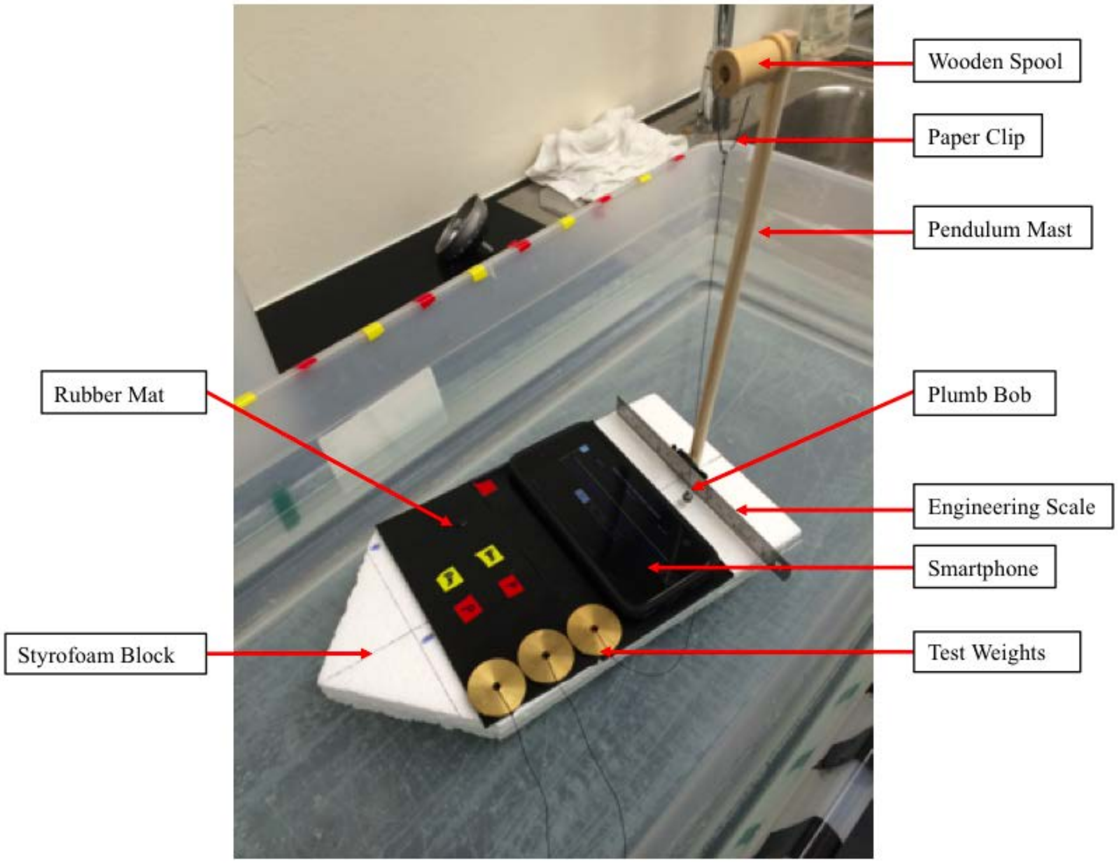

Figure 24. Assembled V-Hull Model to Measure Induced Heel Angles

To conduct this experiment, the first step was to visually inspect all equipment to ensure correct set-up and alignment. This included inspecting the pendulum and all of its components. First, a sufficient air gap between the Styrofoam board and the plumb bob was examined. The plumb bob needed to be free of obstructions to obtain reliable results. In addition, verification of the engineering scale used for measuring pendulum deflections was inspected for vertical alignment with the pendulum mast. The engineering scale and pendulum needed to be nearly perpendicular to gain accurate readings during the IE. After the engineering scale was confirmed to be properly set-up, it was glued to the pendulum mast to lower the risk of it inadvertently moving during the experiment. Finally, the plumb bob was aligned to the assumed zero point on the engineering scale. This was done by first choosing the zero point to use. After the point was chosen and marked, the paper clip that the plumb bob hung from was permanently fastened to the wooden spool via glue in order for the plumb bob to nearly align to that mark when the model was in the even keel position.

Next, the model and all other test equipment used during the experiment (i.e., smartphone, test weights) were assumed to be part of each models' lightship displacement. To measure the total displacement of the model, a digital scale was used with all equipment resting on the hull. The digital scale was verified to be calibrated and accurate to 0.1 grams. Furthermore, a rubber mat was placed on top of the hull to act as a non-skid surface for the different pieces of equipment as well as to make markings for the exact position for the test weights to be shifted. Therefore, prior to the experiment beginning, a trial run was conducted to visualize the approximate distances the test weights would need to be shifted to achieve the required heel. Since the same rubber mat was used on every model, the red and yellow markings seen in Figure 26 represent the initial and final test weight positions for the different hull configurations. It was found during the trial run that as test weights were shifted, a large amount of human contact with the model was needed. This in turn created substantial waves in the tub thus causing large oscillations to the pendulum and large fluctuations to the smartphone readings. To reduce disturbing the water during the experiment, strings were attached to the different test weights in order to minimize contact with the hull. Also, during each weight shift, a pen was used to dampen the oscillation by placing it in the direct path of the plumb bob and slowly backed off until the oscillations nearly diminished. However, the plumb bob still swung approximately 0.4 cm to either direction and therefore the mean value was taken from the period it produced.

