THE PENNSYLVANIA STATE UNIVERSITY
SCHREYER HONORS COLLEGE

SCHOOL OF ENGINEERING

A COMPUTATIONAL ANALYSIS OF THE CAPSIZE OF THE *S/V CONCORDIA*

MATTHEW DONALD ERDMAN
SPRING 2013

A thesis
submitted in partial fulfillment
of the requirements
for a baccalaureate degree
in Mechanical Engineering
with honors in Mechanical Engineering

Reviewed and approved* by the following:

William Lasher
Professor of Mechanical Engineering
Thesis Supervisor

Amir Khalilollahi
Assistant Professor of Mechanical Engineering
Honors Adviser

* Signatures are on file in the Schreyer Honors College.

ABSTRACT

On February 17th, 2010, the Sail Training Yacht *Concordia* capsized off the coast of Brazil. The Transportation Safety Board (TSB) of Canada issued a Marine Investigation report (M10F0003) investigating the causes of the knockdown. One of the possibilities discussed was the occurrence of a downward component to the wind due to a microburst. In a draft of the report they concluded that there was insufficient evidence of a microburst to support that possibility, and suggested that the knockdown could be possible without the presence of a vertical component of wind. The captain of the *Concordia* at the time of the incident issued a response challenging this conclusion. In his response, the captain outlined supposed deficiencies in the report, insisting that the ship could not have capsized without a vertical component to the wind.

The purpose of the present work was to investigate whether the *Concordia* could have capsized without a vertical wind component. It was initially hypothesized that the topsails, which were at an angle of attack to the horizontal wind and thus created a downward force similar to that of an airfoil, could have contributed to an additional heeling moment that caused knockdown. A CFD analysis showed that the sail force model used in the TSB report is inaccurate and the forces decreased with heel angle at a much faster rate than predicted. It is hypothesized that this was due to the hull “shielding” the sails from incoming wind, drastically decreasing the heeling moment as the heel angle approached 90°. It was concluded that the horizontal wind present in the squall was incapable of knocking down the ship, and thus at least some vertical component of the wind was present in the knockdown of the *Concordia*. It is recommended that agencies investigate the dangerous role that vertical wind can play in the capsize of sailing vessels.

TABLE OF CONTENTS

LIST OF FIGURES

ACKNOWLEDGEMENTS

I would like to express my utmost gratitude to all of my professors and instructors while at Penn State Erie, The Behrend College. Without their help and encouragement, none of this would have ever come to fruition. I would particularly like to thank Dr. William Lasher, who has certainly gone above and beyond to assist me in this journey. I would also like to thank both of my parents for encouraging me to achieve my full potential.

Chapter 1

Background of the *S/V Concordia* and Summary of the Incident

The S/V *Concordia*, classified as a Sail Training Yacht and owned by West Island College International, was built in Szczecin, Poland in 1991 and is shown in Figure 1. The overall length of the vessel was 57.50 meters, and it consisted of three masts and up 16 sails. On the foremast, or front-most mast, 5 square sails could be flown. From top to bottom, these sails included the Royal, Topgallant, Upper Topsail, Lower Topsail, and Course Sails. The main, or middle mast, supported the Main Sail and the Main Topsail, while the Mizzen, or stern, mast support the Mizzen and Mizzen Topsail. The Royal, Topgallant, and Main Staysails could be flown between the main and fore masts, while the Flying Jib, Outer Jib, Inner Jib, and Fore Staysail could be flown from the foremast towards the bow of the vessel. The full sail configuration can be seen in Figure 1-1 below.

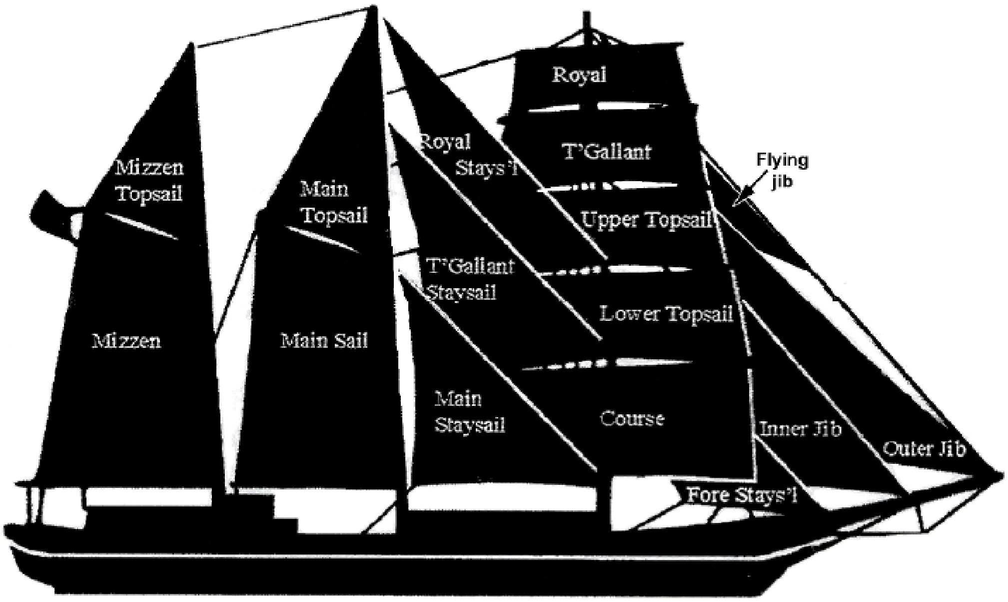

Figure 1-1: Full sail configuration of the *Concordia*[2]

The *Concordia* was chartered to the West Island College International for Education and Sail Training Limited, which is a Nova Scotia-based Corporation. Its main purpose was educational; students would assist the crew in sail maneuvers and watch duties, as well as attend classes. Although day-to-day operations would vary, there were normally 6 students on watch at any time during the day.

