

Creating a Flexible, Web-Enabled Learning and Research Facility
at the M.I.T. Towing Tank

by

Matthew L. Unger

B.S. Naval Architecture and Marine Engineering
Webb Institute, 2004

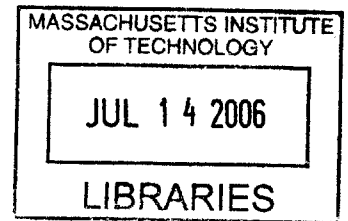
Submitted to the Department of Mechanical Engineering
in Partial Fulfillment of the Requirements for the Degrees of

Master of Science in Naval Architecture and Marine Engineering

and

Masters of Science in Ocean Systems Management

at the
Massachusetts Institute of Technology
June 2006



BARKER

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Signature of Author.....

Department of Mechanical Engineering, Center for Ocean Engineering
May 18, 2006

Certified by

Michael Triantafyllou
Director of the Center for Ocean Engineering, Professor of Ocean Engineering
Thesis Supervisor

Certified by

Franz Hover
Principal Research Engineer
Thesis Supervisor

Certified by

Henry Marcus
Professor of Ocean Systems Management
Thesis Supervisor

Accepted by

Lallit Anand
Chair, Department Committee of Graduate Students

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ABSTRACT

The M.I.T. Towing Tank has served as an invaluable research and educational platform for over 50 years. The hands-on learning experiences of towing tank tests have helped countless students to grasp the concepts and theories that are taught in the classroom environment. A recent upgrade of the M.I.T. Towing Tank increased the accuracy and capabilities of the facility, but also provided new capabilities to help create an Internet-based, distance learning tool. This new program has enabled M.I.T. to share its towing tank with students from other schools and universities via the Internet. The educational value of this tool was tested via an online set of experiments, performed by a partnered university, and has demonstrated the many benefits derived by this new capability.

The upgrades to the facility have also increased the value of the M.I.T. Towing Tank for educational and commercial research. In recent years, the research interests at M.I.T. have significantly diversified, leading to new demands and capabilities being placed on the towing tank. As a result of the upgrades, the towing tank is now a highly flexible platform, on which a variety of research may be performed.

ACKNOWLEDGMENTS

By any given standard, my thesis is slightly out of the normal scope for an M.I.T. graduate student. Its uniqueness has made it an exciting and very rewarding project, and I must thank Prof. Michael Triantafyllou and Dr. Franz Hover, my advisors, for allowing me to pursue it. My thanks also go to Prof. Hank Marcus, my advisor for the Ocean Systems Management degree, for his flexibility in allowing me to write a joint thesis. (Not to mention Hank going beyond the call of duty by helping me the week prior to the due date, from his hospital bed during his recovery!)

Throughout the process of completing this thesis, I have called on a great number of people for their expertise and help. I could not have done it without any of them. They include: Professor Neil Gallagher of Webb Institute for his guidance throughout the motor replacement and tuning phases. Dr. Rich Kimball and Kelli Hendrickson for their quick work on the iMarine system and arranging a last minute lab. Tadd Truscott, without whose help with LabVIEW, I might still be working today. Keith Michel for his help in supplying a cost estimate for commercial tank testing. Julie Arsenault and Ashley Cantieny, my two UROPs, for the quick work in designing and fabricating the new carriage.

Last, but certainly not least, thank you to my family. My father's guidance on all things electrical was an invaluable help to me. But just as importantly, without my mother, father, and sister's love, support, and encouragement, I would never have made it.

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INTRODUCTION

The M.I.T. Towing Tank is a relatively small facility that is predominantly used for educational and research based applications. The educational value of a towing tank can be considered quite significant, and for this reason, having a facility at M.I.T. is to the benefit of the students. Constructed in the 1950's, the facility has been put to use by many generations of M.I.T. naval architects, marine engineers, and ocean engineers. It has also undergone several upgrades of its equipment, to keep it a modern facility. As part of this thesis, a round of upgrades was completed to modernize the facility with a new carriage drive and control system, new data acquisition hardware and software, and a new light-weight carriage.

These upgrades have allowed for the educational value of the towing tank to be enhanced by enabling the M.I.T. Towing Tank to be connected to the Internet. This connection allows for students from other universities and high schools to have remote access to the M.I.T. Towing Tank. Combined with live web-cams, the students are able to run experiments in the facility from their classroom, watch the tests as they occur, and immediately receive the test data back via the Internet. This system has several potential benefits as an educational tool and as a means to continually emphasize the importance of ocean engineering-related education.

This thesis first discusses the history and importance of towing tank testing and model ship tests, in particular. It then highlights the upgrades that were completed to the facility, and elaborates on the Internet-based learning tools that have been created. The uses of the towing tank from an educational, research, and commercial standpoint are also discussed.

BACKGROUND

Towing Tanks

Modern towing tanks are used as platforms to perform a variety of experimental hydrodynamic research; however, the origins of the towing tank are rooted to the very specific purpose of predicting ship resistance via model testing. It was through this work with ship models, that modern day scaling techniques were developed, and which have allowed the towing tank to be used in a variety of scaled research experiments.

The concept of utilizing scaled ship models is not a new idea, but rather one that spans a timeline from the 15th century to the present. Some of the greatest scientific minds have hypothesized or contributed to this area of research, including da Vinci, Newton, Euler, Bernoulli, Franklin, and d'Alembert. These first model tests were performed in variety of settings ranging from small natural ponds, to swimming pools, to rain ditches, to ship dry docks. Additionally several very small tanks were constructed with the dedicated purpose of model testing. These tanks were typically on the order of 30 feet in length. In most cases, the models were propelled with a tow line rigged to a falling weight (Phillips-Brit 1970).

These early model tests revealed that there was no simple scaling procedure to convert model-scale resistance to full-scale ship resistance. As a result, most experimental model testing primarily yielded qualitative rather than quantitative results. A particular hull shape could be deemed faster (or to have better resistance characteristics) than another hull shape. For example, it is believed that the famous clipper ship bow was, in part, developed by small model tests performed by the shipbuilding firm Alexander Hall & Company of Aberdeen, Scotland in 1830. In a glass-sided tank only 10 feet in length, William Hall experimented with numerous ship models by dragging them through the tank filled with water and “a top layer 1½ inches thick of transparent red-colored spirits of turpentine.” As illustrated in Figure 1, Hall was able to visualize the flow patterns

around the models; thus, qualitatively judging that the Clipper-type bow produced a smooth and favorable flow (Todd 1951).

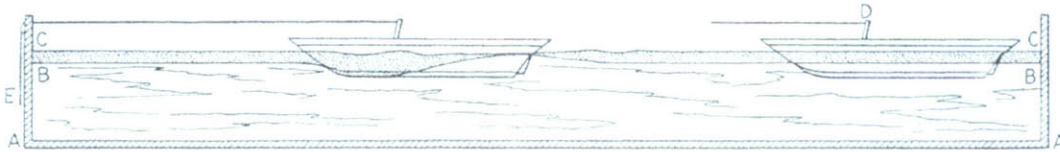


Figure 1. Towing Tank of Alexander Hall & Company (Todd 1951).

In the mid-1800's, with the advent of the steam engine, there grew a sense of urgency toward finding an accurate means of predicting ship resistance. In a paper discussing the history of towing tanks, the legendary yacht designer Olin Stephens states “the fact that the power of a steam engine could be measured while sail could not, made it useful to learn how much drag had to be overcome for a ship to reach a given speed” (Stephens 2006). Fortunately for the field of naval architecture, the scientist William Froude was hired in the 1860's to assist in the creation of a fleet of steamships for transatlantic trade. Froude was introduced to the resistance prediction problem that was plaguing the shipbuilding industry. He started towing ship models in a rain-catching ditch with a gravity tow line, but was unhappy with the sag in his tow line and switched to towing models with a small powered launch. In 1869, as a result of his tests, Froude made the breakthrough discovery which brought model testing into the next generation. Froude called his discovery the “Law of Comparison” and it described how to accurately scale ship model resistance to full-scale ship resistance (Froude 3). To this day, many still consider Froude to be the father of modern day ship model testing.

From 1869 forward, the towing tank took on a new meaning, as ship model tests could now produce quantitative resistance predictions. In 1870, Froude oversaw the construction and operation of the British Admiralty's experimental tow tank. The facility's tank was 278 feet in length and featured the world's first traveling carriage facility, which is now considered the modern-day standard (Lewis 1988). A traveling carriage allows for models to be attached to a rigid carriage, riding on rails along the

towing tank's length. The carriages are propelled via machinery, allowing accurate towing runs to be made. The traveling carriage eliminated the sagging towline that Froude disliked.

Since the days of Froude's first modern towing tank in 1870, many more facilities have been created. Today, towing tanks range in size from small, 100 foot facilities, to huge tanks nearly one-mile in length and whose carriage rails conform to the curvature of the earth. Similarly, model lengths vary from just a few feet to well over 30 feet. Modern machinery and sensing equipment have only furthered the usefulness and accuracy to ship model tests, and have allowed for the testing of a wide variety of hydrodynamic problems and applications.

M.I.T. Towing Tank

The Massachusetts Institute of Technology has a long and rich history pertaining to the study of naval architecture and ocean engineering. This history dates back to 1893 with the formation of M.I.T.'s Department of Naval Architecture and Marine Engineering. Starting in the early 1920's, plans were begun to build a towing tank research facility in the new Pratt Building, which was constructed to house the department. However, time after time these plans met the unfortunate fate of insufficient funding (Page 2001). Interestingly, architectural drawings of the never-built towing tank design for the Pratt Building may be found in the M.I.T. Hart Nautical Gallery archives. Finally, in the mid-1940's, with the upcoming 1949 Development Fund Campaign, the department gained approval for the creation of a "modestly sized" towing tank facility. In June 1951, the M.I.T. Ship Model Towing Tank was officially dedicated. Figure 2 is an early picture of the facility taken after construction was complete.

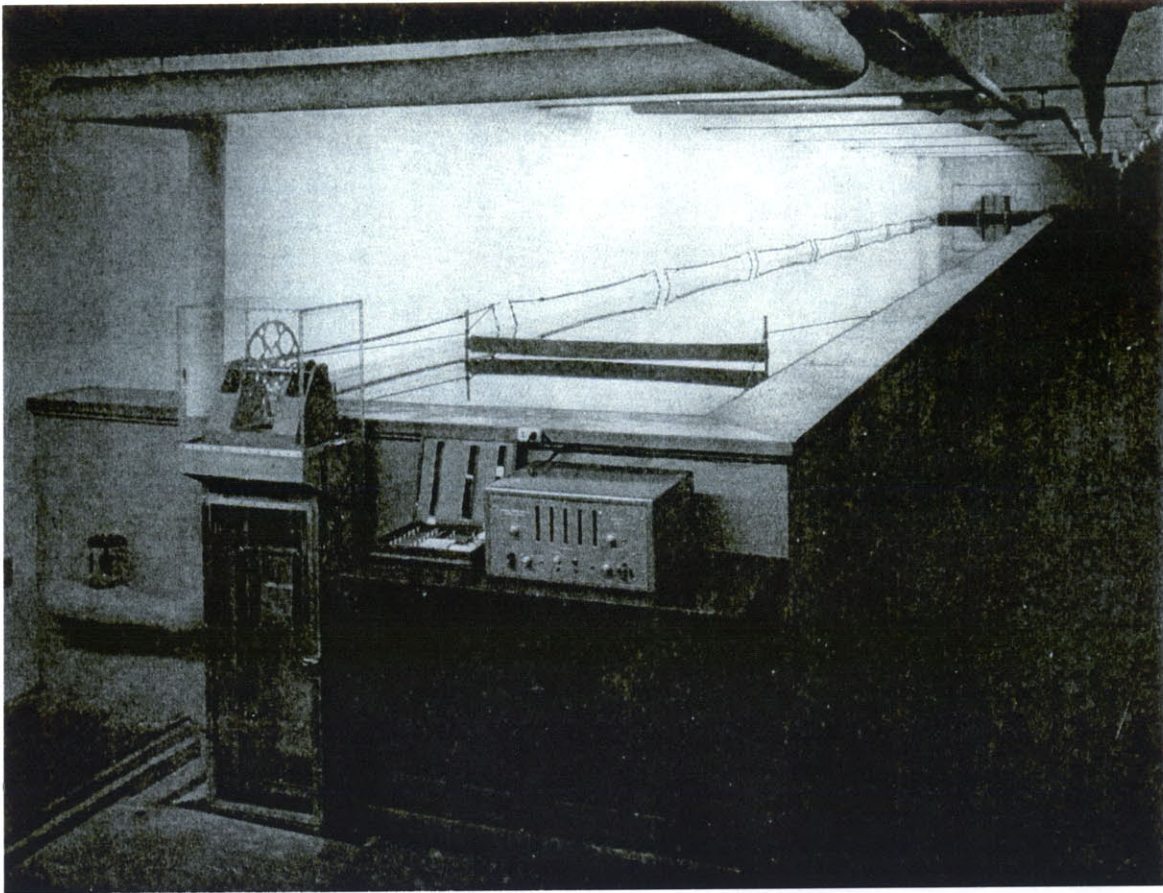


Figure 2. An early picture of the M.I.T. Towing Tank (Abkowitz 1953).

The tank was constructed to the following dimensions: 108 feet (33m) long, 8 feet 7 inches (2.6m) wide, and 4 feet (1.2m) deep for most tests. In its earliest years, the towing tank consisted of little more than the tank, a towing chord strung between a pulley at each tank end, and a “gravity” dynamometer. Through an intricate set of falling weights, an exact force was applied to the towing chord. The resulting model speed was measured, and thus a resistance curve was developed via a series of tests. The applied force could be measured to within 0.0001 pounds, and the resultant speed to within 0.001 knots. A simple wave-maker was capable of producing regular waves down the tank’s length (Abkowitz 1953). A plan-view schematic of the tow tank and gravity dynamometer is pictured in Figure 3.

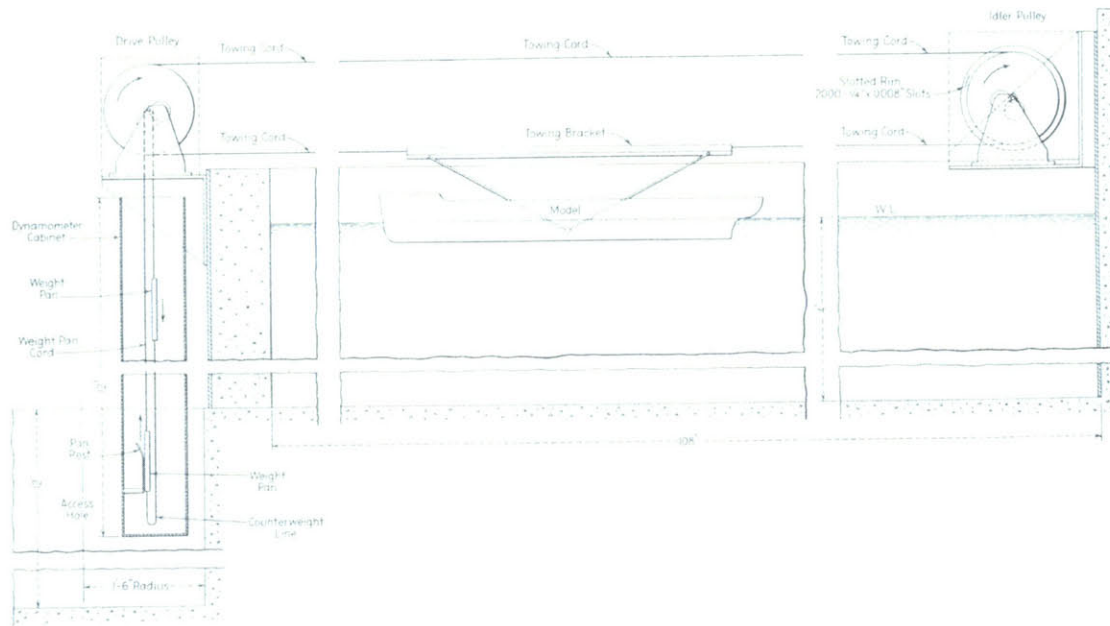


Figure 3. A schematic of the M.I.T. tow tank and early "gravity" dynamometer (Abkowitz 1953).