Prior to beginning the experiment, several measurements were taken that included the dimensions of the model, height of the pendulum mast, and the distance between marks for the test weights. In addition, the test weights were weighed on a calibrated scale. These measurements would be used to calculate various moments, heel angles and ultimately the GM for each model. Once the equipment was verified to be set-up correctly, the experiment began by gently placing the first model into the tub with the test weights at their initial marks. The initial readings from the pendulum and the smartphone were recorded. If the devices had offsets from their even keel position, the offsets would be added or subtracted from the different readings to ensure the deflection or heel angle recorded started from the assumed zero point. With the equipment set, each test weight was individually shifted and the angle and deflection readings recorded. This was done a total of six times, three weight shifts per side, for each weight. The first hull tested was the v-hull followed by the pontoon and barge, respectively.

B. PHYSICAL EXPERIMENT DATA AND ANALYSIS

The raw data gathered from this experiment consisted of collecting the heel angle and deflection readings after each weight shift. The deflection and heel angle readings were measured by a fellow classmate taking the readings while the author recorded and oversaw the experiment. After the three test weights were shifted to one side with the measurements recorded, the model was lifted out of the tub and placed on a lab table. The distances from the initial starting point to its final position were measured. This was done to increase the accuracy of the test weight shift distance. Taking measurements while the model was floating proved to be difficult due to the excessive rolling and pitching produced during the experiment. After the shift distances were recorded, the test weights were placed in the even keel marked positions and the experiment was repeated for heeling the other side of the model. The following sections will detail the data and results for each model. At the end, the devices used for recording heel angles will be compared for analysis.

1. V-Hull Model

The first model tested was the V-hull model. This configuration provides the least water resistance when propelled in the forward direction due to its hydrodynamic design. This is a common hull design especially for smaller platforms that are built for speed in lieu of carrying cargo such as speed boats used in the SPV industry. The downside to this design is that it inherently has less reserve buoyancy for floatation since approximately 131 cm^3 was cut off the port and starboard bow. Figure 25 is a picture of the model during the IE with two test weights shifted to the starboard side.

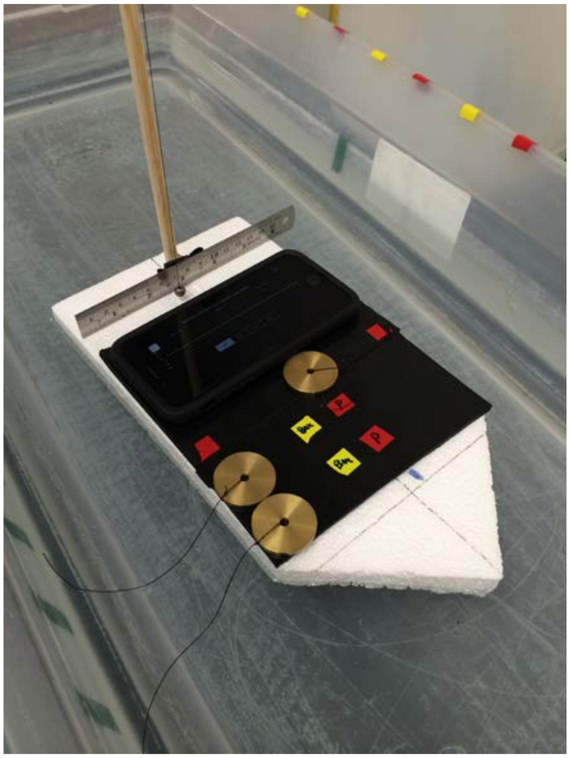

Figure 25. Picture of the V-Hull Model with Two Test Weights Shifted to the Starboard Side.

The principle characteristics of the V-hull model in Figure 26 are presented in Table 7.

Table 7. Principle Characteristics of the V-Hull Model

Principle Characteristic	**Dimension**	**Unit**
Length Overall	30.4	cm
Beam	15.1	cm
Depth	2.5	cm
Displacement	385.3	g
Pendulum Height	27.3	cm

After the data was collected from each heel angle measuring device, a moment-tangent plot was formed to compare the heel angle tangents and moments to validate the model design. Recalling from the previous chapters, the moments and heel angle tangents should plot as a straight line. Figure 26 is an illustration of the V-hull model results from the recorded data.

