Panama Canal Commission
Final Report

Vessel Positioning Project

Contract No. PAP-3926-BGP

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ABSTRACT

In this conceptual design study the task of identifying promising alternative approaches for vessel positioning in the Panama Canal Locks has been addressed. The study has been conducted in a class setting by students and faculty in the Engineering Program at Texas A&M University for the Canal Capacity Projects Office of the Panama Canal Commission. The period of study was January 1, 1999 to June 30, 1999.

The main motivation for the study is the need to improve upon the existing positioning system with respect to inherent excessive wear and maintenance as well as to increase throughput. Primary positioning system functions involve vessel control initiation, towing, stopping, holding, precise dynamic centering, and accommodation of elevation changes in the Locks. The system must perform these functions efficiently and reliably with minimum wear, maintenance, manpower, energy and cost on a wide variety to vessels. The system can either be applicable to the existing locks or to additional new locks that are under consideration by the Panama Canal Commission.

Six possible solutions have been identified in the study. These ideas include an autonomous or joystick automated robot winch, a traveling bit system, a system that employs counterweights for centering, a truss ship attachment concept, a bumper system using viscous cells, and a floating lock. Operational descriptions and system requirements are presented as well as preliminary designs.

Two additional ideas not related to the project scope but that might enhance Lock operations are also presented. One idea involves modifications of the lock gate sills to reduce turbulence, and the other is a recirculating water reservoir concept for water conservation.

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INTRODUCTION

Project Description and Tasks

This final report presents the results of Contract No. PAP-3926-BGP entitled "Project to Identify and Evaluate Alternative Concepts for Vessel Positioning at the Locks." This study was conducted for the Panama Canal Commission's Canal Capacity Projects Office by the Texas Engineering Experiment Station, which is the Engineering Research Division of the Texas A&M University System. The period of this conceptual design study was January 1, 1999 to June 30, 1999.

The objective of the project is to brainstorm a variety of possible alternative techniques for dynamic centering, towing and stopping vessels that transit the system of locks at the Panama Canal. From these possible approaches six of the most promising ideas are to be chosen and analyzed to the extent possible in the time period. The analyses are to include operational descriptions, preliminary designs and cost considerations. The alternative systems can either be applicable to the current system of locks or to possible larger additional new locks that are under consideration by the Panama Canal Commission. Almost no constraints are stipulated except only minimum modifications to vessels are allowable; for example some modifications to the vessels' existing attachment points are feasible, but hull modifications or attachments are not feasible. Also economic considerations are to be secondary to effectiveness, feasibility, practicality, and reliability aspects of the concepts.

This interdisciplinary study is to be conducted by undergraduate and graduate students and faculty from a variety of engineering disciplines at Texas A&M University in close cooperation with Panama Canal Commission Engineers and Pilots. This approach was stipulated, as opposed to the traditional research project, because it was felt that a group of students often can be very creative in envisioning possible solutions that might not be identified in another setting.

Current Positioning System and Motivations for the Study

The current system uses special purpose locomotives operating on tracks on the lock walls to tow, stop, center and hold vessels throughout the locks. These functions are accomplished through the use of winches and cables attached to the mooring points on the vessels, and traction is achieved via electric power driving a pinion gear engaged with a rack that runs the length of the locks. An onboard pilot achieves vessel control through visual sensing of vessel lateral and longitudinal position and velocity. Precise control is critical since there is only two feet of clearance between the lock walls and the hulls of the larger vessels, and wall contact is undesirable. Effective dynamic control is required due to inevitable external disturbances such as water turbulence and wind.

This system has worked fairly well for many years and is generally reliable and safe. However the large shear forces inherent in the system have resulted in heavy wear on the rack and pinion, winch systems and locomotives that require costly and frequent maintenance and replacements. This has accelerated as traffic and the size and weight of vessels have increased, and this trend is expected to continue. Thus the main motivation for the identification of alternative positioning systems is to reduce the wear, maintenance and manpower requirements and associated costs while increasing throughput in a safe and reliable fashion.