As time progressed, further additions and improvements to the facility have taken place. The most notable improvement was the addition of a traveling carriage in 1961 (Baker 1969). To support the carriage, two tubular rails running the full length of the tank were installed. An overhead rail was mounted approximately 39 inches (1m) above the water surface and along the centerline of the tank, while a second rail runs along one side of the tank, approximately 16 inches (0.4m) above the water. Figure 4 is a picture taken looking down the length of the M.I.T. tow tank, featuring the overhead and side rails.

The towing tank has had numerous upgrades throughout the years, each of which has brought it up to the current technology of the time. Researching the various configurations of the facility has proven to be difficult, as most upgrades and improvements were not well documented. As a result, much of the information uncovered was from informal interviews and chance conversations with M.I.T. alumnus of the past 50 years. Among these upgrades were several generations of motors and gearing for carriage control, and the conversion to a hydraulically actuated the wave-maker paddle.

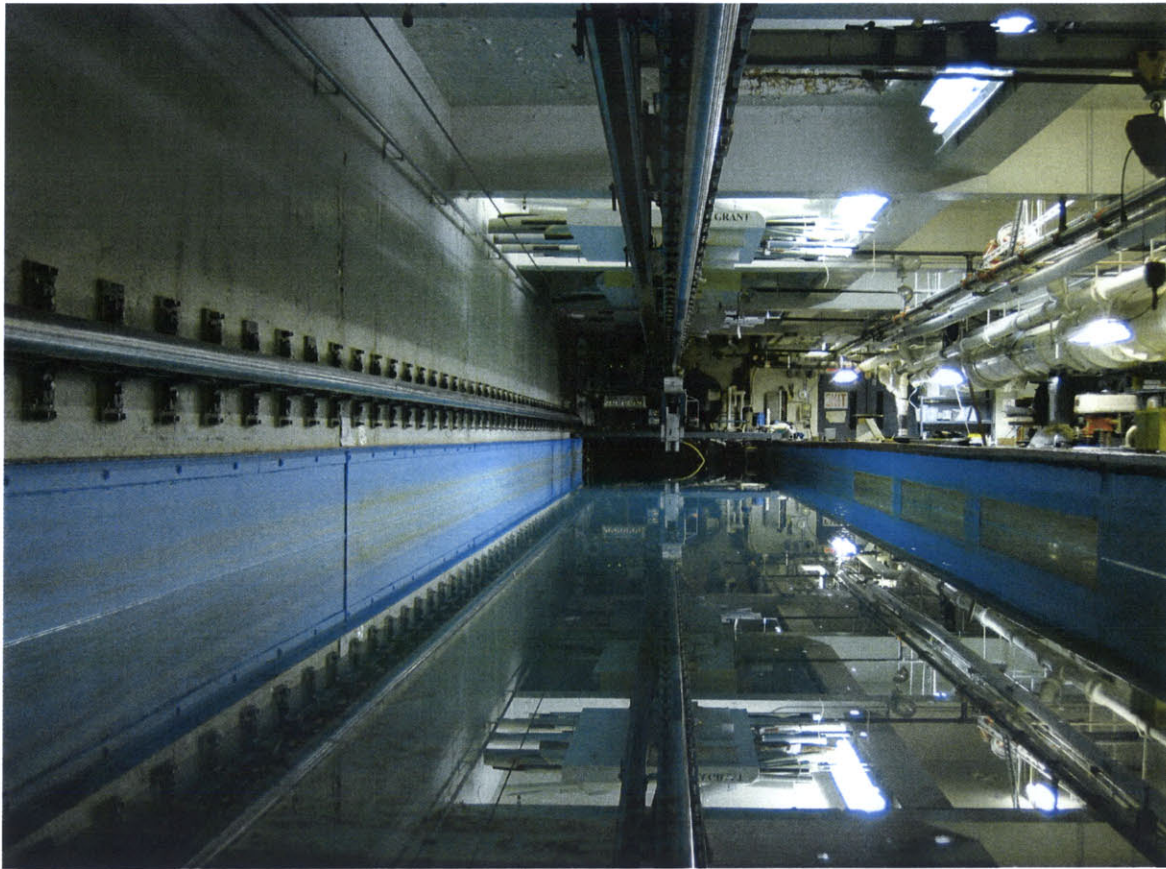


Figure 4: A view down the length of the M.I.T. Towing Tank.

One of the more interesting motor/drive configurations from the 1970's incorporated three 5-speed manual automotive transmissions coupled together and to an AC motor. While the motor would only turn at one speed, by shifting each of the three gearboxes to different gears gave the operators 125 discrete speeds at which to test.

Model Testing Theory

Prior to William Froude, there was no known scaling technique to equate ship model to full-scale ship resistance. Beginning in 1868, Froude began testing various scale models of the same ship and noted that the wave patterns produced by each model were nearly identical, but their speeds did not match. He realized that some form of speed scaling existed. Froude was able to identify that ship resistance needed to be separated into two

basic components frictional and residuary, and did so using the general law of mechanical similitude.

The residuary resistance is simply the residual that remains once frictional resistance is accounted for. In general, residuary resistance is nearly entirely composed of the wave-making resistance; however other items such as eddy-making, wave-breaking, and wind resistance are often lumped together, as well. More simply stated, Froude had found that wave making and frictional resistance scaled differently.

The next few pages explain how dimensional analysis can be applied to the problem of ship resistance. This method is featured in many naval architecture references. Much of the following was taken from Lewis (1988) and Todd (1951).

The total resistance, R_T , of a ship will depend upon several physical quantities:

- V , speed
- L , characteristic length
- ρ , density of fluid
- μ , viscosity
- g , gravity
- p , pressure in fluid

Thus, a relationship between these variables can be written as:

$$R_T \propto \rho^a V^b L^c \mu^d g^e p^f \quad (1)$$

Using the procedure of dimensional analysis, coefficients a , b , and c can be solved, yielding the relation:

$$R_T \propto \rho V^2 L^2 f \left[\left(\frac{\rho V L}{\mu} \right)^{-d} \left(\frac{g L}{V^2} \right)^e \left(\frac{p}{\rho V^2} \right)^f \right] \quad (2)$$

Note that the three expressions within the brackets are each a non-dimensional quantity. Furthermore, knowing that S , surface area, is proportional to L^2 and that \mathbf{m}/\mathbf{r} can be replaced by \mathbf{n} , kinematic viscosity, Equation (2) can be rewritten as:

$$C_T = \frac{R_T}{\frac{1}{2}\rho S V^2} = f\left[\frac{VL}{\nu}, \frac{gL}{V^2}, \frac{p}{\rho V^2}\right] \quad (3)$$

The quantity $R_T / (\frac{1}{2}\rho S V^2)$ in Equation (3) is the non-dimensional form of total ship resistance, which is simply abbreviated as C_T . From this relation, dimensional analysis has shown that if the three parameters on the right-hand side of Equation (3) are the same for a ship and a scaled model of the ship, the flow around the hull will be similar and the non-dimensional resistance will be the same for both cases. The next few sections will take a closer look at each of the three non-dimensional terms individually. This will prove that dimensional analysis has allowed total ship resistance to be broken down into frictional and residuary components, and that each component scales according to different non-dimensional parameters.

Residuary resistance

If the assumption is made that a ship is operating in an inviscid flow, then frictional resistance will not exist and the first parameter, VL/\mathbf{n} , of the right-hand side of Equation (3) can be ignored. For reasons to be explained shortly, the third term in Equation (3) will also be temporarily ignored. Thus, the only remaining term is gL/V^2 , which governs the surface wave system and the residuary resistance. Note that term can be rewritten as V/\sqrt{gL} which is the Froude Number, Fn . This allows a non-dimensional coefficient for residuary resistance, C_R , to be defined as:

$$C_R = \frac{R_R}{\frac{1}{2}\rho S V^2} = f(Fn) \quad (4)$$

Therefore, to obtain dynamic similarity in a model test, Froude scaling must be performed so that the Froude Number at which the ship is operating is the same F_n to which the model will be tested. The ship and model speeds for the same Froude Number are what Froude called “corresponding speeds.” Knowing that the ship model is a geometric scaling of a ship, with model scale: $\lambda = L_S/L_M$. The relationship between ship and model speeds can be solved as:

$$V_S / \sqrt{gL_S} = V_M / \sqrt{gL_M} \quad (5)$$

$$V_S = \sqrt{\lambda} \times V_M \quad (6)$$

As an example: a 125 meter ship traveling at 10 knots can be represented by a 5 meter model traveling at 2 knots. In the same manner as above, the scaling of residuary resistance (or force) can be found:

$$\frac{R_{RS}}{R_{RM}} = \frac{\frac{1}{2} \rho S_S V_S^2}{\frac{1}{2} \rho S_M V_M^2} = \frac{S_S V_S^2}{S_M V_M^2} = \frac{L_S^2 (\sqrt{L_S})^2}{L_M^2 (\sqrt{L_M})^2} = \frac{L_S^3}{L_M^3} = \lambda^3 \quad (7)$$

$$R_{RS} = \lambda^3 \times R_{RM} \quad (8)$$

Based on this relation, a residuary resistance of 1 Newton on the model will correspond to 15,625 Newtons on the ship. The fact that dynamic (Froude) scaling results in small model forces and low model speeds is extremely convenient, as this makes model testing feasible. This will not prove to be the case for kinematic scaling.

Froude’s realization that the wave patterns (and thus wave resistance) scale differently from viscous forces was the key to unlocking the potential of scaled model testing.

Elimination of one dimensional analysis parameter

With dynamic similitude (and residuary resistance) identified, the third parameter of Equation (3), $p/\rho V^2$, can be re-examined. Assuming that atmospheric pressure exists above the water in both ship and model tests, then the pressure p is only the static “water head” acting on a specific location on the hull (i.e. $p = \rho gh$, where h is the draft). The value of p at a corresponding point on the ship and model will be different (because h will differ). However, h is linearly scaled by λ . Additionally, V^2 is scaled by λ , so the parameter $p/\rho V^2$ reduces to a constant. For now, it will be assumed that p only depends on draft, and this term can be neglected. Later on, this simplification will be re-examined.

Frictional resistance

With an understanding of what governs the scaling of wave-making resistance, Froude turned his attention to solving the frictional resistance problem. He started by examining the remaining parameter in Equation (3), VL/ν . If the assumption is made that the ship is actually a submarine, and is operating in very deep water, there will be no waves created on the water’s surface. Thus, only frictional resistance will be exerted on the submarine and only the parameter, VL/ν , or Reynolds number (Rn) exists. This parameter is named after Osborne Reynolds, whose work first discussed water flowing in pipes, and which was then extended to include other types of flow.

Using the Reynolds Number, the non-dimensional coefficient of frictional resistance, C_F , can thus be written as:

$$C_F = \frac{R_F}{\frac{1}{2}\rho SV^2} = f(Rn) \quad (9)$$

If Rn is the same for the ship and the model, then kinematic similitude is established. However, for the same 5 meter model to match the Rn of a 125 meter ship moving at 10 knots, the model will have to travel at 250 knots! This is highly impractical.

For researchers to obtain both kinematic and dynamic similitude simultaneously, the model could be tested at the slower speed corresponding to Froude (or dynamic) scaling, but the fluid the model was operating in would need a kinematic viscosity 1/125 that of water. Unfortunately, scientists know of no stable substance to use.

Thankfully, researchers have found empirical formulas (utilizing Reynolds number) to accurately predict frictional resistance. The first frictional predictions were performed by Froude in the early 1870's, when he measured the frictional resistance on flat plates (Baker 1948). Since that time, further research has resulted in a fairly accurate estimation of frictional resistance. One of the more commonly accepted formulas is the 1957 International Towing Tank Conference (ITTC) method that states:

$$C_f = \frac{0.075}{(\log_{10} Rn - 2)^2} \quad (10)$$

It is assumed that the flow around a ship's hull is dominated by turbulent flow, so Equation (10) only works for turbulent flows. Practically speaking, commercial ships usually operate at $Rn \approx 10^9$. Because of this, the flow changes from laminar to turbulent very close to the bow of the ship. (As a note of interest: the flow at the stern of a ship typically has a turbulent boundary layer of approximately 1 meter in thickness.) To properly simulate this on the model, the flow should also be turbulent. Since most models are run at $Rn \approx 10^7$, which is rather close to the regime of transitional flow, turbulence stimulators are used on the models. A common assumption is that flow naturally transitions from laminar to turbulent at $Rn \approx 0.5 \cdot 10^6$, so the stimulators are mounted at a position aft of the bow that corresponds with this critical Reynolds number (Bertram 2000). Common turbulent stimulators include small studs, sand strips, and trip wires.

Since larger scale models operate at higher Rn than smaller models (and are thus further away from the transitional regime), they are usually considered to produce results with a higher degree of accuracy. In the mid-20th century one thought was to heat the water of the testing tank. This would result in lower kinematic viscosity values, and thus higher Rn flows. In most cases this proved to be impractical (or extremely expensive for very little gain in accuracy).

Since frictional resistance represents up to 80% of the total resistance of slow commercial ships and approximately 50% of high speed vessels, finding methods to calculate frictional resistance was just as important as solving the residuary component of resistance (Todd 1951).

Other components of resistance

Froude’s early work in separating ship resistance into two primary components was the key to unlocking the mystery of scaling model ship tests. However, since Froude’s time, scientists and engineers have been able to further classify ship resistance into numerous other parts. Figure 5, below, is one depiction of how ship resistance can be decomposed.

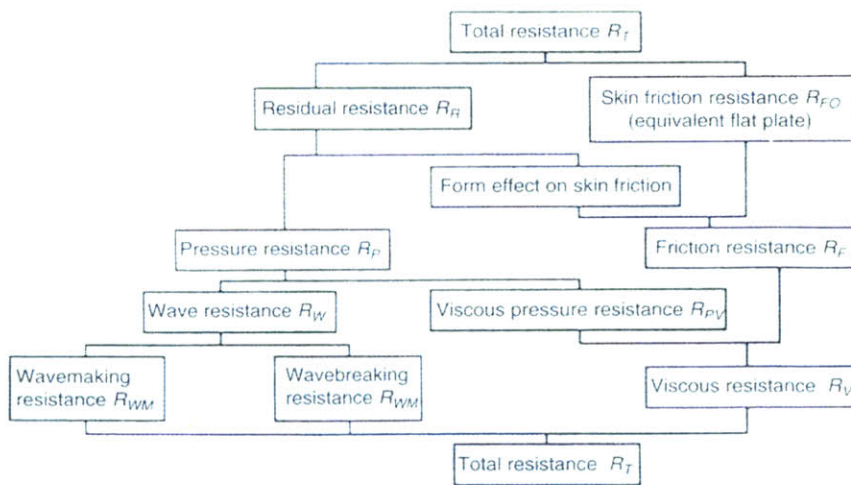


Figure 5. Decomposition of ship resistance (Bertram 2000).