The *Concordia* left Recife, Brazil on February 8, 2010 with a destination of Montevideo, Uruguay. There were 48 students, 8 faculty members, and 8 crew members on board. At departure, the *Concordia* had a forward draught of 3.8 meters and an aft draught of 4.0 meters.[2] On the morning February 17, 2010, the captain, having been informed of an upcoming storm, lowered sails to their last configuration before capsize. At this time, only the Mizzen, Main Sail, Main Staysail, Upper Topsail, Lower Topsail, Fore Staysail, and Inner Jib were unfurled, as shown in Figure 1-2, with the Mizzen partially unfurled.[2]

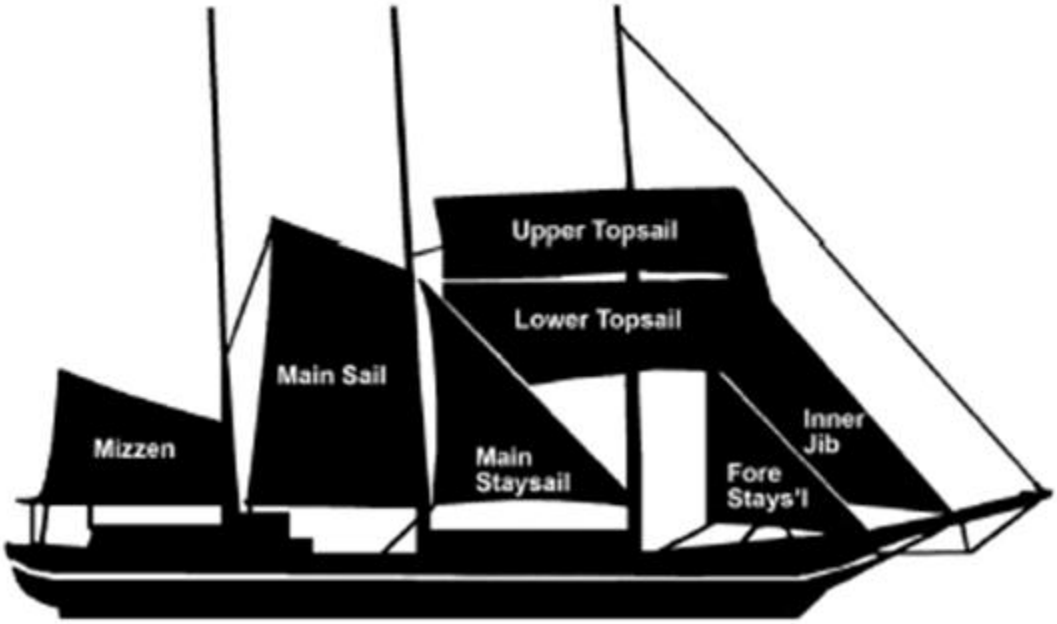

Figure 1-2: Sail configuration of vessel[2]

From 1300 to 1415, the ship registered a heel angle of approximately 10° with an apparent wind speed of around 18.8 knots. At 1420, the second officer observed that the heel angle of the vessel was approximately 23° and that the apparent wind speed was approximately 23 knots. This was chosen as the most reliable condition to use as a basis for confirming the CFD model. According to the TSB report, the apparent wind continued to increase, and at 1423 the winds was 27.9 knots.[2] The TSB report then claims that the sailing vessel, at this point, passed it's critical point and moved continuously from a heel angle of 38° to 68°, pausing momentarily, then continuing to heel to an angle of 88°.[2] The captain of the vessel, however, claims that there was no pause in the continuous motion of the heeling vessel as it heeled from 38° to 88°. After reaching an angle of 88°, downflooding occurred, leading to the eventual capsize of the vessel. Flooding through unsecured openings in the deckhouse doors quickly occurred and the knockdown was completed.

After donning wetsuits and cutting loose the two 20-person rafts, all crew members, students, and faculty loaded into the rafts. On February 19, 2010, the survivors were rescued by two ships and then taken to Rio de Janeiro, Brazil. All passengers and crew members survived the ordeal, and only one of them sustained major injuries (broken bones).

Chapter 2

Analysis and Conclusions from the Transportation Safety Board Report

The Canadian Transportation Board found several contributing factors towards the capsize of the *Concordia*. In order to address this, however, it is first important to know a little terminology. The righting arm is a tool that can be used to calculate the righting moment of a vessel by multiplying by weight of the ship in order to determine the righting moment. Any vessel is at equilibrium when the righting moment is equal to the heeling moment. As a ship heels, its righting moment increases until the shift of its center of buoyancy stabilizes the vessel. This continues until the righting moment reaches a peak, at which point it begins to decrease. In *Concordia's* case, as the deckhouses are submerged, the vessel experiences a sharp increase in righting arm. This is due to the fact that a sealed deckhouse provides a buoyant force on the submerged side. In the case of the *Concordia*, though, all of the deckhouses where not properly sealed. As a result, the TSB suggests a new righting arm curve, seen in Figure 2-1 below. The new suggested righting arm is seen as the solid black line, while the righting arm that would be seen if all of the deckhouses were properly sealed is seen as a dotted line.