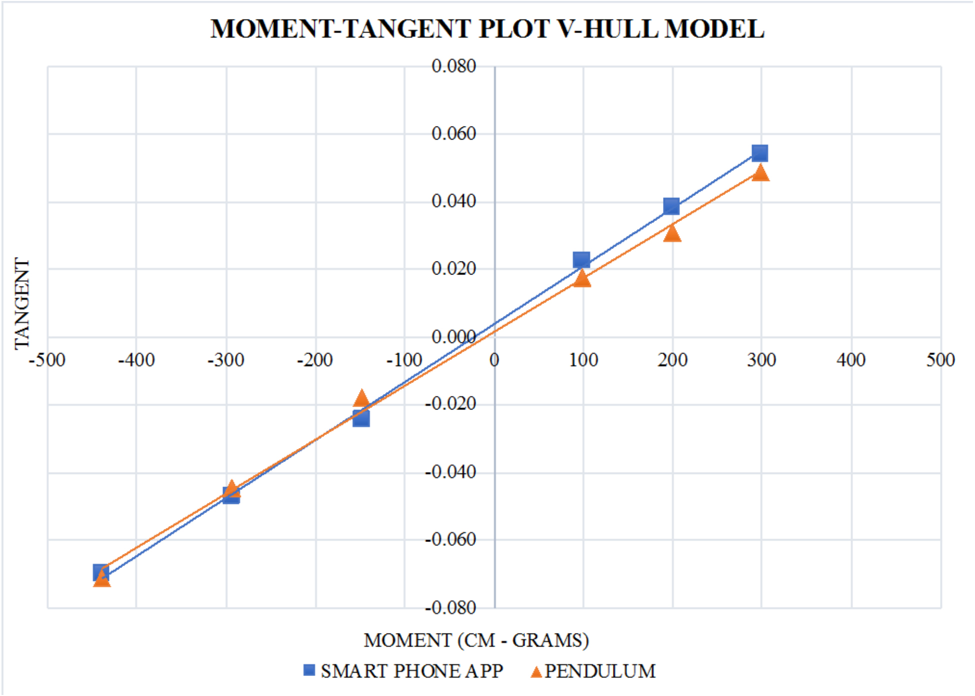

Figure 26. Illustration of the Moment-Tangent Plot from the V-Hull Model.

Based on the results seen in Figure 27, the experiment was successful since the pendulum and smartphone devices plotted as a straight line. It is worth noting that the results were not symmetrical about the y-axis. This is a result of the “toy” nature of the models that were not built to detailed specifications. The proceeding moment-tangent plots for the miniature models were also not symmetrical for the same reason. Next, the results were taken to calculate six separate GM calculations which were then averaged and compared. Figure 27 are the six separate GM calculations for each device used during the experiment. The red dashed line illustrates the mean GM from both devices, which was approximately 15.7 cm.

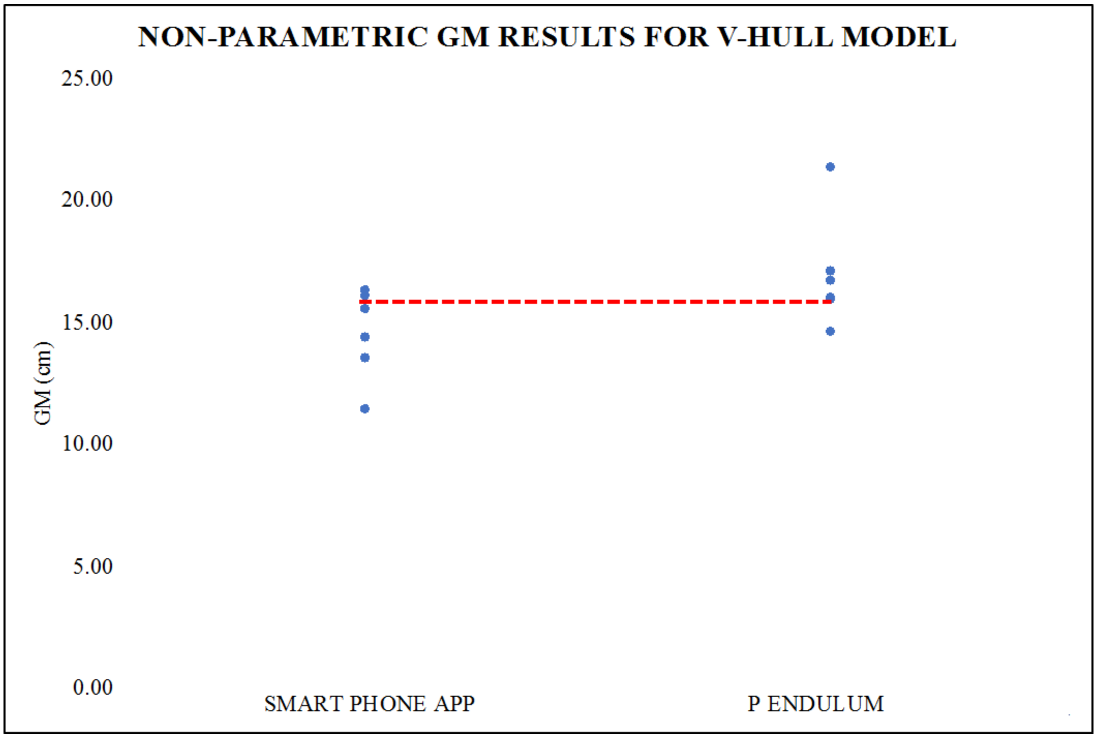

Figure 27. Non-parametric GM Results from V-Hull Model Experiment

Analyzing the results in Figure 27, approximately half of the data points from each device overlapped indicating there was agreement among the devices. Table 8 is the numerical breakdown of the GM results and how they compared.