Perhaps the easiest method of decomposition is to realize that residuary resistance is simply all other “residual” forms of resistance other than frictional. Those components include, but are not limited to: wave-making, wave-breaking, eddy-making, air, and viscous form drag. The dominant component is wave-making resistance, which in most cases accounts for nearly all residuary resistance.

Wave-breaking, eddy-making, and spray drag are other forms of resistance that are grouped into the residuary category. All of these types have proven to be extremely difficult to measure, and even more difficult to scale (their rather small contribution to residuary resistance adds additional challenges). Both wave-breaking and spray-making resistance will, at least in part, rely on surface tension in their calculation. The full scale ship will also encounter air resistance; however, it will nearly always be several orders of magnitude smaller than hydrodynamic resistance.

Finally, viscous form resistance (also called viscous pressure resistance) has proven to be a very difficult component for several reasons. Viscous form drag is best described by Bertram (2000) who explained that a deeply submerged ship (or submarine) will have no wave-making resistance, but its total resistance will be more than frictional resistance. This extra resistance is the viscous form drag. Another approach explains it as the pressure resulting from a viscous fluid flowing around the ship’s hull. The form of the ship thus affects the characteristics of the flow and how the viscous shearing will occur.

Looking back to the dimensional analysis of total ship resistance, one can now see that the elimination of the non-dimensional term $p/\rho V^2$ is most likely not correct, as p is somehow affected by viscous flow. Furthermore, if flow separation occurs, local pressures will differ from hydrostatic pressure, and introduce scaling differences. However, since there is no definite way to precisely calculate viscous pressure, and since wave-making resistance is much larger than viscous pressure resistance, the term is still neglected. Thus, while not complete, there is some explanation on the inaccuracies of scaled tests. Furthermore, smaller models appear to produce less accurate results than

larger models. This, again, is caused by the lack of scaling knowledge of viscous form drag.

Limitations of small models

The M.I.T. Towing Tank is, by all modern day standards, a small towing tank. Several decades ago, small tanks fell out of favor in the industry. Naval architects argued that there were too many uncertainties surrounding scaling effects and repeatability, and that any results from small towing tanks were not to be trusted. The truth is that small towing tanks have certain limitations, and thus, cannot be used for all types of testing. Often times the small size of the models result in flows with Reynolds numbers within the range where laminar flow is transitioning to turbulent flow. As mentioned in the previous section, ship models need to be tested while undergoing fully turbulent flow, which makes turbulence stimulators a necessity. This has proven to be fairly successful, allowing for the accurate testing of small models for resistance properties. Methods of turbulence stimulation have been studied for the past 50 years and include studs, sand strips, trip wires, and Hama strips (Hughes 1951 & Hama 1956).

The key to obtaining accurate and useful results from small tow tanks is, as with all other experiments, realizing the limitations of the facility. With regard to ship model testing, small towing tanks are simply not the correct facility to solve all hydrodynamic-related problems. Many papers have been written about small towing tank uses and limitations, including Fireman (1982) and Fisher (1982). The findings demonstrate that small tanks do provide a means of accurately comparing designs for bare hull resistance and added resistance in head seas. They do not work well in self propulsion tests or seakeeping experiments (at wave angles other than 0 or 180 degrees). Additionally, sailboat or other tests with appendages have proven to be uncertain because of the small operational Reynolds number of the scaled appendages.

Another limitation of small models is that they have small boundary layers, as compared to the full scale ships. Since the boundary layer changes the flow of water around the

hull, any scaling inaccuracies in the model tests will result in differing flows. This effect also brings back the problem of viscous form drag, which changes with boundary layer shape. If viscous form drag scales differently, something scientists do not definitively know, then the accuracy of small model tests may be experiencing slightly reduced accuracy.

Another point that is made by Kirkman (1979) in addressing small model testing of yachts is that the proportion of the resistance coefficients of the frictional and residual components is not the same for small models, large models, and full scale ships. This is best demonstrated in Figure 6, where the residuary and frictional resistance coefficient values are indicated for both a small model and ship. As Kirkman states, for the model, the residuary resistance represents a smaller portion of the total resistance, while at full scale, the residuary resistance is the largest contributor to the ship's overall resistance.

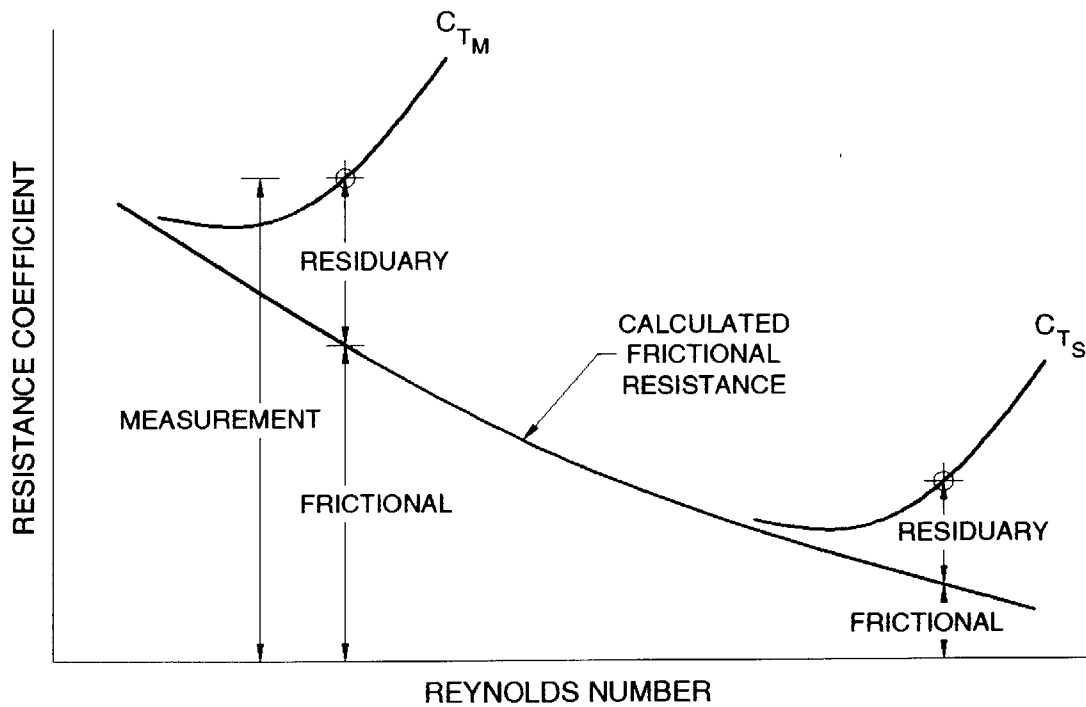


Figure 6. Graphic representation of resistance extrapolation to full scale (Kirkman 1979).

Despite these limitations, small model tanks still hold an important and useful place in research and education, and these benefits will be discussed in the remainder of this text.

UPGRADES AND MODIFICATIONS

The upgrades performed to the M.I.T. Towing Tank are part of the continual process of keeping the laboratory equipped with current technology. Modifications have been made to the carriage drive and control systems and to the data acquisition hardware and software. The goal of the upgrade process was to provide a system that is user friendly and offers accurate and higher carriage speeds than the previous system. Additionally, the new equipment allowed for the development of a web-based control system, which will be discussed in a later section.

Today, the research interests at M.I.T. have diversified and the M.I.T. Towing Tank serves as a research platform for many types of experiments, other than ship model testing. These tests include: the simulation of fish swimming (RoboTuna), ROV design tests, and the study of vortex induced vibration (VIV) on cylinders. Presently, additional tests are planned for flapping foil and pressure sensor testing. In short, there seems to be no limit to the diversity of applications that can be tested at M.I.T.'s towing tank. As a result, one requirement for the upgrades was that they provide a highly flexible system to allow for a variety of carriage control and motion profiles.

The upgrades consist of a new carriage drive and control system, upgraded data-acquisition hardware, and a new set of software programs to seamlessly join all functions at one desktop computing station. Additionally, a lightweight carriage for small testing loads (such as ship model tests) has been designed and constructed.

Carriage Drive and Control

The towing tank carriage is driven down the length of the tank by a simple drive system that has worked well for over 50 years. To produce carriage motion, an electric motor turns a drive pulley mounted at one end of the tank. As this pulley rotates, it drives a thin metal belt that is looped between the drive pulley and an idler pulley located at the opposite end of the tank. A tensioning device is attached to the idler pulley and allows

sufficient tensioning of the drive belt, which eliminates belt slippage. The carriage is connected to the drive belt, thus as the motor and drive pulley turn, the belt and carriage undergo linear motion. Figure 7 is a basic schematic of this system, with the large arrows indicating the turning motion of the pulley and the linear motion of the carriage.

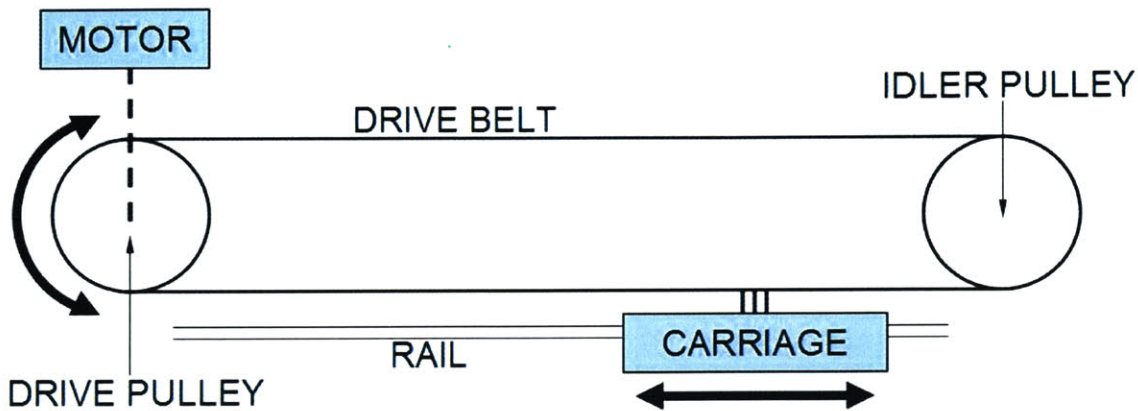


Figure 7. Schematic of the carriage drive system (large arrows indicate direction of motion).

Under the previous configuration, the drive motor was a 3-phase, commercial grade, AC motor coupled to a reduction gearbox. The motor was powered by an Emerson brand, adjustable frequency AC drive, which was controlled by a Fenner brand motion controller. This system combined the devices with an RPM sensor to create an open-loop feedback control. The user had two methods of interfacing and controlling the carriage. One method was to enter the desired carriage speed on a touch pad, and command motion via control buttons. The second method involved a DOS-based computer program. Figure 8 and Figure 9 depict the previous user interface and drive components, respectively.

While this system provided many years of reliable service, it was beginning to grow outdated. The integrated limit switch control board began causing problems, requiring the user to manually press a “stop” button to stop carriage motion. Additionally, the DOS-based program continually encountered errors because of the failed communication with the limit switches. Over the years of operation, the carriage gradually increased in

size and weight. As a result, the motor and corresponding controls began to meet their limitations. In comparison to modern day motor control methods, the open-loop feedback control was not providing the most accurate form of speed control.



Figure 8. Previous carriage controls.



Figure 9. Prior carriage motor drive components.

Thus, these upgrades can be considered an investment in the facility. This investment was made only after conducting a careful analysis of several different upgrade options.

The primary goal of the upgrade was to bring the facility up to a modern state, where testing could be conducted more efficiently and with greater accuracy; thus expanding the potential of the towing tank for educational, research, and commercial applications. Several different carriage motor and drive systems were investigated and priced. The four most promising options were:

- Option 1: A complete servomotor system by Parker Hannifin.
- Option 2: A Vector Drive variable speed AC motor system by Baldor.
- Option 3: A servomotor system by Mitsubishi.
- Option 4: Reuse the existing motor and install a new drive/controller.

To assist in the final selection, a wish list of features for the upgraded system was developed and used to evaluate each of the motor options. The criteria consisted of various aspects desired in a new system. This included:

- the motor’s accuracy
- the ability to program a variety of motion profiles
- enough power to accelerate heavy loads and achieve relatively high speeds
- a proven track record in similar applications
- ease of programming the controller and interface
- the ability to control carriage position, in addition to velocity
- the availability of the manufacturer’s technical support
- the capability to track the carriage’s position and velocity.

Prior to ranking each motor option, the criteria was first evaluated to determine which categories were most important to the upgrade. This was done by weighting each criterion on a scale of 1 to 10. Next, each motor option was ranked for its fit to each category. The final percentage score for each option was found by incorporating the weighting with each criterion and summing for each option. The results of the evaluation are outlined in Table 1 below.

Table 1. Merit-based analysis of motor/drive upgrade options.

	<u>Weighting</u>	<u>Parker Servo</u>	<u>Vector</u>	<u>Mitsubishi Servo</u>	<u>Old Motor/ New Controller</u>
Accuracy	10	10	7	10	5
Flexibility of motion	10	9	6	8	4
High speed/power	10	10	10	10	7
Known system w/proven applications	9	10	10	0	0
Ease of programming	8	8	5	5	5
Position control	8	10	8	10	6
Manufacturers support	8	9	7	8	7
Position/velocity feedback	5	9	7	9	7
Price:		\$8,276.00	\$7,448.00	\$8,500.00	\$3,000.00
Overall Score:		94%	76%	75%	50%

This analysis highlighted many of the strengths and weaknesses of each option. While the Mitsubishi servomotor would result in a similar amount of accuracy to the Parker system, it was not a fully packaged product and would require third party controllers and

complex programming. This also meant that versatile functionality would be more difficult to accomplish. The Vector AC motor system would achieve slightly less accuracy, and also had more limited capabilities. It would not allow for accurate positioning control of the carriage. The last option to keep the old motor proved to be the least favorable, as it provided the least amount of accuracy and lacked enough power for the system. Another important criterion was to evaluate if each motor option has a proven track record in similar applications. Both the Parker and Vector systems have been installed in the Webb Institute and U.S. Naval Academy tanks, respectively. Both have provided reliable service and as such, received higher scores for this category than the other options.

In the final analysis, the Parker system proved to be far superior to the other choices. Interestingly, it was comparably priced to the other systems. As such, it appears that the selected system provides significantly greater value per dollar spent.

The final choice was to purchase a brushless DC servomotor system manufactured by Compumotor, a division of the Parker Hannifin Corporation. This new configuration consists of two parts: the servomotor with reduction gearing and a Gemini drive/control unit (pictured in Figure 10 and Figure 11 respectively). The servomotor provides more than ample power and torque for the carriage; and with a closed loop control configuration, offers the benefits of precise motion control with fast response capabilities. The drive/control unit powers the motor, but also contains a processor to control all motor functions. A personal computer, connected to the drive/controller either via serial or Ethernet communications, acts as the user interface for the system. Limit switches, emergency stop buttons, and other optional devices all connect to the drive/controller. Utilizing proprietary Compumotor software on the PC, motion profiles can be programmed and uploaded to the drive/controller's processor. From that point, the computer acts as a simple interface, transmitting commands from the user to the controller. The result is a highly flexible and very capable motion control system.