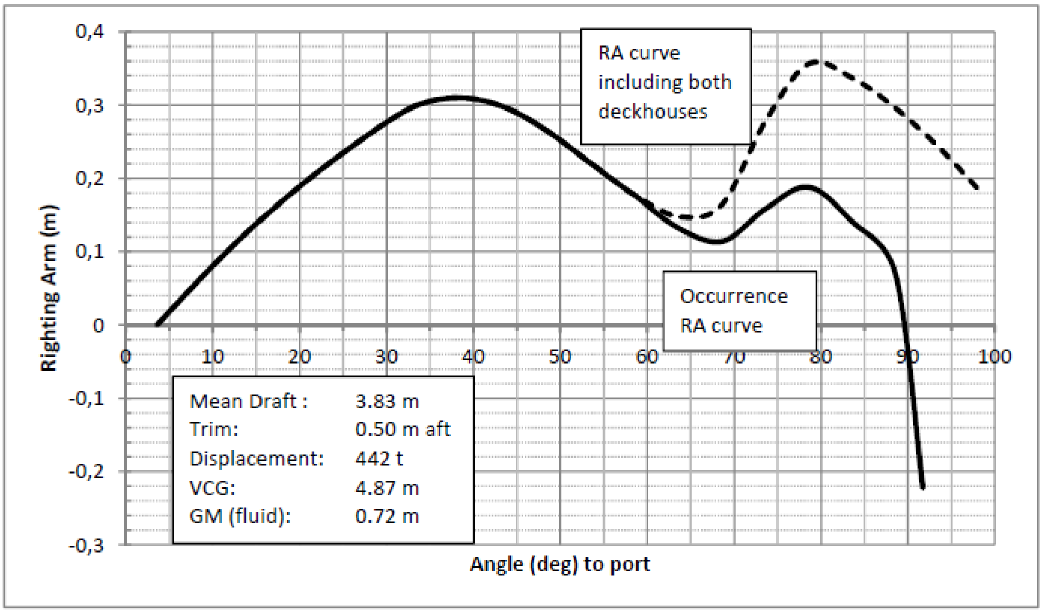

Figure 2-1: Figure 2-1: Righting arm of the vessel[2]

For analysis of the horizontal winds, TSB report used a model which assumes that the heeling moment will decrease as the heeling angle increases by a factor of $\cos^{1.3}(\theta)$, where θ is the heeling angle. This decrease in heeling moment, commonly referred to as roll-off, occurs because the angle between the horizontal wind and the sails is changing. As the wind and sails become more parallel, the force on the sails decreases, thus decreasing the heeling moment. This roll-off model (specifically the exponent of 1.3) is used by the Maritime and Coastguard Agency (MCA)[2], an British agency that works to prevent sailing accidents and deaths.. The MCA is also directly responsible for British maritime law and safety policy. Using the MCA model, the TSB report finds that with *horizontal* winds, wind speeds of 27 to 37 knots could have caused the vessel to heel to an angle of 68°.[2] In order to understand this conclusion, it should be recalled that the vessel will come to heel at the angle at which the heeling arm and righting arm intersect. Figure 2-2 below depicts a righting arm and wind heeling arm. In this case, the vessel would be resting at approximately 68°. Although the vessel may be at or close to equilibrium in the range of 40°-68°, the worst case scenario is assumed. Thus, under this scenario, a horizontal 27 to 37 knot wind would only be enough to cause the vessel to heel to 68°.

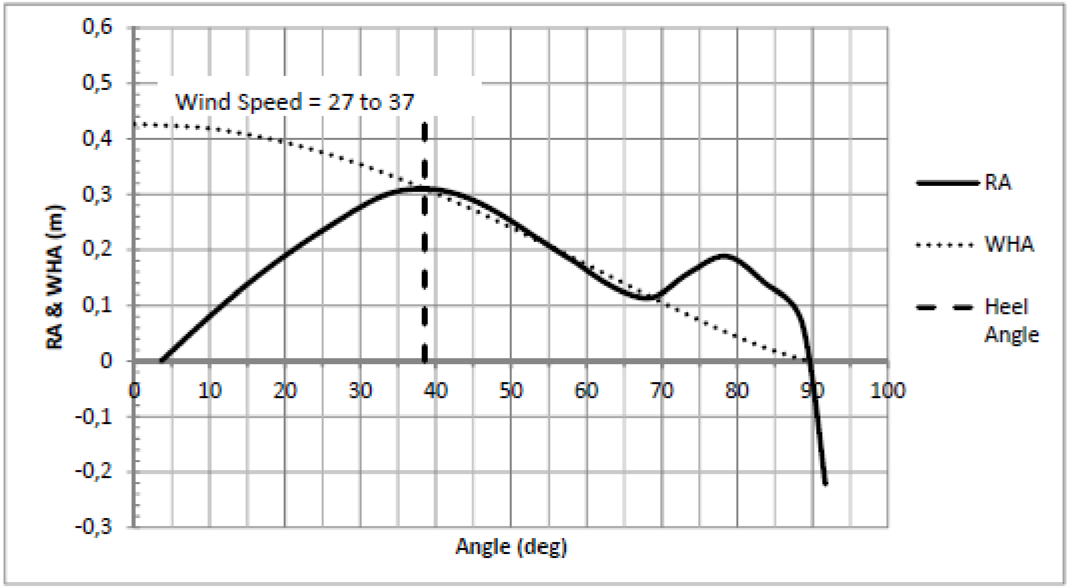

Figure 2-2: Wind heeling arm and righting arm[2]

The draft of the TSB report initially concluded that the horizontal winds were sufficient to cause the ship to capsize, assuming that downflooding would cause the rest. Following a written response from the Captain, the TSB then considered the effect that winds inclined from the horizontal would have on the ship.[2] An inclination of a certain angle of wind can be approximated by shifting the heeling arm curve horizontally by that angle as shown in Figure 2-3. Although this is an unproven approach, it is correct to account for the increase in heeling arm that results from a downward component of wind. Figure 2-3 depicts the new wind heeling arm that the TSB suggests would result from a 30° inclined wind.