Table 8. Non-parametric GM Results from the V-Hull Model Experiment

	Smartphone (cm)	**Pendulum (cm)**
Mean	14.53	16.93
Standard Deviation	1.84	2.31
Median	14.94	16.34
Minimum	11.44	14.60
Maximum	16.26	21.31
Range	4.82	6.72

Looking at the results in Table 8, the smartphone yielded the best overall results. The standard deviation for the smartphone was approximately 0.5 cm better than the pendulum indicating overall better precision. The range between the smartphone and pendulum GM results were a little less than 2.0 cm. Furthermore, a two-sample t-test was conducted for the six GM calculations that the devices produced. Assuming equal variances and a hypothesized mean difference of zero, there was approximately 93% confidence that there was a statistical difference between both sets of data. This high level of significance was expected since half of the data points in Figure 28 did not overlap.

2. Pontoon Hull Model

A pontoon boat design is a popular hull form found on SPVs that incorporates two independent buoyancy chambers that the vessel rides on. These types of hulls generally have shallower drafts and wider beams. This enables them to sail in higher sea states due to the increased stability and traverse areas with shallower water. This experiment was set-up in the same manner as the V-hull and followed the same procedures for recording heel angles from the smartphone and pendulum deflections. Figure 28 is a picture of the pontoon model prior to beginning the experiment with the pontoons circled in red.

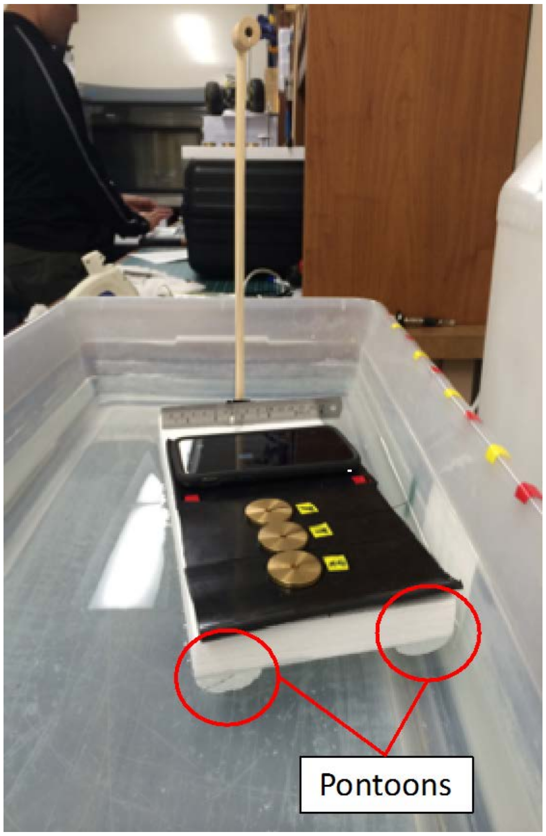

Figure 28. Picture of the Pontoon Hull Model in the Even Keel Position.

The principle characteristics of the pontoon model in Figure 28 are presented in Table 9.

Table 9. Principle Characteristics of the Pontoon Model

Principle Characteristic	**Dimension**	**Unit**
Length Overall	30.4	cm
Beam	15.0	cm
Depth (including pontoons)	4.0	cm
Displacement	492.2	g
Pendulum Height	27.5	cm

Following the same established procedure to collect data, six weight shifts were conducted to induce three heel angles to the port and starboard side of the model. The model required three 20-gram weights to be shifted. Each weight shift produced approximately one degree of heel. There was no other error noted during the experiment. The data collected was transformed into a moment-tangent plot to analyze the validity of the experiment. Figure 29 is a plot of the moments and heel angle tangents from the data collected during the experiment.