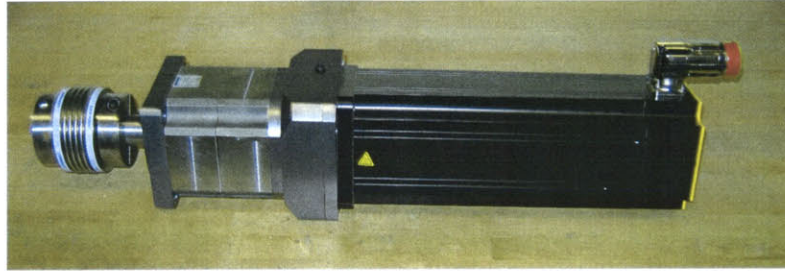


Figure 10. Compumotor servomotor, gearhead, and shaft coupling.

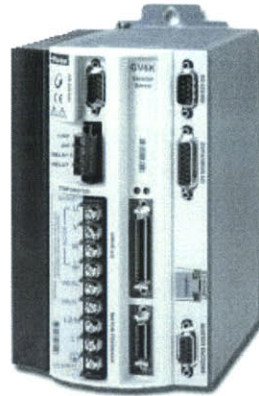


Figure 11. Gemini servomotor drive/controller (source: Compumotor website).

The Gemini drive/control utilizes several basic motion programs, and adapts them for specific use. The motion program to be used most often in the M.I.T. Towing Tank is the “S-Curve” profile. All usable test data will come from the steady-state, constant speed portion of the carriage’s motion. Therefore, it is highly desirable to accelerate the carriage up to speed as quickly as possible, allowing it to run for the maximum distance at the set speed, and then decelerate to a stop. However, the acceleration and deceleration stages exert large and undue forces and jerk on the model (or test apparatus). Rather than having the carriage accelerate and decelerate at a set value, the drive/control unit is capable of creating smooth starting and stopping motions, thus minimizing jerk on the carriage. This ramp-up and ramp-down speed profile resembles the letter “S”, and as such, has acquired its name. This is best demonstrated by a comparison of Figure 12 and Figure 13. Figure 12 shows constant acceleration and deceleration, with its resulting “trapezoidal” velocity profile, while Figure 13 graphs the “S-Curve” velocity and acceleration profiles.

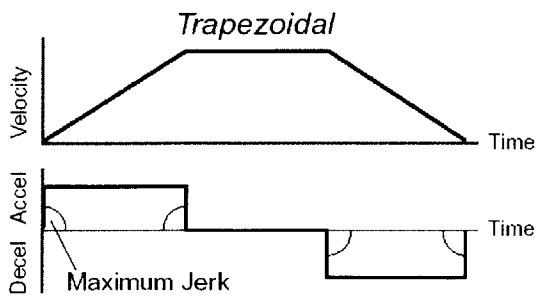


Figure 12. Trapezoidal (or constant acceleration and deceleration) velocity and acceleration profiles (source: Compumotor).

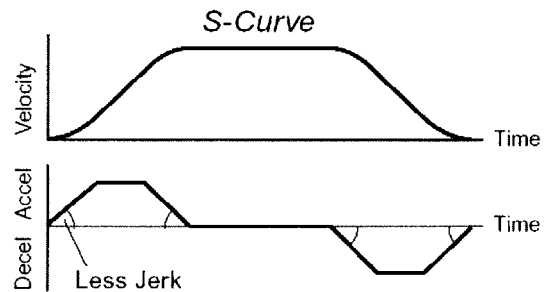


Figure 13. "S-Curve" velocity and acceleration profiles (source: Compumotor).

The Gemini Drive offers additional flexibility, in addition to “S-Curve” motion. Due to the high accuracy of the 8000 count encoder, built into the servomotor, the carriage can be positioned anywhere along the length of the towing tank to within an accuracy of 14 millimeters. This feature can expand the uses of the towing tank for applications where precise distances are needed. It may also prove useful for testing sonar equipment in the towing tank. Another feature of the Gemini is that it can allow the motor to become a “slave” follower, to mimic a particular motion profile that is fed into the unit. One application where this may prove useful is when testing flapping foils. The lift and drag of the foil can be measured, the forward advance speed calculated, and immediately fed into the motor to advance the carriage accordingly. This new motor and controller configuration offers a degree of flexibility to the facility that opens it to a variety of new testing possibilities.

The installation of the motor required the fabrication of a steel bracket to which the motor could be mounted. The motor was attached, the drive/controller was wired, and motion programs were created. Figure 14 and Figure 15 are pictures of the assembly process and final outcome.



Figure 14. Motor/bracket/pulley configuration prior to final assembly.



Figure 15. Servomotor assembly permanently attached to the drive system.

Data Acquisition System

Depending upon the experiment, sensors are typically mounted to the “test subject” whether it is a model ship, VIV cylinder, or other device. To collect this data, all the sensors are wired to a BNC connector breakout board on the carriage. Wires which follow the carriage connect to a corresponding breakout board in the control station of the towing tank. From here, each individual sensor channel is wired to a third BNC panel that is connected to a PC via a data acquisition (DAQ) card.

A new Dell PC was purchased to act as the interface with the new servomotor system, as well as serving as the data collection computer. This is a change from the previous system, where one station controlled the carriage motion, while another computer collected the experimental data. The new system combines all functions at one computer for several reasons, which will be discussed shortly.

The new DAQ system consists of several pieces of hardware, all manufactured by National Instruments. The sensor channels will now be wired to two new BNC boards (NI BNC-2090 adaptors), pictured in Figure 12, that are connected to a new PC DAQ card (NI PCI-6259). This new configuration allows for 32 analog-in, 4 analog-out, and 48 digital I/O channels. For software, National Instruments LabVIEW software package is utilized to record all data. LabVIEW is also used for several other important functions,

to be explained shortly.

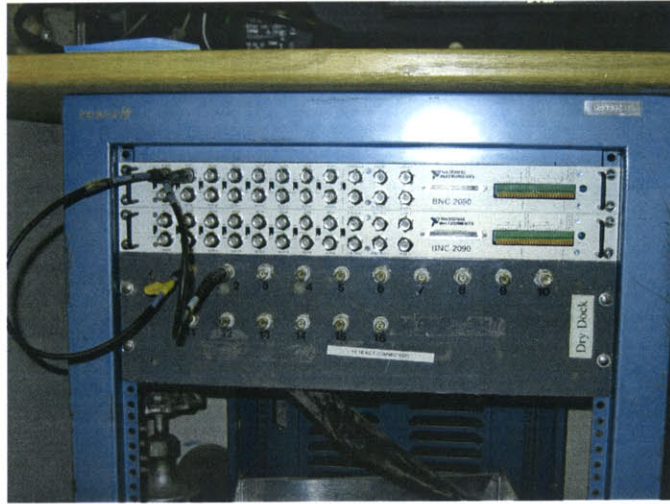


Figure 16. The new BNC DAQ adaptors are rack-mounted above the BNC breakout board that is wired to the carriage.

Software Programs

Since one goal of the upgrade was to simplify operation of the towing tank, it was decided at the onset of the project that all important functions should be easily controlled from one, central station. To accomplish this, National Instrument's LabVIEW software was used to control all functions. LabVIEW is a very powerful software package used for data acquisition, motion control, signal processing, and a variety of other functions. Unlike most computer languages, LabVIEW is graphically-based, rather than text-based. LabVIEW programs are called "Virtual Instruments" or VIs, and consist of two windows. The first is the "Front Panel" which serves as the user interface screen when running the VI. The Front Panel consists of the buttons, text inputs, and other items necessary to control the VI, and is customized during programming. The "Block Diagram" window is only used when programming the VI. Specific tasks are represented by graphical icons within the Block Diagram, which are wired together to transfer data from one task to the next. The flexible nature of LabVIEW programming has allowed several VIs to be created for controlling the various tasks necessary in the M.I.T. Towing Tank.

LabVIEW VIs have been created to fully control the carriage. The Front Panel, pictured in Figure 17 below, allows the user to home the carriage, enter the desired test speed, command motion, and reverse the carriage. An emergency stop button allows the user to immediately stop the carriage motion. This emergency feature is in addition to several other safety stopping features. Complete instructions for carriage operation can be found in Appendix A.

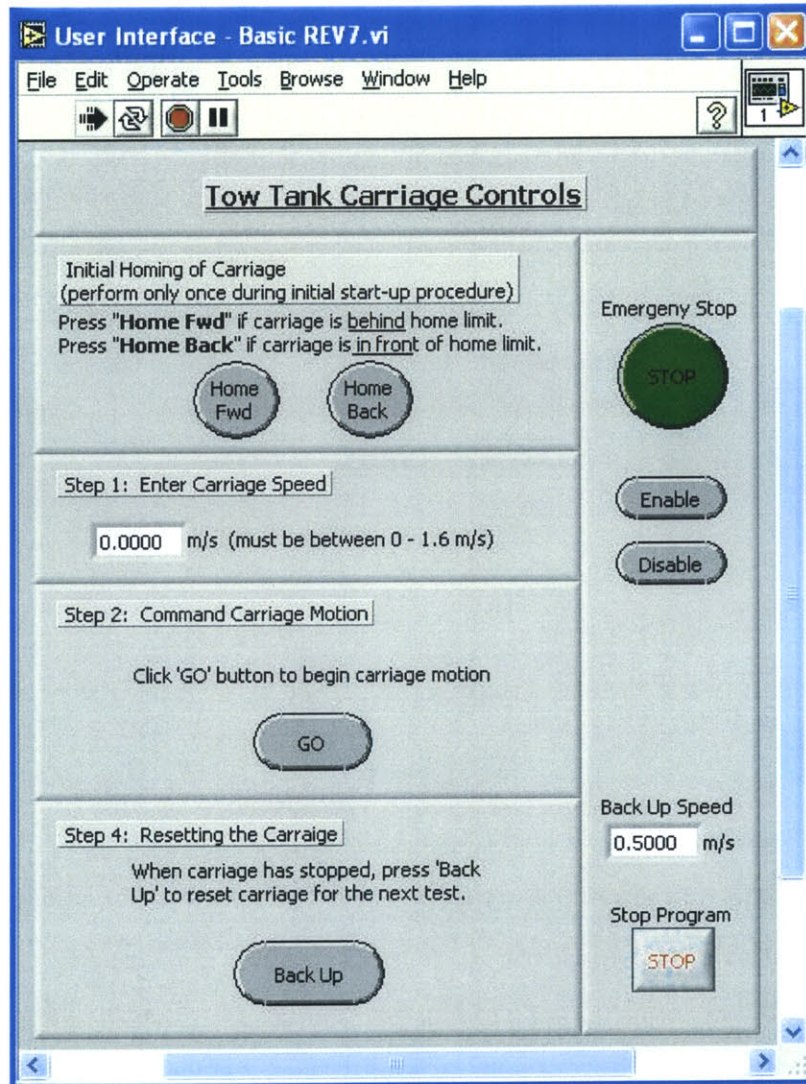


Figure 17. LabVIEW Front Panel for controlling the towing tank carriage.

Data acquisition is very easily accomplished with LabVIEW, and several VIs have been created for this purpose. In most cases, however, experiments conducted at the M.I.T.

Towing Tank require slightly different data acquisition setups. Often the number of data channels, sensor types, and scaling vary. Fortunately, the LabVIEW VIs for data acquisition are very easily modified to suite the requirements of the experiment. One useful Labview feature allows for the raw data to be scaled according to sensor calibration tests, prior to testing. This allows for the recorded data to be in experimental units, rather than pure voltage. Detailed instructions for LabVIEW data acquisition are also located in the User Guide in Appendix A.

LabVIEW was also used to create a VI to control the towing tank's wave-maker. The paddle-type wave-maker spans the full width and height of the tank, and is normally in an upright position. It is connected to the bottom of the tank via a hinged connector. A hydraulic cylinder, attached to the top of the paddle, actuates motion and, thus, generates waves in the tank. The hydraulic cylinder is connected to a servo-amplifier, which receives an analog signal from a wave generator. By feeding sinusoidal waves into the servo-amplifier, regular waves of varying frequency and amplitudes are possible. Since the new DAQ system has analog-out functionality, the wave-maker servo-amplifier receives all commands from a new LabVIEW VI, as opposed to last system which used a simple signal generator. This results in increased accuracy and flexibility in the wave-making capabilities of the tank. It also allows for the operation of the wave-maker from the same single computer control station.

LabVIEW has allowed for the control of the carriage, data acquisition, and wave-maker to be seamlessly integrated at a single user station, as pictured in Figure 18. This has significantly increased the capability and ease of use of the towing tank.



Figure 18. New tow tank control station.

New High-Speed Carriage

The towing carriage has proven to be an excellent and quite versatile platform from which to perform tests. However, as previously mentioned, it is quite heavy and large. A photograph of the carriage during resistance testing of a 3-foot barge model can be seen in Figure 19. In comparison to the model, the carriage is extremely large. To attain higher test speeds, a lighter carriage is necessary. As a result, a new lighter-weight carriage was designed and built.

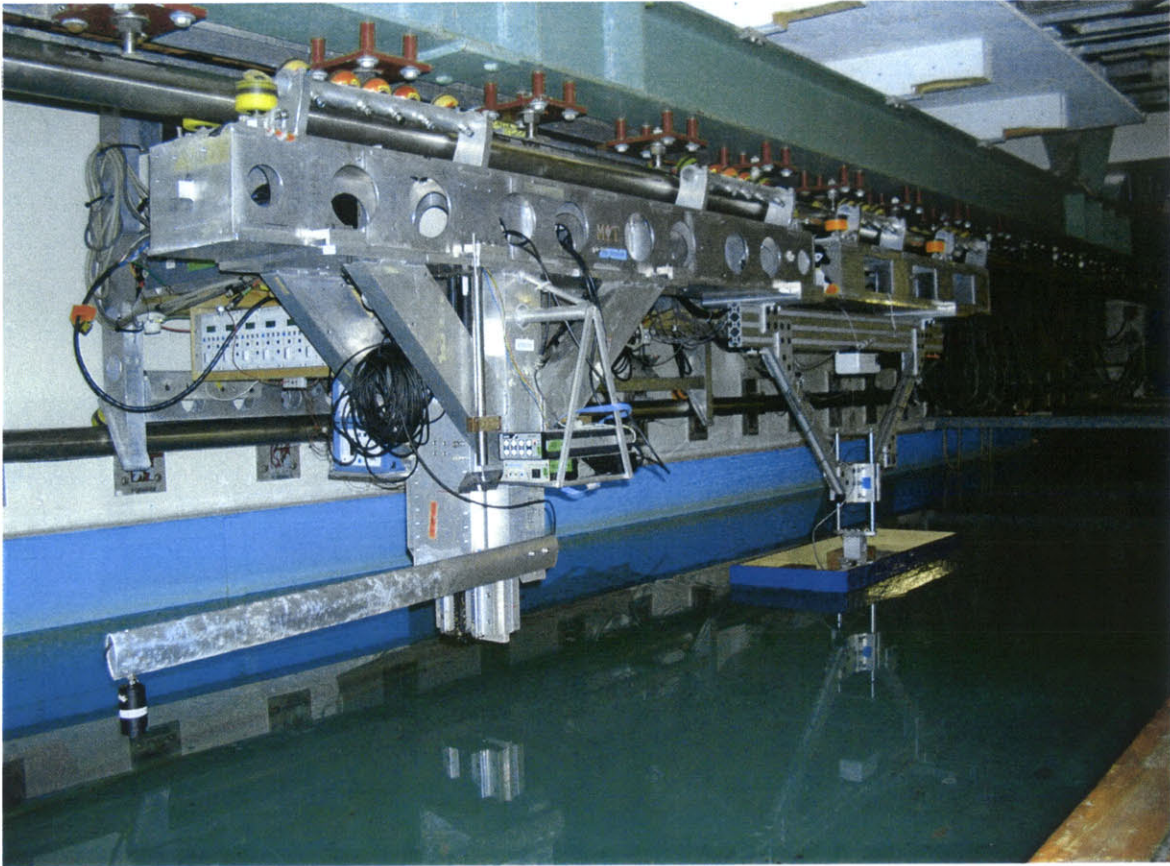


Figure 19. Primary carriage with 3' barge model mouted (at right).