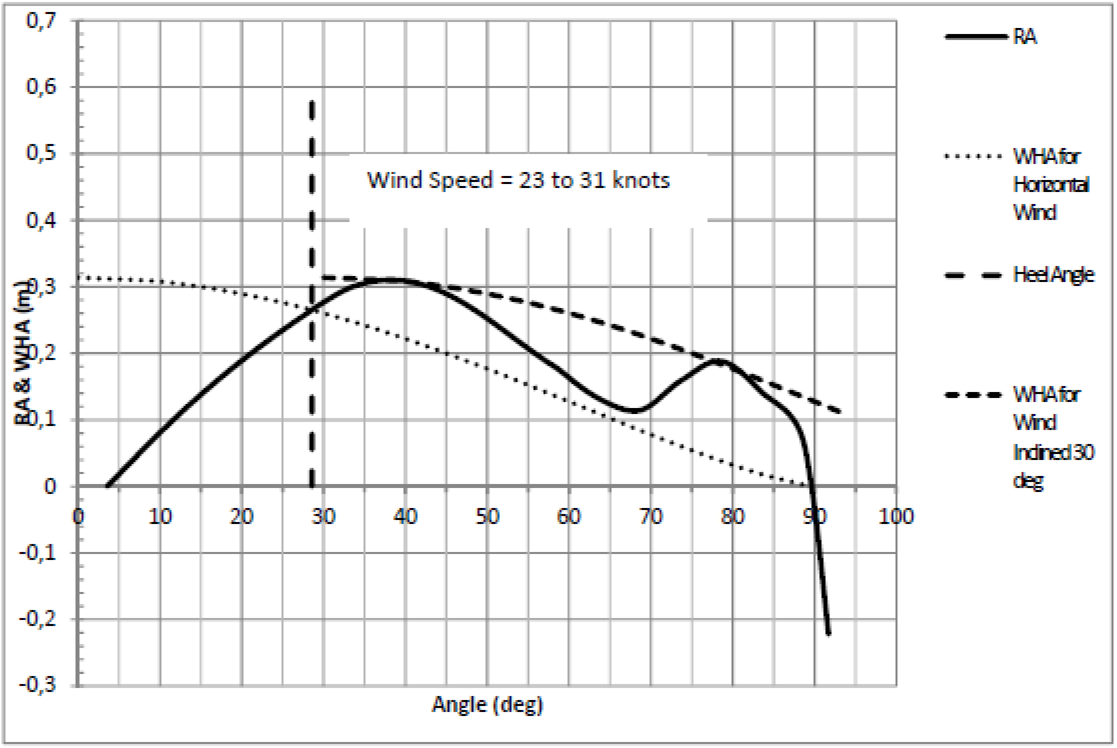

Figure 2-3: TSB Occurrence righting arm and wind heeling arm[2]

In this case, the wind heeling arm surpasses the increase in righting arm provided by the deckhouse. As a result, this suggests that the vessel will fully capsize. Based on this analysis, the TSB report concluded that winds inclined at an angle greater than 30° would create a heeling moment sufficient to completely knock the vessel down.[2] Although the TSB acknowledged this, it also mentioned that no microbursts were known to have occurred and that the vertical component was only a possible explanation.

Chapter 3

Captain's Response

In response to the draft TSB report, the captain of the *Concordia* issued a statement addressing his grievances. The captain insists that "The TSB Report has erroneously discounted the central role of the most likely cause of the knockdown: a microburst squall." The captain goes on to suggest that the capsize was not a result of insufficient knowledge of the stability of the vessel, as implied by the TSB. Instead, the knockdown was a result of vertical winds from a microburst and the subsequent downflooding of the open ship. He claims that the effects of downward flow have not been properly investigated in the heeling of a sailing vessel. As a result, vessels that would be deemed stable could in fact be unstable in the presence of a vertical component of wind. He proposed that the TSB investigate microbursts and downbursts and better determine their effects on the stability of sailing vessels. Although the TSB report claims that no evidence of a microburst exists, the captain argues that crew testimony and that of an independent meteorologists suggest that a moderate microburst occurred. The TSB defines a microburst as one in which the wind speed is at least 50 knots; however, experts have suggested that numerous microbursts can occur at speeds well below this threshold.

The captain also challenged the TSB's effect of downflooding on the vessel. Since the vessel remained at a heel angle of about 15 minutes before fully capsizing, it is improbable that the downflooding caused the capsize.