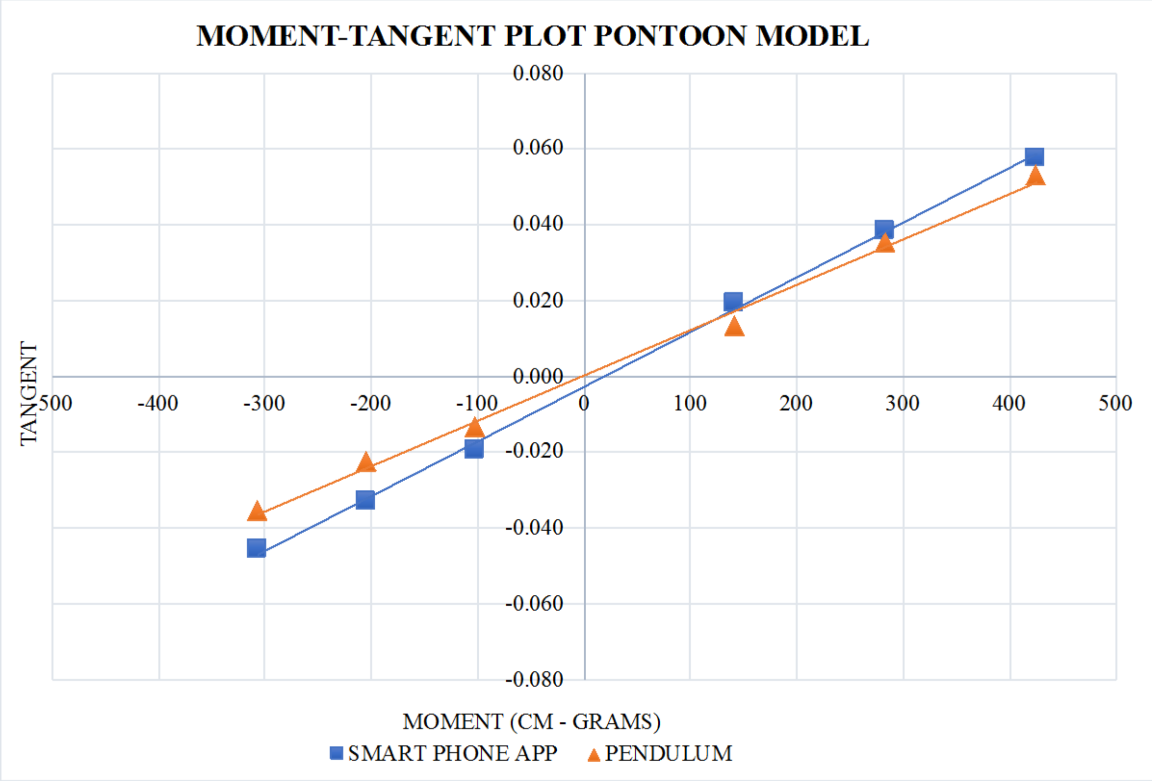

Figure 29. Illustration of the Moment-Tangent Plot from the Pontoon Hull Model.

Visually observing the plot from Figure 29, both devices were linear with one faulty reading from the pendulum. The faulty reading was the first weight shift to the starboard side or where the first plotted point in the first quadrant has a moment of 130 cm-grams and a tangent of 0.010. The smartphone plotted points all touch the linear line indicating consistent results. It is suspected that the faulty reading for the pendulum was due to the excessive oscillations during the experiment which caused the observer to incorrectly average the total period. In addition, based on the vertical spacing between plotted points, there were discrepancies in the heel angles recorded between the smartphone and pendulum. This could have occurred due to the position of the smartphone or pendulum along the centerline, error due to small water disturbances in the tub used, or human error when reading the deflections. Next, the data collected was used to calculate six separate GM values for the two separate devices. Figure 30 are the GM calculations from each device used during the experiment. The red dashed line illustrates the mean GM from both devices which was approximately 15.7 cm, the same as the V-hull model.