This new carriage, pictured in Figure 20 and Figure 21, is constructed of 80-20, a modular aluminum alloy building material. This carriage has been primarily designed for testing model ships, but because of the versatility and modularity offered by the 80-20 building material, the carriage can serve for any type of experiment with relatively small loads and which requires higher speeds. Due to the two rail system, the new carriage has a shelf, with surrounding cage-style railings, to hold amplifiers and signal conditioners. The new carriage has proven to be extremely sturdy, and should provide a research platform for all model testing and any research that requires light loads and forces.



Figure 20. Front-quarter view of the light-weight carriage and Series 60 model.

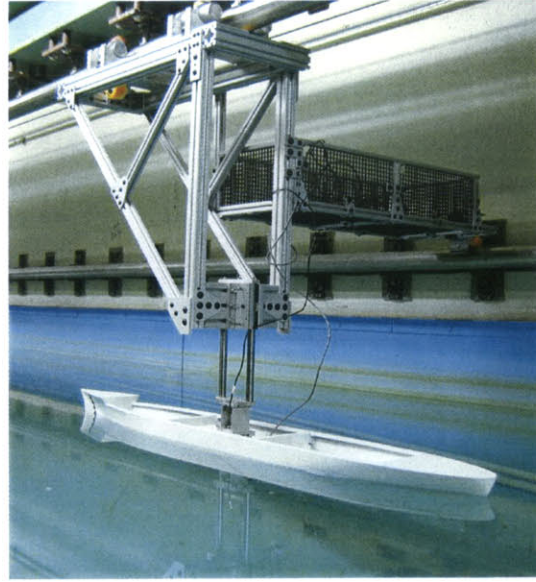


Figure 21. Rear-quarter view of light-weight carriage and Series 60 model.

Results of Upgrades

The new motor and drive system have substantially increased the accuracy, speed, and acceleration of the previous system. The goal at the onset of this project was to improve the acceleration capabilities of the carriage to enable long steady state runs at speeds of at least 1.5 meters per second (or 4.9 feet per second). At the present time, the original carriage has achieved speeds of 1.6 m/s, with what appears to be ample power to achieve greater speeds.

The creation of a lighter weight carriage enables researchers to perform tests at even higher speeds. Since the primary carriage weighs approximately 600 pounds, accelerating and decelerating it will require large amounts of torque. By creating a lighter carriage (on the order of 50 pounds), the loads and torques on the motor are significantly reduced. Table 2 outlines the speeds and accelerations that are obtainable with the combinations of the new motor with the existing heavy and new light-weight carriages.

Table 2. Target maximum velocities and accelerations of the new drive and control system.

Carriage Configuration	Maximum Velocity	Maximum Acceleration
Primary Carriage	1.6 m/s (5.2 ft/s)	1.0 m/s ² (3.3 ft/s ²)
Light-Weight Carriage	2.5 m/s (8.2 ft/s)	1.5 m/s ² (4.9 ft/s ²)

In resistance tests of a Navy ship model prior to the motor upgrades, runs were performed up to 1.5 m/s. However, the highest speeds proved difficult to obtain, as the carriage took most of the towing tank’s length to accelerate to speed. The chart in Figure 22 plots resistance versus time, but the resistance data can also be used to imply the carriage velocity (increasing resistance correlates to the carriage accelerating). This figure shows an initial spike where the carriage began motion, followed by a very long period where the speed was increasing. It is not until the very end of the run, where a “plateau” was possibly reached (the data is slightly doubtful), before the carriage was stopped from reaching the far end of the tank.

Following the installation of the new motor and control systems, the same model was run at 1.5 m/s. Figure 23 is a plot of the results. A comparison shows that the new motor and controller have provided greater acceleration of the carriage, resulting in a long “plateau” or region of steady state, where a resistance measurement can be taken. Note that in both cases there was “noise” within the resistance measurements. This is a normal part of towing tank data, which is accounted for by taking the average reading across time. Furthermore, there is less noise in the older data because it was run through a post-processing filter to reduce noise, while the newer data was not.

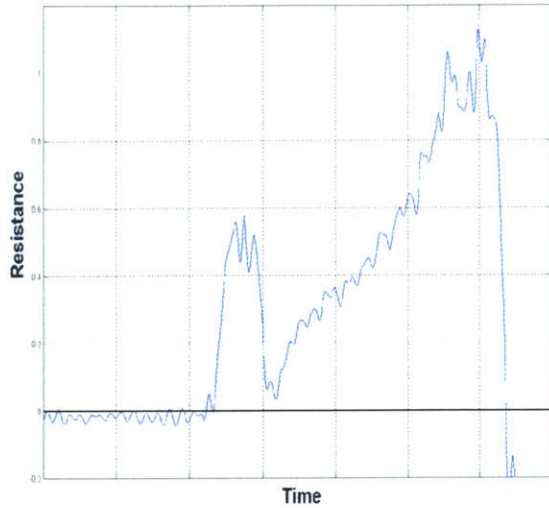


Figure 22. Resistance plot for a Navy Destroyer model, prior to the motor upgrade.

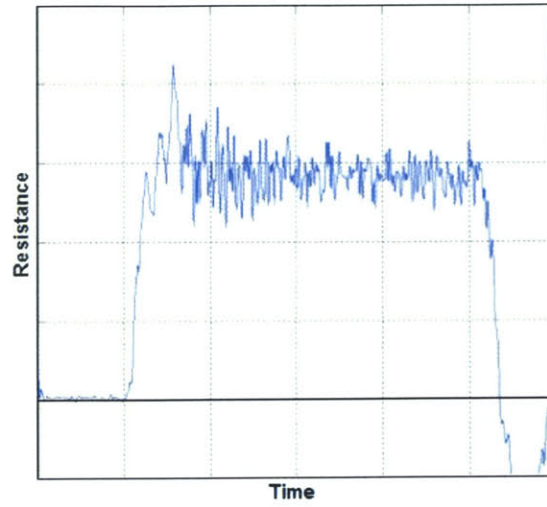


Figure 23. Resistance plot for the same model as Figure 22 after new motor upgrade was completed.

***iMARINE* INTERNET-BASED LEARNING TOOL**

The educational value of towing tanks has been well known for many decades. In fact, it was a driving reason for the creation of the M.I.T. Towing Tank in the 1950's. With the new upgrades and the merger of all controls with LabVIEW, the potential emerged to allow M.I.T. to share the educational value of the towing tank with other schools. This is accomplished via the use of the Internet, and allows for web-based, distance learning experiments to take place. In creating this new system, the towing tank joined the *iMarine* project which was already underway at M.I.T..

The *iMarine* project is a web-based learning application designed to create online tools and educational resources for teaching naval architecture and naval engineering. It has been funded by the Office of Naval Research (ONR) under the National Naval Responsibility for Naval Engineering (NNRNE) project. One part of the *iMarine* endeavor is to create online access to laboratories and experiments that might not otherwise be accessible to students. These laboratories have been termed "*iLabs*". A goal was set to incorporate the M.I.T. Towing Tank as an *iLab*, to allow students from other universities (and perhaps high schools) to perform simple ship resistance tests via the Internet.

The power and capabilities of the LabVIEW software have enabled this integration of the towing tank into the *iMarine* system. Programming was developed to allow for a controlled interface between students and the towing tank. Through the remote connection, students can input testing parameters, are able to watch the tests live via web-cameras, and are instantly supplied with the raw sensor data from the test, upon its completion.

To further the educational usefulness of the towing tank, both for *iMarine* and local M.I.T. class labs, a 5-foot Series 60 - 0.60 block coefficient parent hull was purchased by M.I.T.. The fiberglass model was built by Creative Models and used a mold owned by Webb Institute. While the lines of Series 60 hulls are not "modern," there are several

benefits associated with this model. Series 60 models have been tested in nearly every model basin around the world. Resistance data is well published and accepted. As a result, testing of this model offers the opportunity to validate the accuracy of the M.I.T. Towing Tank. Furthermore, it gives students some baseline results for comparison when performing class-related tests.

Educational Value

Despite the limitations, small towing tanks offer many benefits, especially to educational institutions like M.I.T.. Interestingly, these benefits have not changed very much since the tank was first built in 1951. In their paper describing the M.I.T. Towing Tank, Abkowitz and Paulling (1953) listed the advantages of small towing tanks for university-based research. The list included:

- Small tanks require small models (5 to 6 feet on average), thus decreasing model construction cost and time. Furthermore, small models can be constructed by students; something that would be impossible on larger scales.
- A small facility is easy to use, and can usually be operated short-handed, and even single-handed. This further facilitates student use of the towing tank for research.
- Academic institutions do not usually have sufficient funding to cover the continual costs of operating and maintaining a large towing tank. These costs are significantly less for a smaller facility.
- Since the facility's primary purpose is to serve the academic and research needs of the institute, rather than generate revenue via commercial work, outside work can be chosen based on the availability of the tank and by the "basis of the benefit to the educational process of the staff and students."

Today, this list can be expanded to include the benefit of providing a research platform for many types of experiments, other than ship model testing. This is especially important since research interests at M.I.T. have diversified since the inception of the

M.I.T. Towing Tank. In short, there seems to be no limit to the diversity of applications that can be tested at M.I.T.'s towing tank.

In addition to small scale, university research, the towing tank has many pure educational benefits. The hands-on and experimental nature of towing tanks offer students another means of comprehending the classroom subject matter. For example, watching a ship model generate a Kelvin wave pattern provides a concrete reference to the pictures and theory taught in class. Several times during the year, M.I.T. classes hold laboratory sessions where demonstrations and experiments are conducted in the towing tank. These tests include bare-hull resistance, resistance in waves, and seakeeping applications.

The educational value of a towing tank has been evident since well before the creation of M.I.T.'s towing tank, and the university has capitalized on these benefits for many decades. With the advent of new technology, linking the M.I.T. Towing Tank to the Internet was made possible; and under the same educational premise, this link was created for the purpose of learning. While hands on experiments are almost always the most educational, a web-based experiment can be considered the next best alternative for schools that do not have the resource of their own towing tank.

iMarine Features

Utilizing the functionality of LabVIEW, several of the towing tank controls were simplified, automated, and linked to the Internet. This allows students to have limited control of the towing tank, and offers them the opportunity to run customized experiments.

Students are able to use the towing tank by logging onto an *iMarine* webpage that has been specifically created to act as the user interface. The webpage allows the student to input the desired testing speed. It also features two web cameras, from which the students can watch their live experiment. Figure 24 is a screen shot of the two web camera views during an actual experiment. The top camera is attached to the carriage to

allow students to see the ship model and the waves that are generated. The bottom camera is fixed to the side of the tank, and provides a view of the carriage approaching and then moving past the camera.

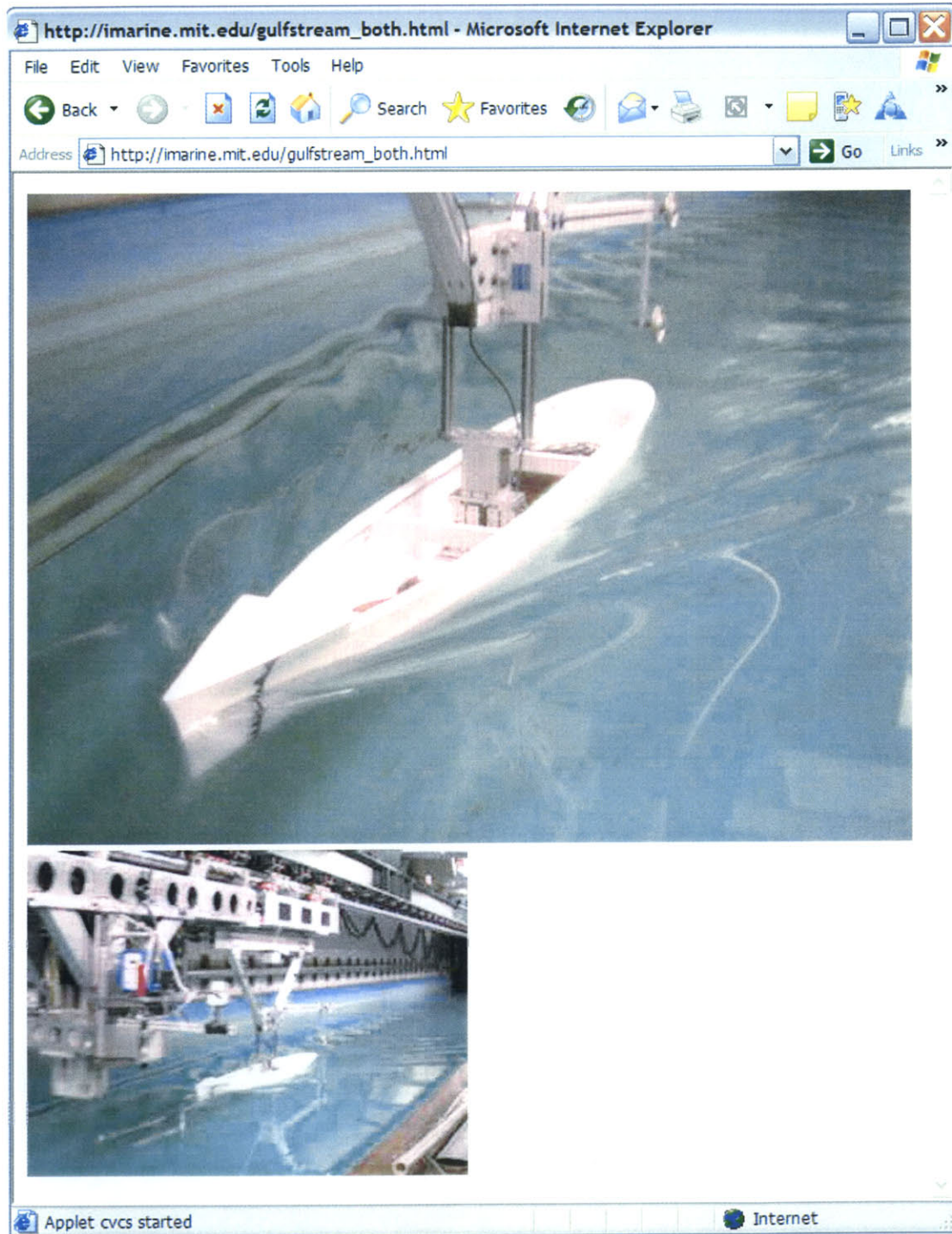


Figure 24. Screen capture of the iMarine web cameras during a model test.

At the M.I.T. Towing Tank, the LabVIEW program monitors the Internet and receives commands from the iMarine website. When the students submit a test, this speed is read by LabVIEW and a fully automated run sequence is initiated. LabVIEW uploads the speed to the motor, triggers the DAQ system to begin recording data, and commands the carriage to begin moving. Once the carriage has completed its run, the DAQ stops recording and immediately posts the data file to the iMarine website. This gives students immediate access to the results of the experiment. Simultaneously, the carriage begins its backup procedure to reset itself for the next test run. Lastly, a timer forces the system to wait a predetermined amount of time to allow the waves to dissipate in the tank before the next test is run.