Excessive Wear

The first observation that we have made in the study is that the wear on the current system is excessive for several reasons. A primary reason is due to the positioning system configuration. If there are locomotives with flexible attachment cables only on one lock wall for towing and stopping, then because the cable is never parallel to the vessel an undesirable lateral force is created that tends to pull the vessel into the lock wall. Consequently additional locomotives must be used on the opposite walls whose functions are not only to tow and stop, but also to counteract the opposite lateral forces so centering can be achieved. Thus "wasted forces" and associated excessive wear and necessary over design of system components are inherent. On the other hand, this lateral stretching action provides a built-in impediment to external disturbance forces to some degree, and thus enhances lateral control. In an ideal *minimum wear* configuration that only applies forces that are necessary and no more, the longitudinal and lateral forces should be uncoupled. That is, longitudinal towing and stopping forces should only be directed from the centerline of the locks to the centerline of the vessel. On the other hand, lateral-positioning forces should only be directed perpendicular to the vessel and never applied unless needed due to external disturbances arising from water turbulence, wind etc. An alternate system that achieves or reduces this longitudinal and lateral applied force coupling would be desirable from the viewpoint of minimizing wear, but lateral position control may or may not require more complexity than in the current system. This would depend entirely on the nature of the positioning system used.

Another observation related to excessive wear in the current system is that a rack and pinion cannot effectively accommodate large shear loading. Shear loading is inherent in the current configuration and cannot be avoided except through an alternate design.

Also, it appears that unnecessary over control is occurring in the current process, resulting in more shear loading than is necessary to effectively laterally position the vessels. The over control that is occurring is due to the uncoordinated action of the various locomotive operators. Maximum winch forces are being applied at times when less force would be adequate. Another factor affecting the over control is the time delay that occurs between the time a vessel begins to lose its centerline position (due to disturbances) and the time this error in position is noted by the pilot, corrective action is determined, communicated and actuated by the locomotive operators.

The time delay or lag between an error in vessel position and applied control action is particularly detrimental and often occurs to varying degrees in any system that relies on human operators in a feedback control loop. This is due to the fact that humans lose attention easily, grow weary of repeated tasks, and the fact that visual sensing is often imprecise, particularly in poor visibility conditions.

To demonstrate the effect of excessive time delay and other phenomena in the system we have developed a simulation (see Appendix) using MATLAB SIMULINK of the lateral and longitudinal motion of any vessel in water subject to any type of forces, disturbances or initial conditions. Using SIMULINK the vessel can also be coupled to a "perfect" lateral positioning control system. The control system employed receives sensed lateral position error information in real time and automatically applies appropriate lateral corrective forces using an industry standard Proportional-Integral-Derivative (PID) controller.

As an illustration of the detrimental effect of time delay in control actuation, consider a 65,000 ton vessel, 600 feet long with a 12 foot draft, an aspect ratio of 12.5 and a freeboard height of 24 feet. The PID control system can supply lateral forces on the vessel up to a maximum of 140,000 pounds on either side. Suppose the vessel is for some reason positioned laterally one foot from its desired position and is moving at that instant laterally at a rate of 0.1 feet per second further away from the desired position. This deviation is sensed at that time and appropriate control action is automatically applied without delay to restore the vessel to the desired position as indicated in Figures I.1 and I.2.