Chapter 4

Overview of the Model

In order to best model this situation, it was determined that the CFD program Fluent would be used to determine the heeling moments produced by the sails of the sailing vessel. The heeling moment of the hull was calculated using both Fluent and using a simple drag coefficient approach. Since both methods returned similar results with negligible differences relative to the overall heeling moment, the CFD results for the heeling moment of the hull were used. In order to account for the spars and rigging, the simple drag coefficient approach was used. This will be discussed shortly.

A major area of concern existed since the wind speed measured by the anemometer will differ from the free stream wind speed used in the simulation. However, since the wind speed measured at the anemometer would vary directly proportional to the input wind speed, the model was run with a uniform input velocity of 12.09 m/s (23 knots). It was then assumed that the resulting heeling moments would vary proportionally with the square of the velocity. In this way, it was possible to scale the computed heeling moment to an actual heeling moment at any wind speed.

Chapter 5

Creation of the Model

The hull of the ship was created in DesignModeler. Since the exact dimensions of the ship were not supplied, the hull was scaled from the hull diagram provided in Appendix B of the TSB report. This model included the two deckhouses located on deck. The sails themselves were modeled as surfaces using the dimensions scaled from Figure 1 of the TSB report. The areas of these sails were made to match the areas of the sails at time of capsize. These areas can be found in the appendix of the Stability report for the *Concordia*.[3] The sails were then placed above the hull in their corresponding regions. The hull and the sails were place in a volume that was 300 meters wide, 300 meters long and 100 meters high in order to allow room for the flow to fully develop. The volume of the hull was removed, leaving fluid volume. The sails were converted to solid surfaces by combining them with the fluid volume as a new part. After that, the model was ready for simulation.

Since flow around the model was turbulent, the realizable k-epsilon model was used. The pressure under-relaxation factor remained at 0.3, while the momentum and all turbulent under-relaxation factors were 0.4. The discretization schemes for momentum and turbulence terms were set to QUICK (Quadratic Upstream Interpolation for Convective Kinematics). This ensured that the solution was 3rd order accurate and eliminated false diffusion. Additionally, the six boundary surfaces, including the velocity inlet and outlet conditions were set. The inlet velocities were specified according to the known 88.9° apparent wind angle and 12.09 m/s windspeed. In order to avoid backflow, the sides of the model were also specified to have this wind velocity. A pressure outlet was used at the exit of the domain. A symmetry boundary was used as the water surface.

The model was then verified, as discussed in Chapter 6. After the verification of the model was complete, the angles at which the sails were oriented were varied. By slightly changing the angles of the sails, it was observed that slight deviations in their angle made very little difference in the heeling moment of the vessel. This was important, since the angles of the sails were estimated and not known with 100% accuracy. Because slight inaccuracies in these angles did not have a large influence on the heeling moment, it was concluded that the approximation was sufficient. The model was then run at different heel angles. The simulations started with the ship without heel, and for each computation the heel angle was increased by 10°. In this way, it was possible to generate a heeling moment versus heeling angle plot, which was used in the next chapter. For computing the heeling moment due to the spars and rigging, a simple drag coefficient analysis was used. The heeling moment was calculated from:

$$Heeling\ Moment = C_s \frac{1}{2} \rho v^2 (A\bar{y})$$

The coefficient of drag (Cs) was 1.13,[1] the density (ρ) was 1.225 kg/m^3, the first moment area (Aȳ) was 1,025 m^3 from the TSA report, and the velocity was 12.09 m/s. This heeling moment was reduced by cos(θ) in order to account for the reduced projected area. The results of this analysis were then added to the heeling moment computed from the CFD analysis.

Chapter 6

Verification of the Model

At 1420 on February 17, the apparent wind speed was 23.5 knots at an apparent wind direction of 88.9°. This corresponded to a measured heel angle of 23°. In order to ensure the validity of the model, the CFD analysis of this scenario was performed. At the reference velocity of 12.09 m/s, the heeling moment of the hull as calculated by CFD was approximately 77 kN-m. The hand calculations estimated a heeling moment of 68 kN-m, so it was assumed that the model for the hull was reasonably accurate, since this moment was minor compared to the heeling moment from the sails. The combined heeling moment of all the sails computed from CFD was 535 kN-m. The simple drag calculations for the spars and rigging added a heeling moment of 96 kN-m, for a combined heeling moment of 708 kN-m. With an inlet velocity of 12.09 m/s, the anemometer, located at the top the foremast, would have measured a wind speed of 10.79 m/s (21.0 knots). It is important to note that, since the anemometer only reads velocities in a plane perpendicular to its axis, this 10.79 m/s is the velocity of the wind in a plane inclined at 23°. In order to calculate this number, the CFD wind velocity at the point atop the foremast was translated onto the 23° inclined plane

The TSB report provided a righting arm curve shown in Figure 2-2 of this thesis. At an angle of 23°, the righting arm is 0.22 meters. Since the mass of the loaded vessel was approximately 442 megatons, the righting moment at 23° was calculated to be 954 kN-m.

As mentioned earlier, the anemometer is located atop the foremast. As the wind encounters the sails and hull of the vessel, the flow field is altered. Therefore, the anemometer does not see the input windspeed. The input wind velocity and the windspeed that the anemometer reads are assumed to be proportional, though. In that way, it is possible to predict what the anemometer will see, given an inlet velocity.