Throughout the design of the system, safety and security was of primary concern. To achieve a safe test setting, several layers of security were incorporated into the system. First, the iMarine system cannot run without first being initialized by a supervising individual at the M.I.T. Towing Tank. When runs are being conducted, no input from this individual is required, but this person must remain at the facility as a precaution, and has the capability of terminating the Internet connection and stopping all testing at the press of a button. Second, the website is username and password enabled, which means only authorized users may use the *iMarine* system. Lastly, the LabVIEW program has been equipped with a queuing feature that allows the student to upload multiple runs. These runs will then commence in the order received, and only after the waiting period from the prior run has expired.

A set of detailed instructions for the set up and operation of the *iMarine* system is located in Appendix A.

An Extended Example

In April 2006, the students of the Engineering Fluid Mechanics course at Maine Maritime Academy (MMA), instructed by Dr. Richard Kimball, participated in the first *iMarine* laboratory experiment of the M.I.T. Towing Tank. The lab was a series of simple ship

resistance tests, in which total drag was measured. The procedure and results of which are described below. The lab instructions that were provided to the students can be found in Appendix B.

The setup for the *iMarine* lab is extremely simple for the educator. At MMA, the classroom setup consisted of a computer with Internet access and an LCD projector. For the MMA test, the entire class participated in one lab; however, it could be run in small groups, to allow for more interaction. Figure 25 is a photograph taken during the MMA *iMarine* lab.



Figure 25. *iMarine* lab underway at Maine Maritime Academy.

At the time of the experiment, the instructor logged onto the *iMarine* website with the pre-assigned user name and password. The instructor opened the webcams for the class to view the ship model and then opened the “submit experiment” webpage. This

webpage allowed the instructor or student to input the testing speed decided upon by the class. While a maximum speed is predetermined and limited by the *iMarine* and LabVIEW software, the open-ended input for test speeds gives the students to opportunity to learn about scaling techniques and perform the calculations. With the speeds determined, the speed, an experiment name, and any additional comments or notes for the test were entered on the *iMarine* website, as pictured in Figure 26.

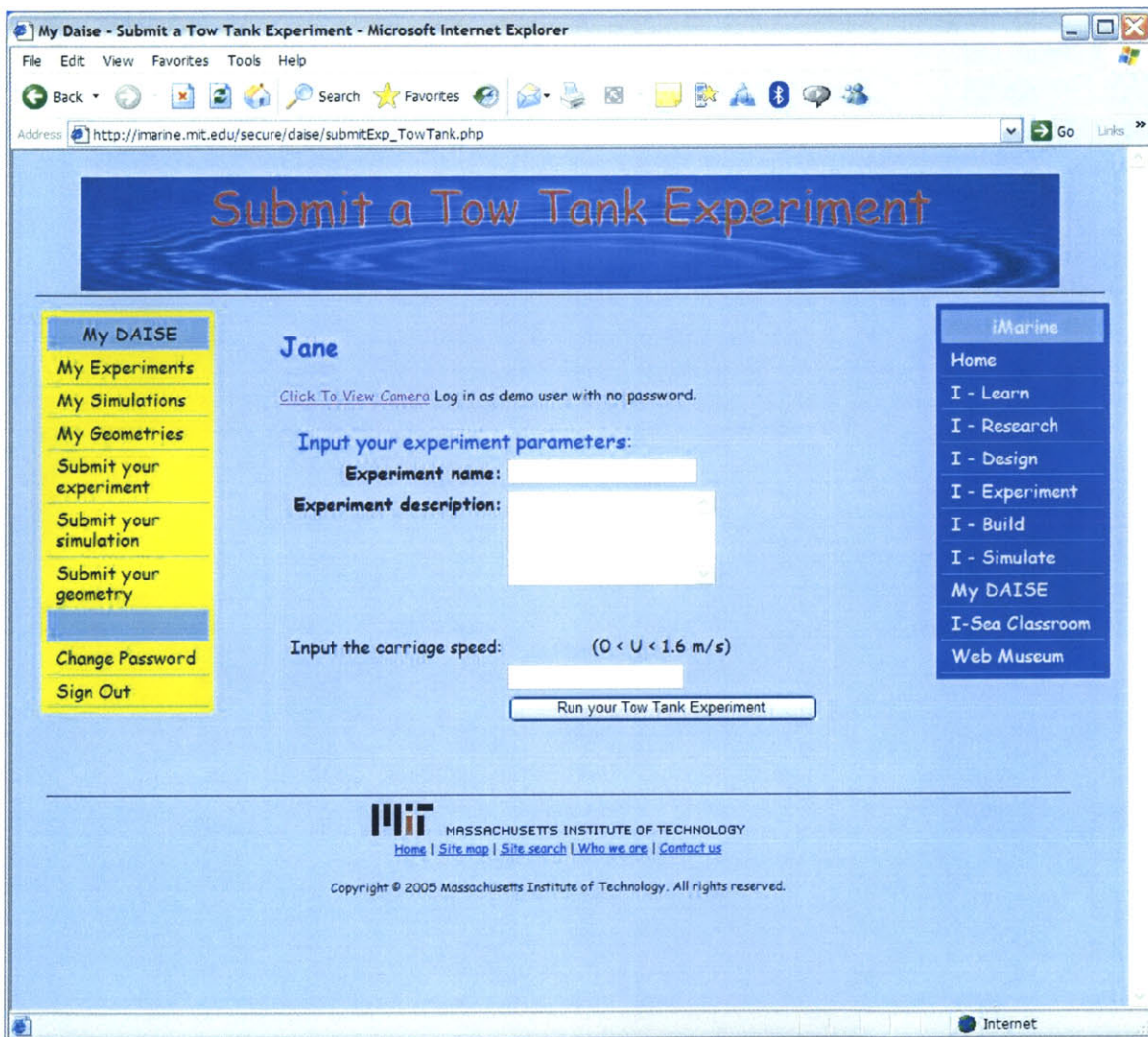


Figure 26. *iMarine* website screen capture.

Upon clicking the “Run your Tow Tank Experiment” button, the data was transmitted over the Internet to the towing tank computer running LabVIEW. As previously

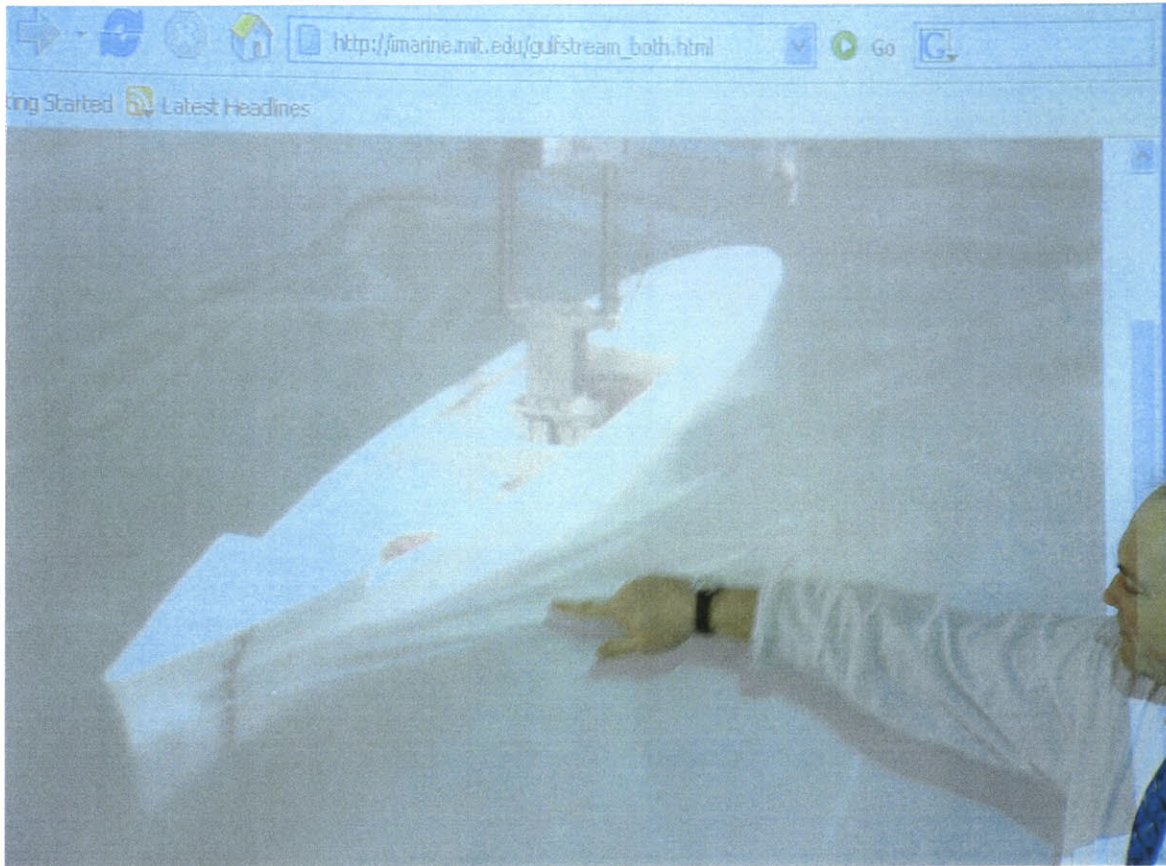


Figure 27. The webcams and automated iMarine system allowed for discussion during model testing.

Dr. Kimball also suggested a potential extension of the iMarine system, beyond a simple model test demonstration lab. During the past semester, Dr. Kimball directed his class in a project to design a barge. A model was constructed and was tested at the M.I.T. Towing Tank; however, this was prior to the implementation of *iMarine*. As such, tests were performed, but few students were able to attend the tests. In the future, the testing of models that students have designed and constructed can be performed at the M.I.T. Towing Tank with the *iMarine* system. This would allow for the entire class to witness the testing via the Internet, while simultaneously recording very important resistance data on a hull form of their own design.

Another noteworthy extension of the iMarine enabled towing tank is that the experiments can record additional types of data such as heave, pitch, and a wave cut. Furthermore, the experiment does not necessarily have to be ship model testing. Since the webcams can be

lab because it was conducted on the students' last day of the Spring semester, at a time when students were more likely to be interested in summer plans than ship model testing. This peak in interest is especially promising for the future use of *iMarine*.

One student commented on the class demonstration:

Overall I was very impressed by the lab. It was a valuable learning tool that brought to the foreground the need for non dimensional scaling. With this lab being the inaugural run for (hopefully) more labs to come, I feel that things were organized and presented in a "user friendly" approach. I would find it interesting if more opportunities were available to do more experimentation and research through MIT's tow tank. The staff that ran the tow tank that day was gracious in allowing us to utilize their facility and for this I thank them.

Dr. Kimball made additional comments about the lab and some of the unexpected benefits. First, he found that with the LCD projector and classroom setting, all the students had an excellent view of the experiment, as recorded by the webcams. He compared this to actual tests in the towing tank, where the view is limited, and decreases as the number of students participating increases. This was not the case for the *iMarine* lab. Second, it was reported that because the tank operation was automated, meaning that the students were not responsible for its operation, their full attention was directed toward watching the experiment. This gave Dr. Kimball the opportunity to point out key features of the testing, while it was happening. For example, Figure 27 depicts Dr. Kimball highlighting the wave-making properties of the model during an actual test.

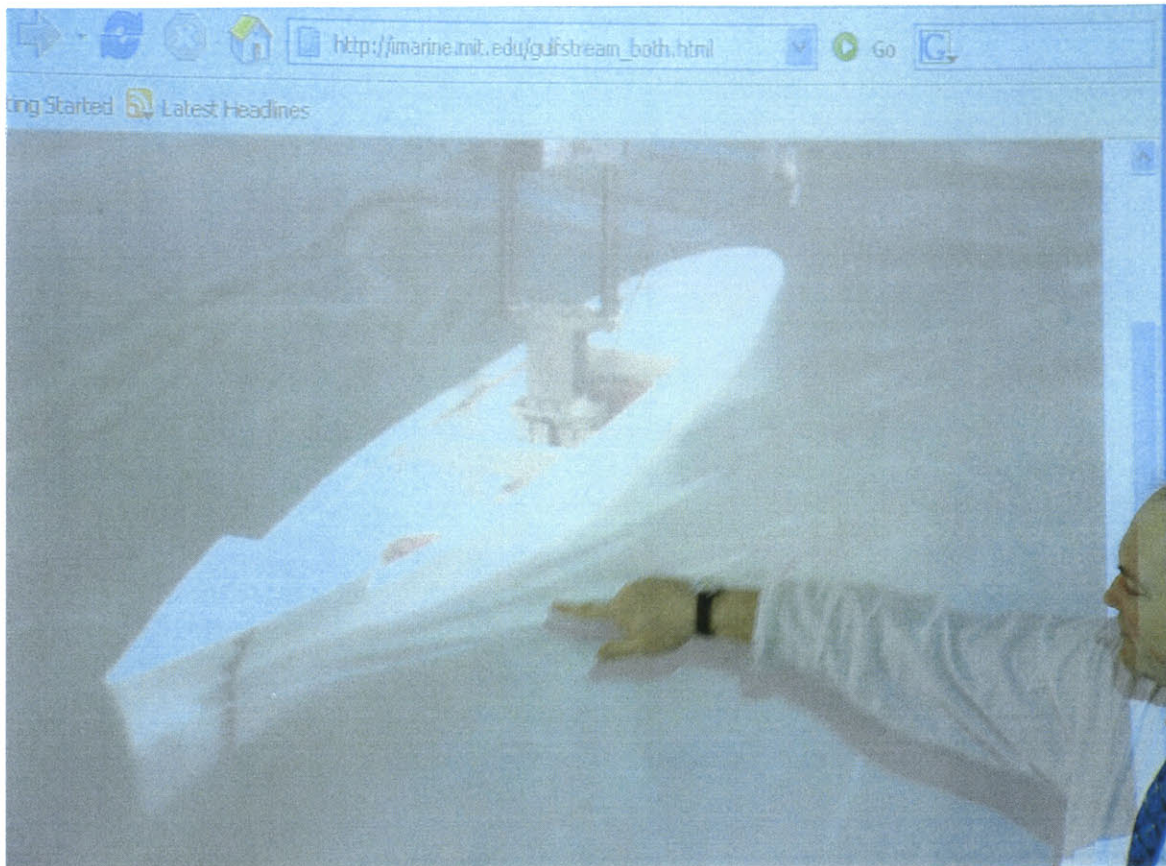


Figure 27. The webcams and automated iMarine system allowed for discussion during model testing.

Dr. Kimball also suggested a potential extension of the iMarine system, beyond a simple model test demonstration lab. During the past semester, Dr. Kimball directed his class in a project to design a barge. A model was constructed and was tested at the M.I.T. Towing Tank; however, this was prior to the implementation of *iMarine*. As such, tests were performed, but few students were able to attend the tests. In the future, the testing of models that students have designed and constructed can be performed at the M.I.T. Towing Tank with the *iMarine* system. This would allow for the entire class to witness the testing via the Internet, while simultaneously recording very important resistance data on a hull form of their own design.

Another noteworthy extension of the iMarine enabled towing tank is that the experiments can record additional types of data such as heave, pitch, and a wave cut. Furthermore, the experiment does not necessarily have to be ship model testing. Since the webcams can be

mounted nearly anywhere, and LabVIEW's DAQ system is highly flexible, the *iMarine* system can be customized to put nearly any towing tank test on the Internet.

The *iMarine* program should be considered an invaluable, 21st century tool that extends the educational benefits of the towing tank research facility to a broad range of students who would otherwise not have access to such a facility.

COMMERCIAL APPLICATIONS

The M.I.T. Towing Tank will always be an educational and research-based facility; however, commercial testing is still a very real possibility. The upgrades of the facility make the likelihood of commercial tests even greater.