Figure I.1

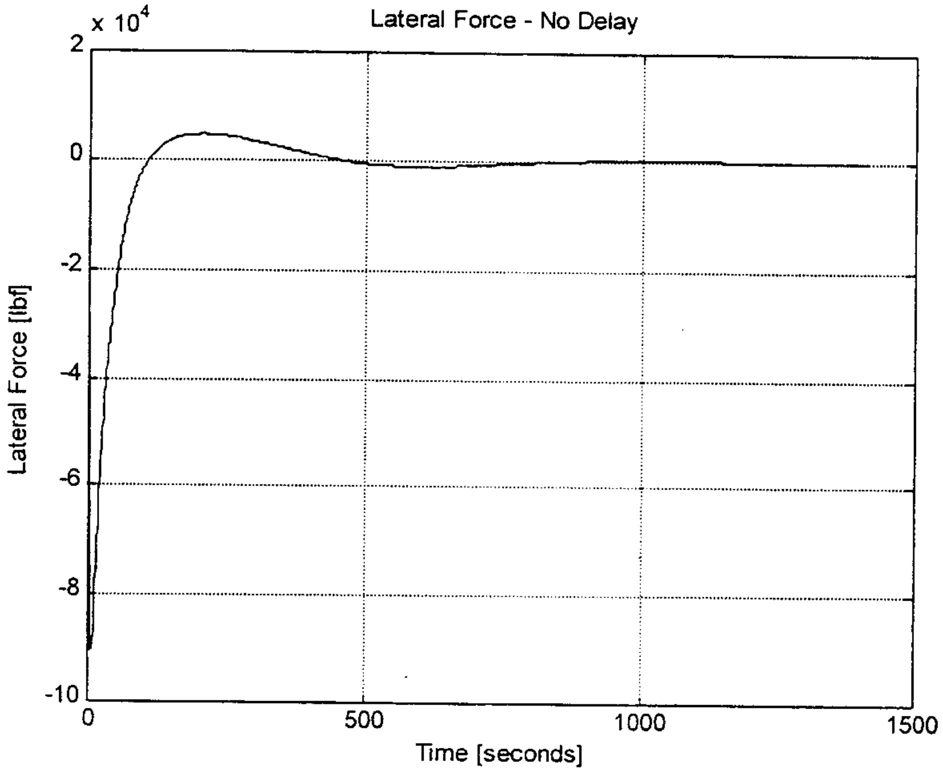


Figure I.2

Notice that the control system is very stable, it easily and smoothly accomplishes the centering task, and no control saturation occurs.