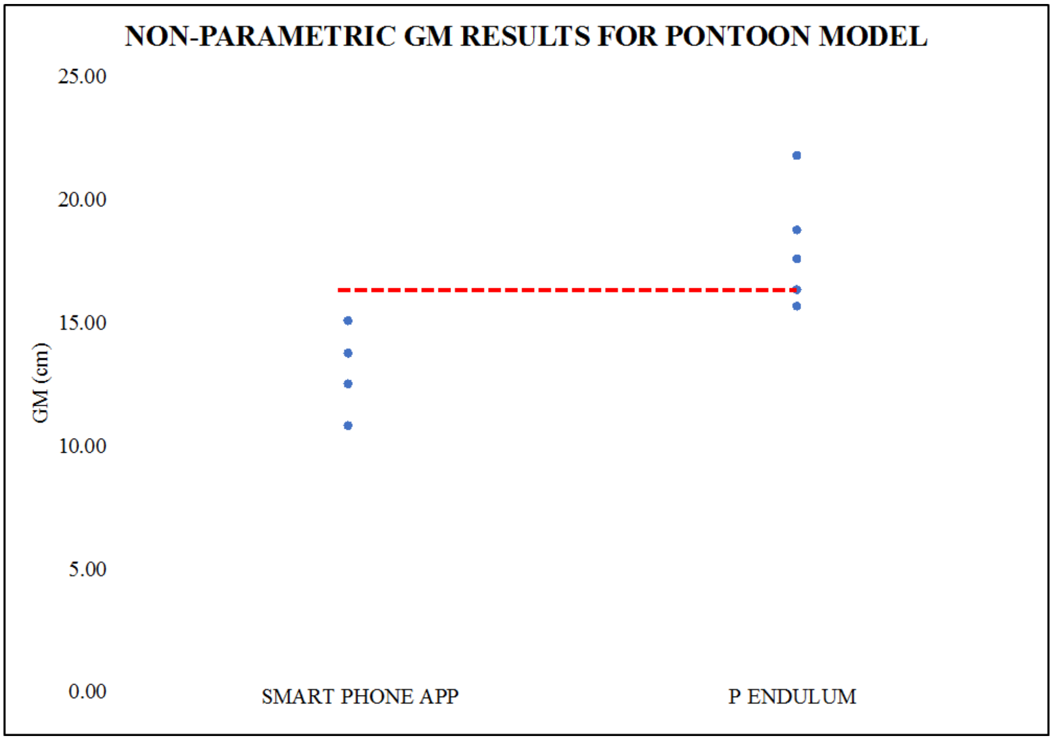

Figure 30.Non-parametric GM Results from Pontoon Model Experiment

Based on Figure 30, there was no overlap in the data indicating an accuracy difference between both devices. To further examine the GM results, Table 10 is the numerical breakdown of the GM calculations from the data collected.

Table 10. Non-parametric GM Results from the Pontoon Model Experiment

	Smart Phone App	Pendulum
Mean	13.67	17.71
Standard Deviation	1.74	2.26
Median	14.35	16.93
Minimum	10.79	15.61
Maximum	15.03	21.73
Range	4.23	6.12

The results from Table 10 are very similar to those found in the V-hull model analysis. The precision for the smartphone yielded better results than the pendulum by approximately 0.5 cm and nearly 2.0 cm lower in the range between the minimum and maximum values. There was also a two-sample t-test run on both sets of GM calculations to determine whether there were significant differences between both samples using a 90% confidence interval. The t-test resulted in 100% level of significance meaning the null hypothesis of assuming there is no difference between heel measuring devices would be rejected.

3. Barge Hull Model

The last model used for the experiment was a rectangular shaped barge model. The barge design is not common in the SPV industry and generally is used to transport large amounts of cargo through inter-coastal waterways via tug boats. Unlike the V-hull and pontoon models, the entire barge underwater hull interacts with the water. This means that the model has additional buoyant forces that would enable it to carry heavier loads. Once again, the same procedure was followed of shifting three 20-gram weights to the port and starboard side of the model while recording heel angle and deflection measurements. Figure 31 is a picture of the barge model prior to beginning the experiment with the test weights in the even keel position.

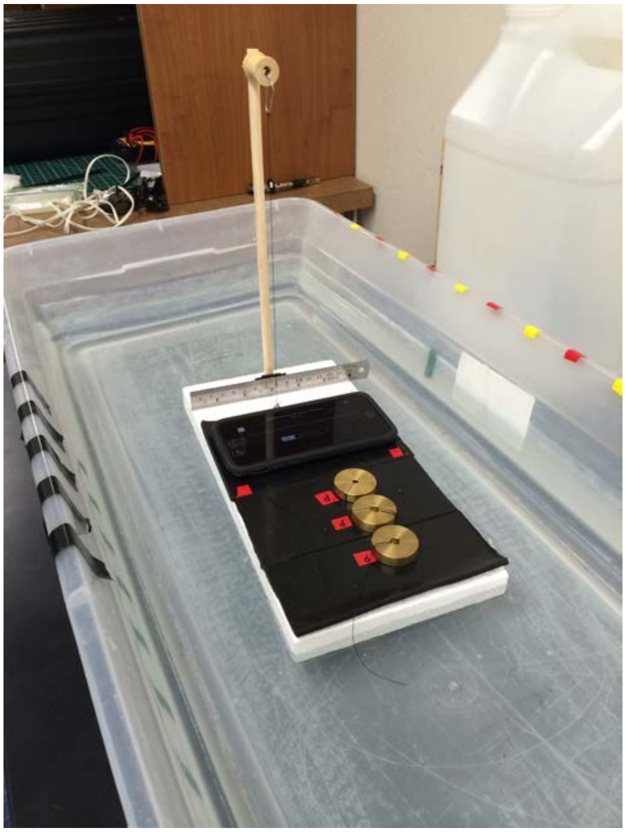

Figure 31. Picture of the Barge Hull Model in the Even Keel Position.

The principle characteristics of the pontoon model in Figure 31 are presented in Table 11.

Table 11. Principle Characteristics of the Barge Model

Principle Characteristic	Dimension	Unit
Length Overall	30.4	cm
Beam	15.1	cm
Depth	2.5	cm
Displacement	456.5	g
Pendulum Height	27.0	cm

Based on the data collected, the moments and heel angle tangents were plotted to validate the experiment. Figure 32 is an illustration of the moment-tangent plot for the barge hull model.