For the vessel to be stable at 23°, the heeling moment and the right moment must be equal. According to the CFD model, the righting moment provided 135% of the computed heeling moment. This was based on an inlet wind velocity was 23.5 knots. Assuming that the heeling moment varies with the velocity squared, it is possible to adjust this inlet velocity in order to find adjust the heeling moment so that it is equal to the righting moment. As a result, the reference wind required for the correct heeling moment can be calculated as 26.2 knots. As mentioned in the previous paragraph, the anemometer does not read the inlet velocity. Given the ratio between inlet velocity and anemometer measured windspeed, it was calculated that the anemometer would measure a windspeed of 23.4 knots in order for the vessel to experience equal righting and heeling moments. Since this is very close to the observed windspeed of 23.5 knots that the *Concordia* actually experienced, it is concluded that the model is accurate with only a small degree of error.

Chapter 7

Results and Discussion

Using the validated model, the heeling moment was calculated for various heel angles. The results are shown below:

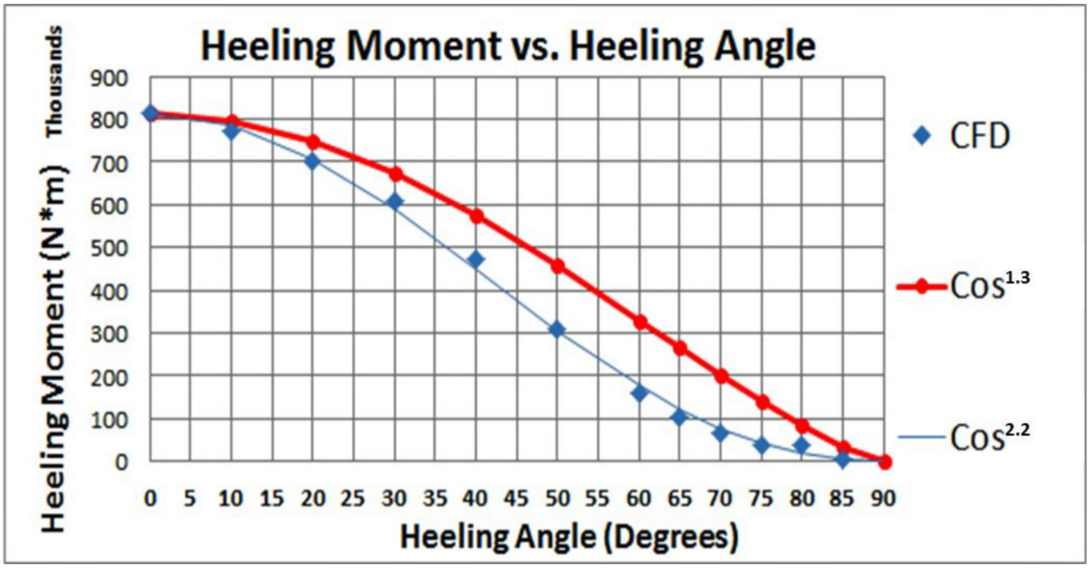

Figure 7-1: Experimental results for the heeling moment of the vessel

The roll-off model for these results was calculated to fit the form of $HM = HM_0 \cdot \cos^n(\theta)$. In the MCA roll-off model, it is assumed that the exponent n was 1.3. However, in this case, the CFD results show that the exponent is approximately 2.2. Since there is a significant difference between these two models, it is suggested that the MCA model is not suitable in this case. The heeling moment appears to decrease to a much higher rate as heeling angle decreases.

Originally, it was hypothesized that the air would cause the topsails to act like an airfoil, as suggested in Figure 7-1 below:

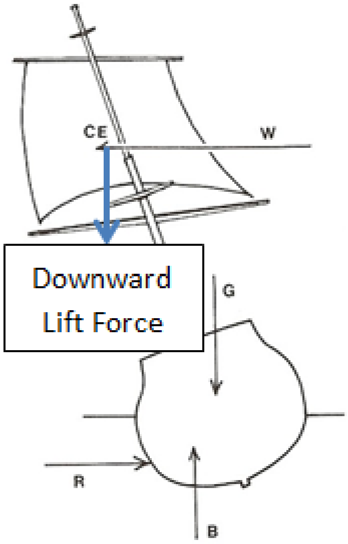

Figure 7-2: Downward force on vessel

This proved not to be the case. Although the downward force did in fact contribute more as the heel angle increased, it was discovered that the roll-off actually decreases at a faster rate than the the TSB model. Thus, the downward force did not significantly decrease the original roll-off rate.

The reason that the roll-off increases so quickly in this case is probably due to shielding of the sails by the vessel. As shown in Figures 7-2 through 7-4, as the heel of the vessel increases, the sails fall into the dead zone behind the hull. By the time the ship reaches 70°, much of the sail area is in a low velocity region (shielded from the hull), resulting in a significantly reduced heeling moment.