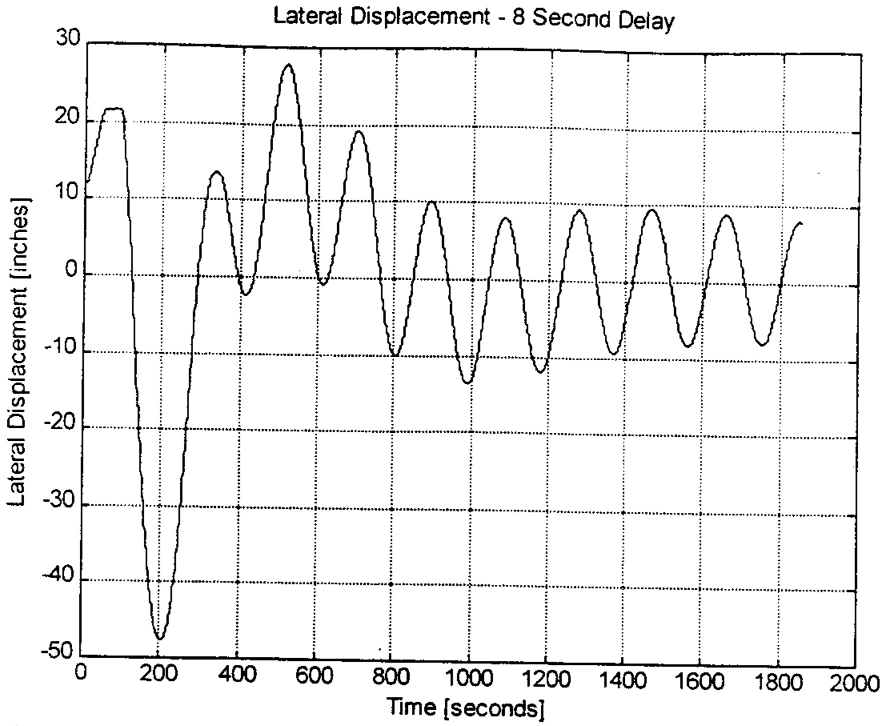


Figure I.3

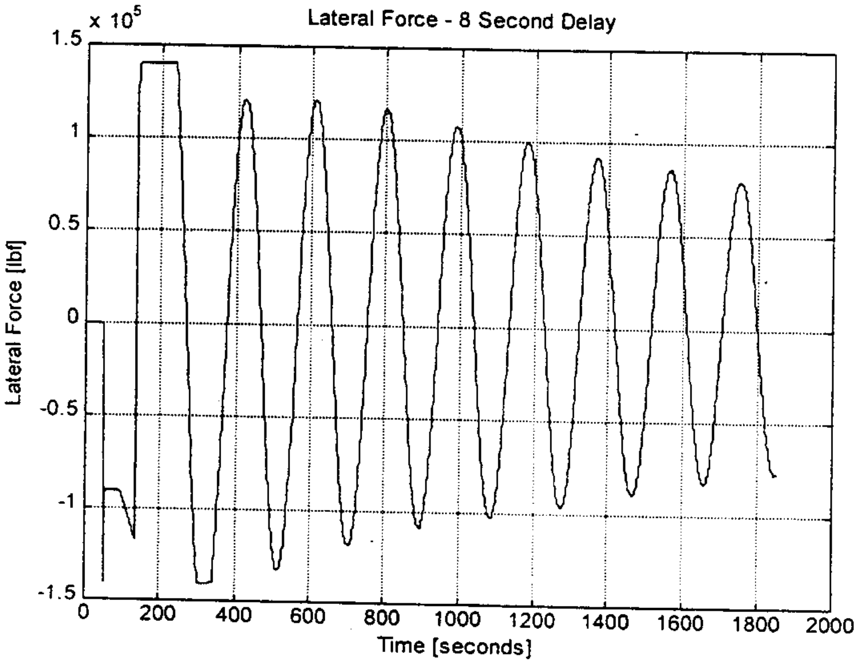


Figure I.4

Now consider the same vessel under the exact same control system and with the same initial perturbation, but with an 8-second delay before any control action is applied (Figures I.3 and I.4).

Because of the time delay the response is highly oscillatory and large control forces are applied over a long time period causing excessive wear on the system that is unnecessary. An eight-second delay is probably extreme, but serves to illustrate what can happen in a worst case scenario. In addition, when there is time delay even more control force occurs when the control system is not perfect, for example using "bang-bang" control whereby only maximum forces are applied, similar to the current positioning system.

The point of this simulation and discussion about control actuation time delay is to point out that in order to minimize system wear it is very important to accurately and rapidly detect vessel deviations from the desired lateral position and apply corrective restoring forces as soon as possible. This has been one of the guiding principles in the identification of alternate positioning systems in this study.

Class and Process

To accomplish the study a new course entitled "Creative Solutions to Engineering

Systems Problems" was created, and 12 graduate and undergraduate students were selected from mechanical, electrical, industrial and ocean engineering. The course began with discussions of the brainstorming and creative processes, the "systems engineering" process, on working in groups effectively, and of course on the nature of the problem. An essential aspect was a class trip to the Panama Canal early in the semester to gain first hand knowledge of the operation and issues. Equally important was a visit to Texas A&M University later in the semester by Mr. Boris Moreno Vasquez and Mr. Juan Wong H. from the Canal Capacity Office and Captain Raul Brostella for further understanding and guidance.

Approximately two thirds of the semester was spent in developing a function structure, brainstorming a multitude of possible approaches, and selection of six of the most promising approaches. The remainder of the semester was dedicated to further development and design of these selections. An important tool in the whole process was a dynamic Web Page (http://pcc-tamu.edu) that served as a central location for information and activity for the class as well as a vehicle for featuring the project.