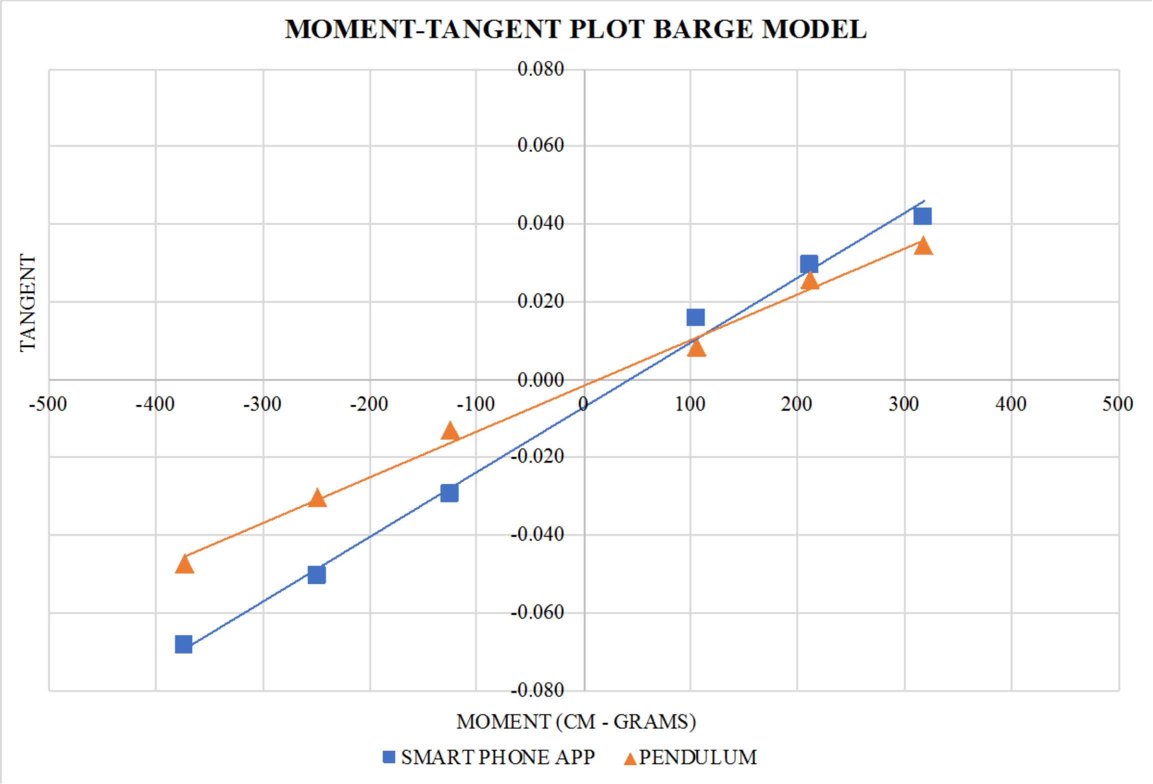

Figure 32. Illustration of the Moment-Tangent Plot from the Pontoon Hull Model.

Based on the moment-tangent plot in Figure 32, both devices plotted as straight lines but the difference in tangents between plotted points at each weight shift was the greatest out of all three models. The weight shifts that occurred on the port side of the model produced better results than the weight shifts on the starboard side. This was based on the plotted points on the right side of the graph not touching the linear line. Figure 33 are the GM calculations from each device used during the experiment. The red dashed line illustrates the mean GM between both devices which was 14.7 cm, approximately one centimeter lower than the V-hull and pontoon model.