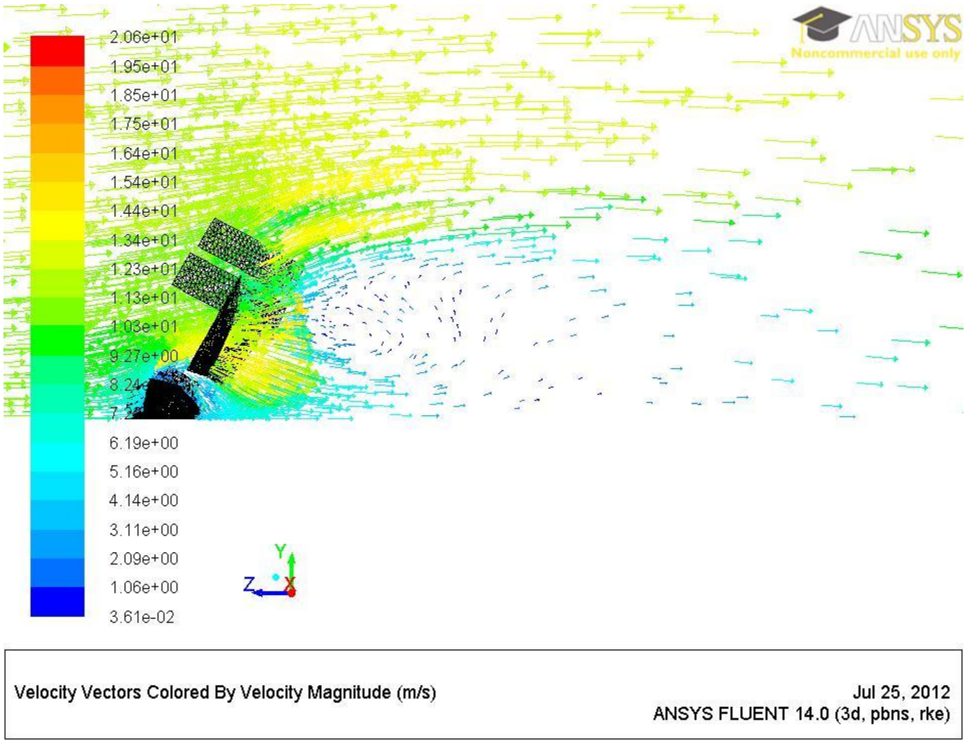

Figure 7-3: CFD Velocity vectors at 30° of heel

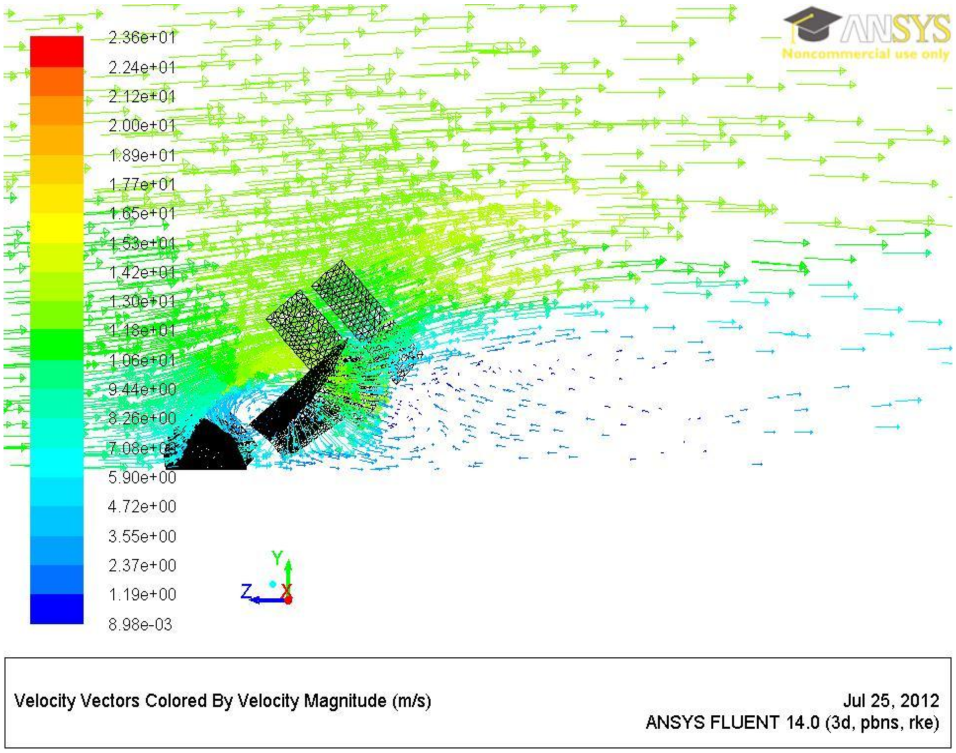

Figure 7-4: CFD Velocity vectors at 50° of heel

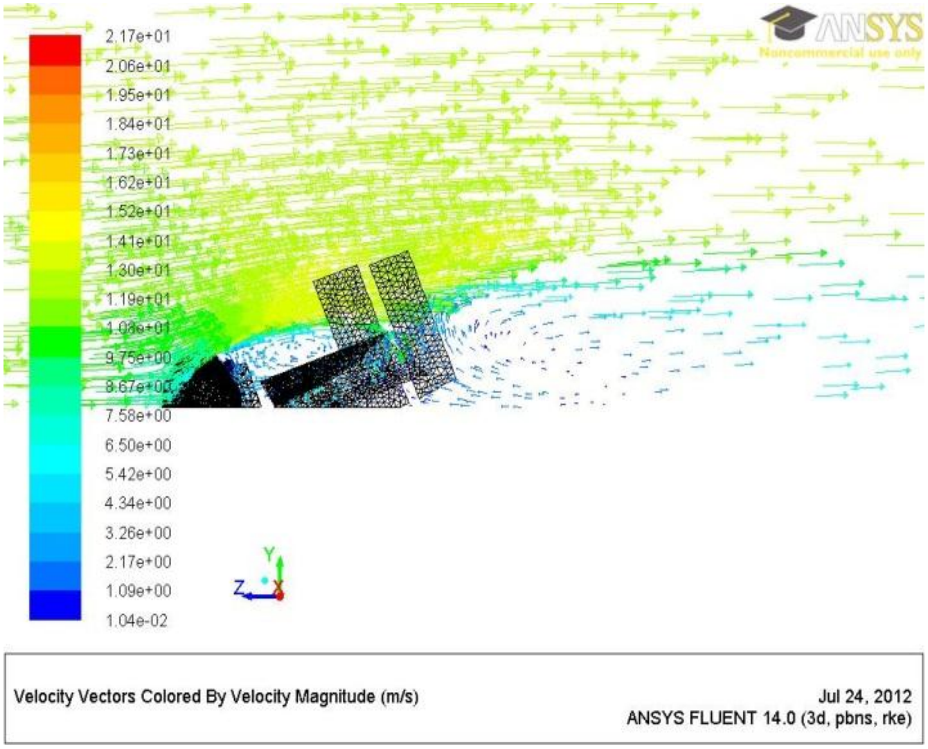

Figure 7-5: CFD Velocity vectors at 70° of heel

This model assumes that the wind is fully horizontal. Referring back to Figure 2-2, TSB's roll-off model claims that a windspeed of 23.5 knots would cause the vessel to heel to 68°. It has since been found that the roll-off rate was faster than even the TSB model suggests. Therefore, it can be concluded that the vessel would heel to an angle smaller than the 68° predicted by the TSB. In order to clear the hump in the righting arm curve, the model suggests that a horizontal windspeed of 92 knots would be required. Not only is this significantly larger than the measured windspeed, meteorological evidence suggests that such high windspeeds could not have been present at the time of capsize. Thus, a horizontal wind would have been incapable of knocking the ship over. However, if there was a vertical component to the wind, such a capsize could still be possible. As the ship heeled, the vertical component of the wind would be more perpendicular to the sails. This would lead to a decrease in the roll-off rate, which in turn would lead to higher moments at larger angles of heel. Thus, a vertical component to the wind could enable the heeling moment to overcome the hump in the righting arm. In that scenario, the ship would capsize.

As a result of this, it can be concluded that a least some component of vertical wind would have been required to knock down the *Concordia*. This disputes the TSB horizontal wind heeling theory. Although the TSB mentions later in the report that a vertical component of the wind may have been present, the report also concluded that an inclined wind of 30° would be enough to capsize the sailing vessel. Since this statement relied on the horizontal translation of an incorrect roll-off model, it is suggested that the wind would have to be inclined at an angle greater than 30° in order for the sailing vessel to capsize.

It should be noted that only steady-state conditions are illustrated in the CFD analysis performed. In actually, it is possible that the angular momentum of the heeling vessel could carry the ship over the hump in the righting arm curve. This suggests that dynamic effects should be investigated.

Chapter 8

Conclusions and Recommendations

In summation, the horizontal wind present in the squall was incapable of knocking down the *Concordia*. Therefore, at least some vertical component of wind was present. Further analysis of the effect of vertical winds on heeling moments should be researched.