Function Structure

The problem is very challenging due to the fact that there are a multitude of functions that must be effectively accomplished. First, a critical task is to initiate control at the lock entrance. This is a difficult task because of the severe currents and tides that are often present, and the necessity of connecting cables to the vessels in the current process. Next the system must provide effective centering throughout the lockage, towing, stopping and holding at the lock gates, and accommodation of the inherent level changes. The system must be able to accommodate a large variety of vessels and operate in rain, fog and poor visibility. A critical element is failsafe operation, particularly with respect to stopping at the gates in the event of failure of any part of the system. The design should provide maximum throughput and exhibit minimum wear, maintenance, manpower and energy requirements. In addition a desirable feature is a system that will ameliorate the so called "piston effect." Finally the importance of capital costs is evident.

In the initial brainstorming process for concepts it is important to identify only the basic required system functions and associated parameters without influence from the additional desirable features. For example, if cost is allowed to be an initial important factor, it is very likely that some idea that might possibly evolve into a practical solution would never surface or receive adequate consideration. The Project Objective Statement and Function Structure that was used to guide the initial brainstorming process follows in Figure I.5.

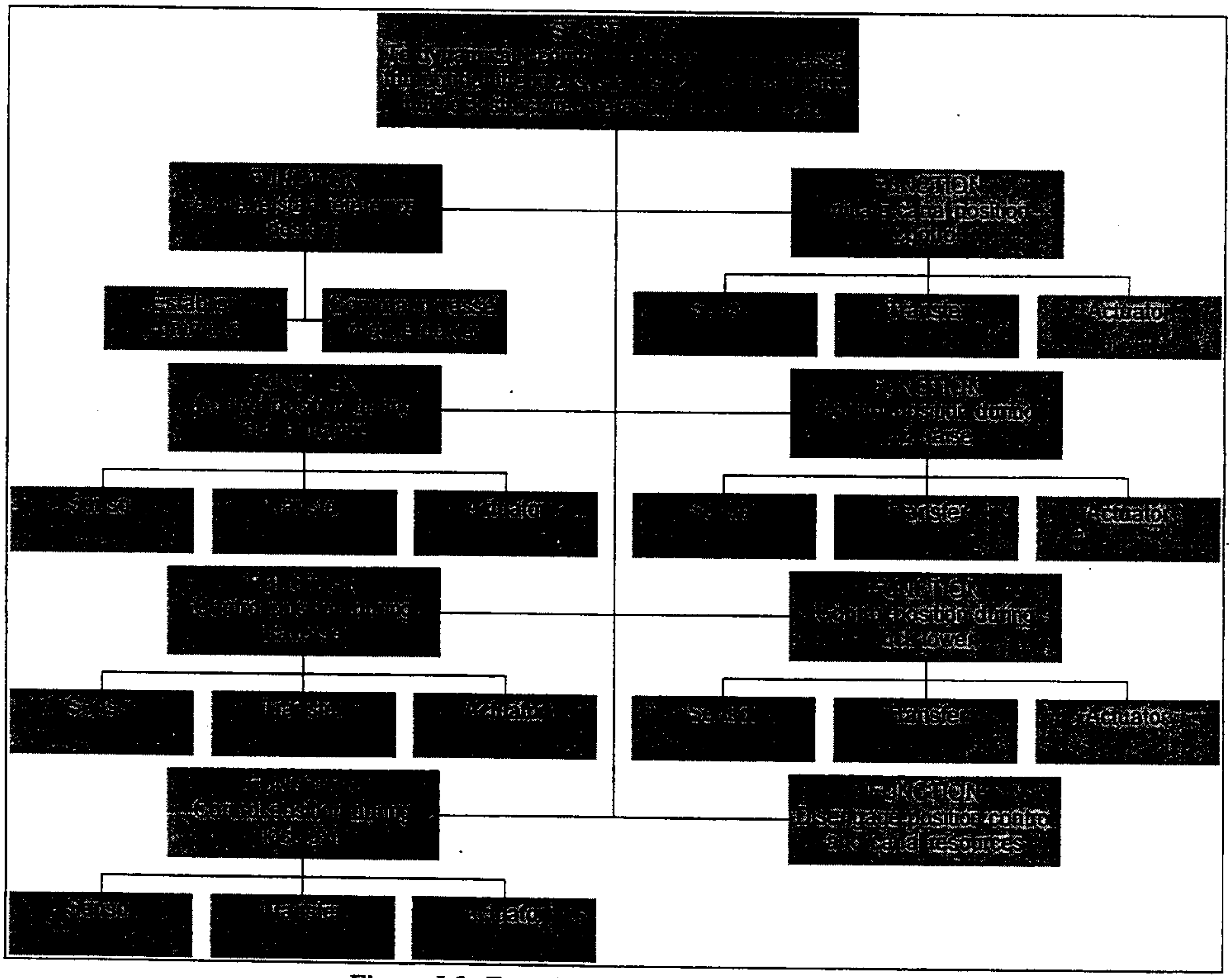


Figure I.5: Function Structure.

Brainstorming and Evolution of Ideas

Following the identification of the problem, the brainstorming process was carried out. Starting with a list of basic natural and technological phenomena capable of providing and imposing forces on a vessel (see Appendix for the list), several conceptual ideas were proposed. The research group was divided into small teams of four members each to do a preliminary study on the feasibility of the ideas. All these ideas were documented (see Appendix) and discussed with the representatives of the Panama Canal Commission. Some of the initial ideas were farfetched, but such thinking was encouraged to engender creativity. The research team then developed a matrix consisting of the most important factors. The matrix was then used, along with feedback from the representatives from the Commission, to select the ideas that the research group felt were worth exploring in more detail (refer to the Appendix for the complete matrix). For every concept that was determined improbable, the team took on the challenge of "how to make the idea work." It should be noted that while reviewing the ideas, Dr. Len-Rios' idea for a magnetic self-centering mechanism was reviewed (see Appendix).