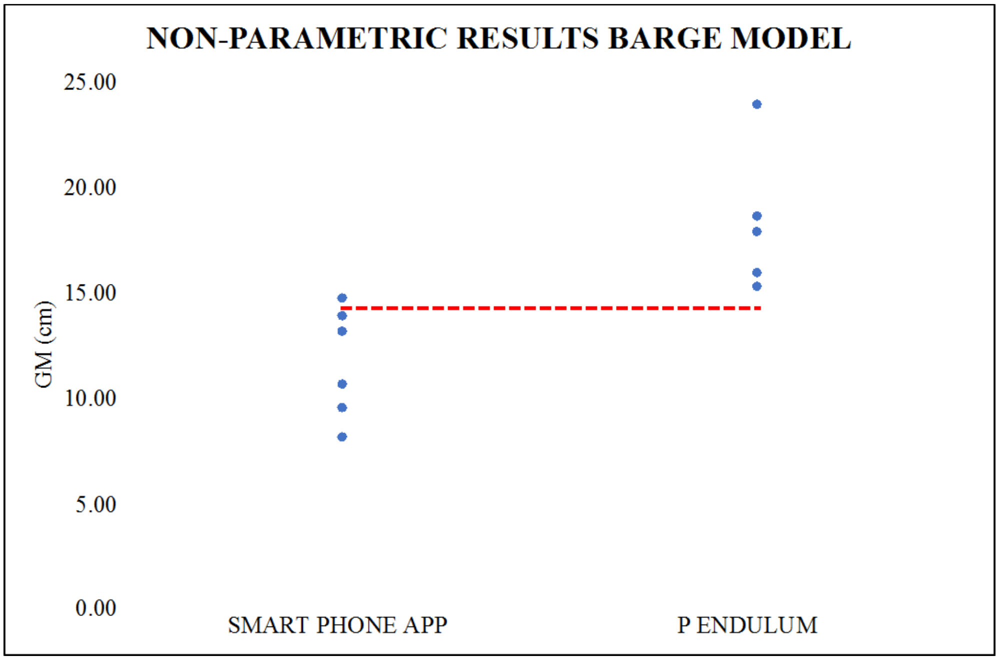

Figure 33. Non-parametric GM Results from Pontoon Model Experiment

The results in Figure 33 indicate that there were significant differences between the heel angle measuring devices. This is based on the lack of overlap among the data points. Furthermore, the GM calculations appear to be normally distributed since there does not appear to be skewness in the data and no apparent outliers. To further examine the GM results, Table 12 is the numerical breakdown of the GM calculations from the data collected.

Table 12. Non-parametric GM Results from the Barge Model Experiment

	Smartphone (cm)	**Pendulum (cm)**
Mean	11.62	17.87
Standard Deviation	2.63	3.19
Median	11.81	16.88
Minimum	8.09	15.19
Maximum	14.69	23.81
Range	6.60	8.62

The results from Table 12 has similar standard deviations and differences in the range of minimum and maximum as those found in the V-hull and pontoon models. The precision for the smartphone yielded the best results by approximately 0.5 cm and nearly 2.0 cm lower in the range between the minimum and maximum values. There was also a two-sample t-test run on both devices to detect significant differences in the data. The t-test resulted in 100% level of significance meaning the null hypothesis of assuming there is no difference between heel measuring devices would be rejected based on a 90% confidence level assuming no hypothesized mean difference.

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VII. CONCLUSIONS

This chapter includes conclusions regarding the problem definition, analysis for determining significant factors during the IEs, and overall results. In addition, it provides recommendations to the established regulations governing inclining experiments and future work recommendations.

A. CONCLUSIONS

The purpose of this research was to use the systems engineering process to examine the feasibility of conducting IEs without using pendulums as the primary device. From the analysis conducted, the type of device used provided the highest level of significance in all five vessels regarding GM determination. This meant the null hypothesis of assuming there was no statistical difference between pendulums and digital inclinometers was rejected. All other factors and their interactions did not provide the same pattern and their order appeared to be random. Except in vessel four, accuracy was not a strong predictor affecting GM calculations.

To further analyze the strong statistical differences among devices, the non-parametric data for the GM calculations that each device produced was observed. This identified any outliers or skewness within the data. It provided insight if any device disproportionately shifted the GM which would account for the strong level of significance in each DOE. Three out of the five vessels each had one device that had a wide range of GM results, but the median values were mostly consistent across all three vessels. There was no clear indication that one device was superior to the other during each IE.

Finally, three separate miniature models were constructed by the author to conduct IEs in a controlled environment. The three models each had different hull configurations to control the external factors that were unknown for the DOE analysis. The devices used for each model were a smartphone and pendulum. After conducting IEs on each model, it was clear that the smartphone provided overall better precision, but without specific design calculations, the author was unable to state which device was more accurate in the calculation of GM.

B. RECOMMENDATIONS

Based on the data provided in the MSC submittals and the experiments conducted with the miniature models, it is recommended that the current regulations remain intact. This means that at least one pendulum should be used for IEs until further research is conducted and analyzed. In both sets of analysis, the null hypothesis that there are no statistical differences among measuring devices was rejected. Until consistent results are obtained from a larger sample size, it is recommended that the IMO and USCG leave the regulations unchanged.

C. FUTURE WORK

Future work for personnel researching this topic should include collecting and analyzing IE data from local shipyards that conduct stability tests on commercial or military vessels. The submittals to MSC that were used for this thesis do not contain a myriad of external factor data that may have influenced the overall error for each IE. By physically witnessing IEs at shipyards, additional data could be recorded such as: weather conditions, tautness of the lines from the ship to the dock during each weight shift, location of measuring devices relative to the vessel, approximate distance off centerline, and number of personnel performing the measurements. In addition, other factors previously not identified could be observed and analyzed.

Furthermore, constructing more miniature vessel models with different hull configurations could also be carried out. Prior to conducting the experiment, the height of metacenter (M) and center of gravity (G) could be calculated using naval architecture software or manual calculations so that the accuracy of the test results could be further analyzed. The experiment performed by the author was limited to only examining the precision between devices. In addition, the miniature vessel model results could be analyzed via design of experiment (DOE) as was done in the previous chapters.

While the results of this thesis consistently show differences between heel measuring devices, it is feasible that with more data and using the spreadsheet model developed by the author could yield better results.

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