Model Testing

Despite the technical limitations of small model testing, there still exists a place in the ship design process where small model testing makes financial sense. Both Fireman, *et.al.* (1982) and Fisher (1982) described how small models can work in conjunction with a large model testing program. Small models cannot produce precise powering estimations that large models can. However, they can be used on a comparison basis, such as in evaluating designs with slight geometric evaluations.

A brief survey of several of the leading commercial towing tanks was conducted to gather information on basic model fabrication and resistance testing costs. On average, the costs of producing a large ship model with relatively simple lines, on the order of 25 or 30 feet in length, is approximately \$18,000. The cost of conducting a very basic set of resistance tests is \$10,000. These costs can be compared to a small model which can be constructed for approximately \$3,000 and tested at a small university tank for under \$1,000 per day. In a small towing tank, a set of resistance tests can be accomplished in under one day.

The modern process of developing a commercial ship hull form combines large model testing with computational fluid dynamics (CFD) programs. First, CFD is used to find an optimal hull form. Next, the model is constructed and a series of resistance and power tests are performed. The results are then studied, and modifications are made to the ship model. Finally, a more thorough set of resistance and powering tests are performed on the final hull form. Generally speaking, the costs of this type of design and tank testing program total \$150,000. Presently, the total design and engineering costs for a commercial ship is approximately \$6 million. This is assuming the engineering and

design work are being performed in the Far East, since the process of full design and engineering of large commercial ships has moved out of the U.S. in the past decades. It is thus appropriate to say that tank testing accounts for roughly 2.5% of the total design costs of a ship. Fireman performed a similar study of several military craft in the early 1980's and found the average percentage of design costs from model testing accounted for 5%. It is very likely that this value still holds true today.

The argument can then be made that CFD has taken over for the small model to identify optimal hull forms. This argument has merit. However, CFD requires considerable man-hours to input hull shapes, and huge quantities of computer processing hours. For every hull form configuration, this process needs to be repeated. As such, small models tested at M.I.T. or other university tanks may be competitive in cost and time, considering that the testing of a hull will cost approximately \$4,000.

As CFD use increases, the techniques and codes used will receive additional validation. For simple hull forms CFD is likely to produce results that are more accurate than small model tests. Furthermore, the large commercial towing tank facilities have well developed programs for hull form optimization of particular hull shapes. For example, these commercial facilities are likely to have an efficient and accurate method of optimizing containership or tanker hull lines. As such, small model testing may not prove to be competitive. However, CFD still has limitations, and in some applications, the validation of even a small model may prove useful.

One argument strengthening the validity of using models is that CFD codes do not simulate sea states. Model testing can be performed to find the added resistance in a seaway, such as a head sea, but CFD codes cannot simulate this. Thus, model testing and small models in particular, become an easy and relatively cheap way to perform such tests.

A further breakdown of the \$150,000 tank testing cost shows that approximately half this cost is used for the final set of resistance and propulsion tests. This leaves \$75,000

towards preliminary hull form testing. This sum of money could easily allow for the construction and testing of numerous small ship models, representing varying hull form designs. From this series of tests, the most efficient hull form can be identified, and then a large model can be constructed and thoroughly tested. If even a one percent increase in hull form efficiency results from testing and selecting the best design with small models, then the savings in fuel costs alone, over the lifetime of the ship can add to a significant sum of money. For instance, assuming a ship's annual fuel costs are \$13 million and a ship life of 25 years; then a one percent reduction in fuel consumption would result in a savings of over \$1 million in present dollars. This also makes the assumption that fuel costs will not rise any further, which at the present time is doubtful. Such a savings is extremely significant, especially since this is over six times the total model testing costs for the initial hull design.

Other Commercial Work

Today, more commercial work is being performed on vortex induced vibrations (VIV) in the M.I.T. Towing Tank, than any other type of commercial work. The upgrades of the facility only serve to enhance the accuracy and capability of these tests, and could serve as a stimulus to bring additional work to M.I.T..

Independent of this project, there has been recent interest within the towing tank research group to obtain a rapid prototyping or 3D printing system. Such a system would allow students and researchers to create models for testing. Given the size of a ship model, it would need to be produced in several pieces, but still would offer a very quick and nearly labor-free method of constructing models. The systems being considered cost approximately \$20,000 to \$30,000. By adding a 3D printing machine, the opportunity would be made available for rapid fabrication and testing of any type of research, whether educational or commercial.

A Differentiated Service

With the new upgrades, the M.I.T. Towing Tank has become a very viable option for commercial testing applications. Furthermore, with the creation of software to automate the towing tank and link it with the *iMarine* system, a new mode of using the towing tank has been created. This concept can very easily be extended from its primarily educational purposes, to become a commercial testing tool.

Tank testing is a time consuming process, and while naval architects would like to be present for all testing, they often are not able to spare the full amount of time required. By creating a commercial version of the *iMarine* system, the naval architect may not have to leave his or her office. In the simplest of cases, the small models can be shipped to the M.I.T. Towing Tank. One at a time, the models can be ballasted, prepared, and mounted to the carriage by M.I.T. operators. The commercial *iMarine* system could be enabled and the control of the tank testing would be relinquished to the naval architect, sitting in the comfort of his or her office.

With a buffer system in place, the naval architect could upload a series of desired speeds to test at, and the towing tank would take over and perform the tests. As each test is completed, the data would be instantly sent to the naval architect via the internet or email. This new capability would expand the commercial uses of the M.I.T. Towing Tank by offering a service that has never been attempted before.

CONCLUSION

The goals of this thesis were to increase the accuracy and usefulness of the M.I.T. Towing Tank via an upgrade of its systems, and then to utilize these capabilities to create an online learning tool for students. The results have shown that the facility is now more capable to suit the research needs of a variety of experiments, while also serving as an educational learning tool for students at M.I.T. and at distant schools and universities.

The effort to modernize the facility resulted in the replacement of the carriage drive and control system. The new servomotor system has improved accuracy, the capability for increased speeds and accelerations, and the ability to perform a wide variety of motion profiles. Combined with new software control programs and data acquisition hardware, the new system offers a simplified method to operate the M.I.T. Towing Tank.

Additionally, the upgrades have enabled the linking of the towing tank with the Internet, thus tying the towing tank into the existing *iMarine* program. The educational value of this new system has been demonstrated by the recent online tests performed by Maine Maritime Academy students, and serves to identify the potential the *iMarine* program has toward educating the next generation of scientists and engineers.

The M.I.T. Towing Tank has provided over sixty years of service as a research and education facility. While small towing tanks have their limitations, M.I.T. has consistently utilized its facility to its full potential, and the newest upgrades only add to this endeavor. Simultaneously, the upgrades and combination of remote access to the tank will allow for additional commercial work to be sought after, thus making the facility and extremely well rounded and very valuable tool to the M.I.T., education, research, and industry communities.

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APPENDIX A: MIT TOWING TANK USER MANUAL

Overview

This manual will discuss how to operate the following systems and features of the M.I.T. Towing Tank:

1. Carriage Operation
2. Data Acquisition
3. Wave Maker
4. iMarine web-based, distance learning program
5. Switching between carriages

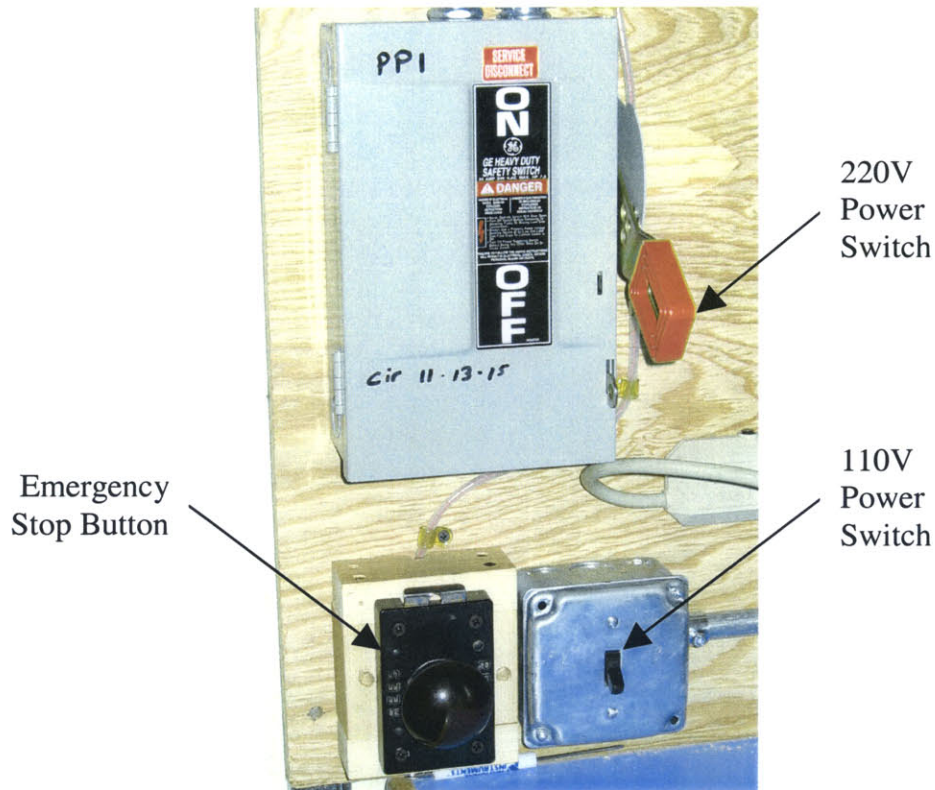
The Towing Tank is capable of performing a variety of tests. The facility has two testing carriages. The larger carriage is the steady platform on which most tests are performed. It can operate at speeds up to 1.6 m/s, with accelerations of approximately 1 m/s/s. The lightweight-carriage is suitable for experiments that do not generate large loads, and that require higher speeds. It is capable of speeds of 2.5 m/s and accelerations in excess of 1.5 m/s/s.

The following pages are step by step instructions for operating each feature.

Carriage Operation

Setup

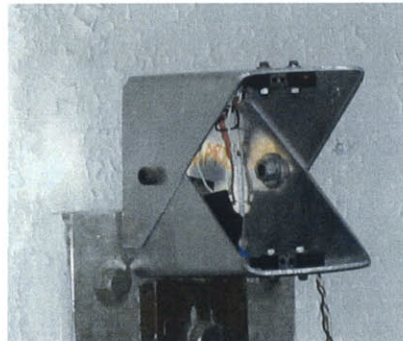
1. Check that there are no obstructions along the towing tank that could be in the line of motion of the carriage.
2. Power up the motor and controller by turn on the two switches (220V and 110V) on the wall to the left of the towing tank control computer (as identified in the picture below).



3. Ensure that the two emergency stop switches are released. One switch (as pictured above) is located next to the power switches. Release this switch by pressing the metal bar (at the top of the switch) down. The second emergency stop switch is located halfway down along the side of the tank (pictured below). It is released by turning the knob counterclockwise, as indicated by the arrows.



4. Open the appropriate carriage control program. You must use the correct program for accurate and safe operation! These program are located on the desktop of the towing tank control computer:
 - For velocity control of the large carriage open the “Normal Carriage Velocity Control” LabVIEW program
 - For velocity control of the light-weight carriage, open the “Light-Weight Carriage Velocity Control” program.
 - For position control of either carriage, open the “Carriage Positioning” program.
5. Be sure that the carriage you are using is connected to the drive belt, and that the other carriage is moved to the extreme end of the towing tank, out of the normal range of motion.
6. In the LabVIEW program, click the “run” arrow located in the menu bar in the upper left corner of the window.
7. You must home the carriage before any other motion is permitted. The homing limit switch is mounted to the wall, just above the side rail, at the far end of the carriage (see picture below).



- If the carriage is behind the home switch (that is, between the home switch and the far limit switch), click the “Home Forward” button.
- If the carriage is forward of the home switch, click the “Home Back” button.

Once clicked, the carriage will seek the home switch, and move in both directions. Once the homing operation is complete, you may begin tests. Follow the corresponding directions below for the type of motion you require.

Velocity Control

1. Enter the speed you require (in meters/second) in the field labeled “Enter Carriage Speed.”
2. Check that all obstacles are clear of the carriage’s path.
3. Click the “GO” button to command carriage motion.

If for any reason you need to stop the carriage, you can click the red “STOP” button in the program. This will stop the carriage at a modest deceleration. In an emergency, or for an immediate stop, press one of the two emergency stop buttons (located next to the towing tank control computer and midway down the length of the tank).

Reversing the Carriage

1. Enter the speed at which you want the carriage to back up in the “Back Up Speed” field. The maximum allowed speed is 0.6m/s.
2. Click the “Back Up” button to begin motion.
3. The carriage will return to its starting position.

Position Control

1. The carriage can be commanded to move to any position along the tank, from 0 to 17 meters. The home, or zero, position is located at the far end, by the homing switch.
2. Enter the desired position in the “Position” field.
3. If desired, enter the speed at which the carriage will travel in the “Speed” field. The default speed is 0.4m/s.
4. Ensure that no obstructions are in the way of the carriage.
5. Click the “GO” button to move the carriage.

Shutdown

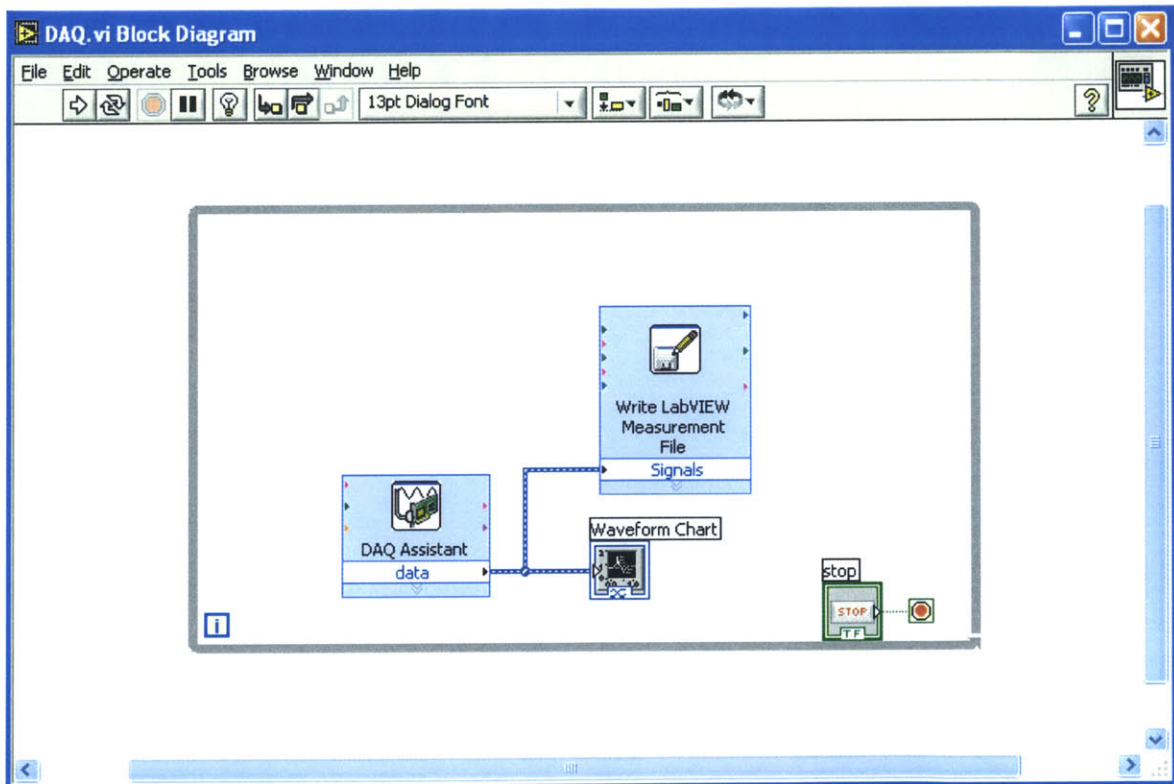
1. Re-home the carriage by clicking the “Home Back” button.
2. Once motion has stopped, turn off the 220V and 110V switches.
3. Click the “stop” button on the menu bar in the LabVIEW program, and then close the program.