As a result of this process, the following ideas were selected:

Integrated Robot Winch – This is similar to an automated version of the current system but does not use locomotives.

Rack and Pinion - A pinion gear is attached to the ship and a rack along the lock wall.

Two Degree of Freedom Winches - Uses a winch on a vertical structure to provide the longitudinal and lateral forces while optimizing cable angles.

High Tension Tight Rope - Uses a cable stretched across the lock with a winch attached to the ship to provide lateral forces.

Spring System with Natural Equilibrium - A truss system that uses springs to passively provide centering forces on the ship.

Lateral Forces Using Counter Weights - Cables attached to the vessel are connected to a counter weight mechanism to passively provide centering forces.

Hydraulic Actuated Side Cars - Provide longitudinal and lateral forces using hydraulic pistons attached to a cart that moves along the side walls.

Truss - Use a telescoping truss to obtain a rigid push pull connection. This connection allows lateral, longitudinal and angular correcting forces.

Floating Lock - Use a floating structure to provide a consistent interface between the stationary lock structures and varying ship geometry.

Synchrolift – Use a conformable cradle to control the ship motion by imparting forces directly on the hull.

Magnetic Systems - Use magnetic forces to control the position of the ship inside the lock. This is the combination of many magnetic conceptual ideas.

Bumper Systems – Use a bumper system to protect the ship from damage caused by lock wall interactions. This is a combination of the many bumper conceptual designs.

Traveling Bit – Attach Cables of fixed length to the vessel and to carts that are propelled by a mechanical drive system mounted on the lock wall.

Floating Approach Wall - Allow any position control system to initiate control before the ship enters into proximity of the non-compliant concrete lock structure by using two floating structure.

Viscous Cells – Hydraulic bumpers along the lock walls provide passive cushions; pulling and stopping are achieved using fixed winches at the gates with long cables.

The research team was then sub-divided into three new groups of 4 people. Each of these four groups then selected four ideas to explore in more detail. The reason for the re-shuffling of the groups was to ensure the best-suited mix of backgrounds to explore the specific ideas the group was assigned. As the groups explored the feasibility of each one of these ideas, some of them were dropped or combined with other concepts to be able accomplish the different tasks required by the traverse process. From the original 12 selected ideas, the list of ideas that were discarded by the research team along with reasons for dismissal follows.