Furthermore, the downward forces associated with square sails at high angles of heel should be investigated. This analysis was limited since very little was known in such cases. Due to the fact that full scale testing would prove to be implausible, it is recommended that wind tunnel testing and advanced CFD be completed on the subject.

Additionally, sailing vessel captains need to be better equipped with the tools and knowledge to account for vertical winds. At the time of capsize, the only tools available to the captain were his own experience, and a set Squall curves based on the MCA rule. These squall curves do not address the dangers of a vertical component of wind. Since a downward component of wind has been shown to be necessary in the capsize of the *S/V Concordia*, it is recommended that the effect of this component be further investigated and included in the information provided to the captains.

REFERENCES

1. Lasher, W.C., Musho, T.D., McKee, K.C and Rybka, W., "An Aerodynamic Analysis of the U.S. Brig *Niagara*", Proceedings of the Eighteenth Chesapeake Sailing Yacht Symposium, Annapolis, MD, March 2-3, 2007, pp. 185-197.
2. Transportation Safety Board of Canada Marine Reports – 2010-M10F0003 Knockdown and Capsizing-Sail Training Yacht Concordia 300 miles SSE off Rio De Janeiro, Brazil.
3. Transportation Safety Board of Canada Stability Report – 2010-M10F0003 Knockdown and Capsizing-Sail Training Yacht Concordia 300 miles SSE off Rio De Janeiro, Brazil.

ACADEMIC VITA

Matthew Erdman

10751 Old Route 99, McKean, PA 16426, m.erdman58@gmail.com

Education

B.S., Mechanical Engineering, 2013, Penn State Erie, The Behrend College, Erie, PA

Honors and Awards

- USA Today Student Leadership Award, Penn State, 2011, 2012
- Penn State Behrend Honors Program, Penn State Erie, The Behrend College, 2011
- Chancellors Scholarship, Penn State Erie, The Behrend College, 2009-2013

Association Memberships/Activities

- Tau Beta Pi, 2013
- Pi Mu Epsilon, 2012-2013
- Omicron Delta Kappa, 2012-2013
- ASME, 2010-2013
- Phi Kappa Phi, 2012-2013

Professional Experience

- Quality Technical Advisor at GE Transportation (Summer 2012)
- Temporary Engineering Employee a Eriez Magnetics (Summer 2011)

Research Interests

I have broad interests in the mechanical energy side fluid and thermal sciences, particularly modeling experimental phenomenon with computational methods. Specifically, I am interested in the use of computational fluid dynamics in the development of chemically reacting turbulent flows.