Data Acquisition

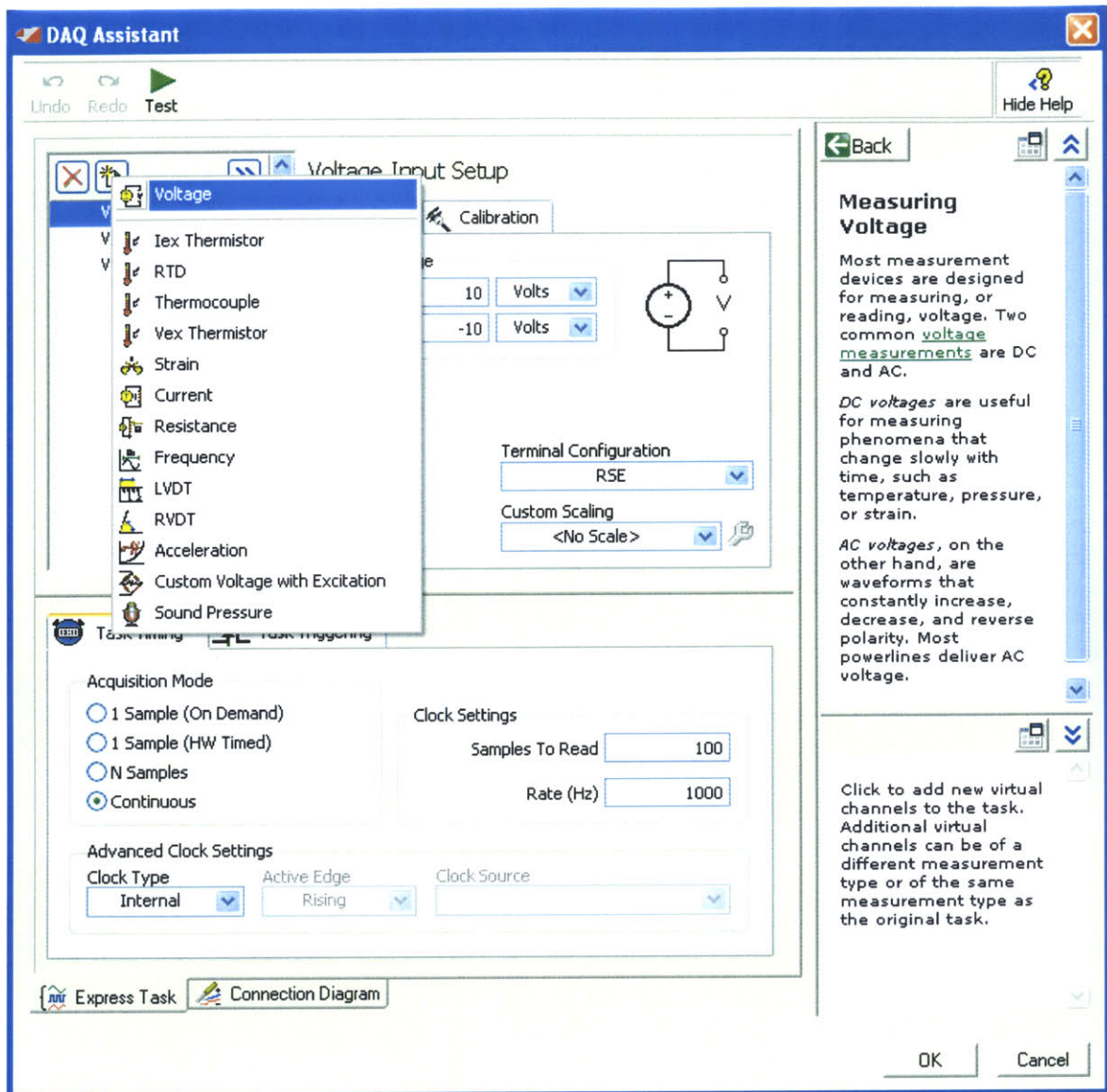
LabVIEW allows for simple and advanced forms of data acquisition. The two National Instruments BNC racks, located below the towing tank control computer, are connected to the computer, and are used for DAQ purposes. There are 32 analog inputs (labeled ACH0 – ACH15 on each rack) and 4 analog outputs (labeled DAC0OUT & DAC1OUT on each rack). Connect your instrumentation to the appropriate plugs.

A simple LabVIEW program has been created for basic voltage DAQ, but can be modified for any type of experiment.

1. Double click on the “DAQ” LabVIEW file on the desktop of the towing tank control computer to open the LabVIEW program. This is a read only file.
2. Click Window > Show Block Diagram, to open the block diagram programming interface. The picture below is the view you will see:



3. Double click on the DAQ Assistant box to access the controls for the DAQ system. A window will pop up. The upper portion of this window describes the channels of data being displayed. In this case, three voltages (labeled 0, 1, and 2) are being accessed.
4. To delete a channel, select it and click the “X”. To add more channels, click the button to the right of the “X”. For additional analog voltages, select the voltage option, as shown on the next page.



5. A new pop-up window will ask you to select the channel. These channels correspond to the BNC racks below the computer. Analog inputs ai0 to ai15 are on the upper rack, while ai16 to ai31 are on the lower rack. Choose the channel that corresponds to the connection you require. (Voltage 0 is connected to ai0, Voltage 1 to ai1 and Voltage 2 to ai2).
6. Continue until all DAQ requirements have been met. When complete, click the OK button to get back to the Block Diagram.
7. Close the Block Diagram. Perform a Save As command to save your new DAQ program.
8. To record data, click the run arrow near the top left corner of the window. You will be prompted to enter a file name and location. Your data will record in a .lvm (LabVIEW measurement file) that can be opened by any ASCII text editing program.

Wave-Maker Operation

Start-up Procedure

1. Open the “Wavemaker control” VI on the desktop of the towing tank control computer.
2. Using a BNC cable, connect the “Signal In” connector on the wavemaker controls to the “DAC00OUT” connector on the top National Instrument rack.
3. Turn the “Wave Height” knob clockwise until it stops. This should be its maximum setting.
4. Turn the “Wavemaker Servo Amp” switch to the on position. The power light should turn on.
5. Make sure that the hydraulic fluid valve (located behind the hydraulic pump) is open (this should already be open).
6. Turn the cooling fan on by plugging it into the 110V receptacle.
7. Turn the hydraulic pump on by pressing the “On” button on the wall behind the hydraulic pump.
8. Close the hydraulic fluid valve.
9. Allow the pressure gage located near the paddle to build up to full pressure (approximately the 2 o’clock position).

Creating Waves

1. In the LabVIEW program, choose the frequency and amplitude at which you want to run the wave-maker. The chart in the bottom right corner of the window will serve as a guide for picking the corresponding amplitude for your desired frequency. DO NOT use too high an amplitude.
2. Click the Run arrow near the upper left corner of the screen to begin waveform generation.
3. Slowly turn the black “On/Off” knob (on the wave-maker controls) clockwise to the “On” position. This will turn the paddle on, and ease into the wave-making.
4. To stop wave-making, turn the “On/Off” knob counterclockwise to the “Off” position.

Shut-Down Procedure

1. Open the hydraulic fluid valve and allow all fluid to drain into the reservoir.
2. After a few minutes you will hear the fluid stop draining. Once this occurs you may shut the hydraulic pump off and unplug the cooling fan.
3. Switch off the “Hydraulic Servo Amp.”

iMarine Setup and Operation Procedure

With the ship model connected to the carriage, the iMarine system can be run as follows:

1. Open the “iMarine Control” LabVIEW program from the desktop of the towing tank control computer.
2. Click the “run” arrow located on the menu bar in the upper left corner of the window.
3. Home the carriage according to the same procedure under normal carriage operation.
4. With the LabVIEW program running, it is now ready to be run via the internet.

Someone should always be present during an iMarine lab. This supervisor must ensure that the iMarine LabVIEW program is operating, and that the carriage can run unobstructed.

If for any reason the runs must be stopped, one of the two Emergency Stop buttons should be pressed.

To reset the iMarine program, click the stop button located on the menu bar in LabVIEW, and then click the run arrow, in that same menu. This will cycle the program and erase any runs that may have been in queue.

The LabVIEW program stands by and listens to the internet for commands. As a test speed is sent, the program sets the motor speed accordingly. It then activates the DAQ system and initiates the run. When complete, it backs the carriage up and waits a predetermined amount of time for the water to calm down.

The back up speed and wait time can be controlled by the supervising individual at the towing tank. The defaults are 0.4m/s for backing up and 3 minutes wait time.

The number of channels and type of data recorded can be adjusted by entering the block diagram and adjusting the “DAQ Assistant” in the same manner as described in the Data Acquisition section of this manual.

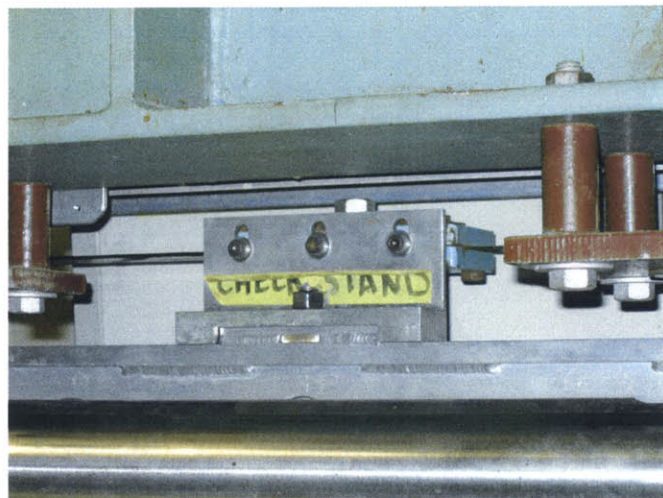
Switching Between Carriages

To switch carriages, the drive belt must be disconnected from one carriage and connected to the other.

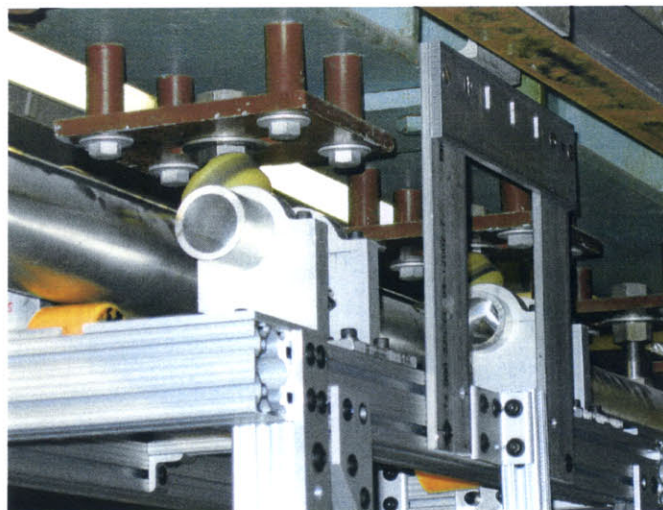
USE CAUTION AS THE BELT HAS VERY SHARP EDGES!

The belt is connected to the carriages by three small socket cap screws and a steel clamping plate. This clamping plate remains attached to the belt at all times. This is the point of connection between the belt and carriages.

Using an allen key, unscrew the three screws that connect the clamping plate to the carriage. Slide the carriage out of the way, and slide the new carriage in place. Then replace the screws. Below are pictures of the belt attached to the large carriage, and the mounting location for the lightweight carriage.



Large Carriage Attachment Point



Light-weight Carriage Attachment Point

APPENDIX B: iMARINE LABORATORY INSTRUCTIONS

ES245 Eng. Fluid Mechanics Spring 2006 MIT Tow Tank Test Lab

NAME: _____

Objective:

For this lab, the class will test a series 60 ship hull model in the MIT Tow tank using their imarine web-based laboratory controls. The model is a 5 foot long scale model of a 400 foot long ship. We will test the model at a variety of speeds and generate the resistance curves vs. speed for the vessel. From this data we can compute the non-dimensional resistance coefficient and estimate the powering and resistance of the full scale ship.

Prelab computations:

Find the range of test speeds for the model if the full scale ship is intended to operate between 0-20 knots (1 knot = 0.54 m/s). (Hint: Froude #)

Model Test Speed Range: _____

Compute the Reynolds number at the max operating speed for both the model and the full scale ship. Assume water density = 1000 kg/m³ and kinematic viscosity of 1×10^{-6} m²/s.

Remodel = _____ Reship = _____

Tow Tank Test:

Using the MIT Imarine system the instructor will submit tow tank test runs to the MIT Tow tank. The model will be instructed to be tested at a constant ship speed for the run and the drag data will be collected. The students need to pick the test speed to generate the resistance curve for the model. We will test for about 4-6 speeds for this model.

The data will be collected on the Imarine server and downloaded to MMA. The data file consists of an ascii file of the instantaneous resistance measured in pounds force during the run. We will need to extract the average resistance for the run. The initial data starts before the model is moving and thus there is no force. Once moving the ship ramps up to speed, then proceeds at a steady speed down the tank before it decelerates at the end of the tank. Note from figure 1 below that the data has a lot of variation. This is due to the vibration of the model while being tested. In order to get the average resistance at the test speed the data in the "constant speed" region must be picked and averaged. This average resistance value at the test speed will be plotted along with the data at other speed to

generate a ship resistance curve. Table 1 is a data sheet of the test speed and average resistance data for the model.

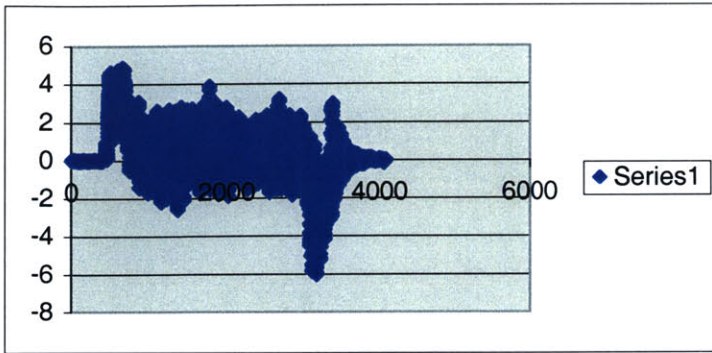


Figure 1: MIT Tow tank run of Drag vs. time.

Test Speed m/s	Drag lbf

Table 1: Data Sheet for drag vs. speed data

Full scale ship predictions:

From the resistance data for the model estimate the resistance and propulsion required for the full scale ship at 20 knots. First compute the appropriate model speed to represent the full scale ship at 20 knots. Then, from the resistance data at that speed compute the resistance coefficient for the model at this speed using the following formula:

$$C_t = \frac{\text{Dragforce}}{\frac{1}{2} \rho V_s^2 L^2} = \underline{\hspace{2cm}}$$

Finally, compute the drag force for the full scale ship at the full scale test speed (20 knots). Also compute the propulsion power required to push the full scale ship through the water at 20 knots.

Full scale Design speed: 20 knots
 Full Scale Resistance: _____
 Full scale Power: _____