Conceptual Idea	**Reason for Dismissal**
Rack and Pinion	Several shortcomings due to having to mount a large device on hull of the vessel.
Two Degree of Freedom Winch	Including a vertical degree of freedom below the lock wall would reduce the maximum size of ships that could traverse the lock. The benefits provided by this design could not justify this “waste” of space
High Tension Tight Rope	Many of the features of this design were used to make the Traveling Bit concept feasible.

Spring System with Natural Equilibrium	This concept is very similar to the Truss idea. They have so many features in common that the spring system could be implemented in the Truss design by replacing the hydraulic cylinders with springs.
Hydraulic Actuated Sidecars	This idea was found to be very similar to the truss idea. Many of it unique features were incorporated into the Truss design. Therefore, further development was not pursued.
Magnetic Ideas	This concept's ability to impart a physical force is inversely proportional to the square of the separation distance from the hull of the vessel to the magnet. This was a fundamental physical handicap for this idea. Additionally, any magnetic idea would not be able to control the traverse of any vessels with hulls non-ferrous.
Bumper Systems	Capital intensive system with limited benefits. Though these systems minimize the potential for damage, they must be supplemented by other systems (e.g. cable/locomotives)
The Synchrolift	The inherent complexity of the linkages associated with conforming to any arbitrary hull geometry and the number of parts that would need to be underwater made this concept unattractive.

Figure I.6: Concepts discarded by the design teams

After the different design groups decided which ideas they wanted to pursue, the final design phase started. Focus was set on exploring the following six ideas:

Integrated Robot Winch

Traveling Bit

Lateral Forces Using Counter Weights

Truss

Viscous Cells

Floating Lock

Designs

The major portion of this report consists of further development of each of the six ideas. Each idea is summarized and represented graphically. Operational descriptions of the concepts which include pilot interface, human elements, lock entrance aspects, centering capabilities, accommodation of elevation changes, towing and stopping are included. System requirements, for example power, sizes, weights, configurations, etc. are presented resulting from design calculations that appear in the Appendix. The main assumption used in the development of these specifications is that the system must be able to apply a lateral force of 140,000 lb. to each side of a vessel and a longitudinal towing/stopping force of 200,000 lbf. Description of maintenance, system reliability and required infrastructure and vessel modifications are presented, and applicability to the existing locks versus potential new locks is addressed. Finally the concept is compared to the "datum" locomotive system currently in use.

Additional Concepts

In the brainstorming process and in the process of understanding the operation of the locks and the positioning system, two additional ideas not specifically related to the project scope were generated that could potentially enhance lock operations. These include a modification of the gate sill configurations to reduce the severe turbulence that is present in the locks, and an innovative water conservation concept that resulted from discussions regarding the concern over the water supply.

Finally, a system that involves a pivoting entrance and exit wall to enhance control initiation, and a description of the simulation used to test and evaluate several concepts are included in the Appendix.

INTEGRATED ROBOT WINCH

Summary

This concept incorporates into the present system an automated "robot-winch", capable of autonomous operation. A rail system, within the lock walls, transports four automated robot winch systems (one for each corner of the ship). Each "robot" carries a clutched winch system, which can be used to vary the length of the attachment cable. The rails are designed at a constant incline in order to avoid sudden elevation changes like the one caused by the ramp in the existing system. Cable length control along with positional control of the robot on the track provides lateral and longitudinal control over the ship's positions. The system can be designed for feedback control (without human interference), or for automated response for pilot control via an operational "joy-stick", of "fly-by-wire" control. The robot winches are driven using Linear Induction Motors and these motors are used to provide the longitudinal towing and braking forces. Small cranes at the entrance of the locks aid the attachment of cable to the ship structure.

The following figure illustrates this idea.

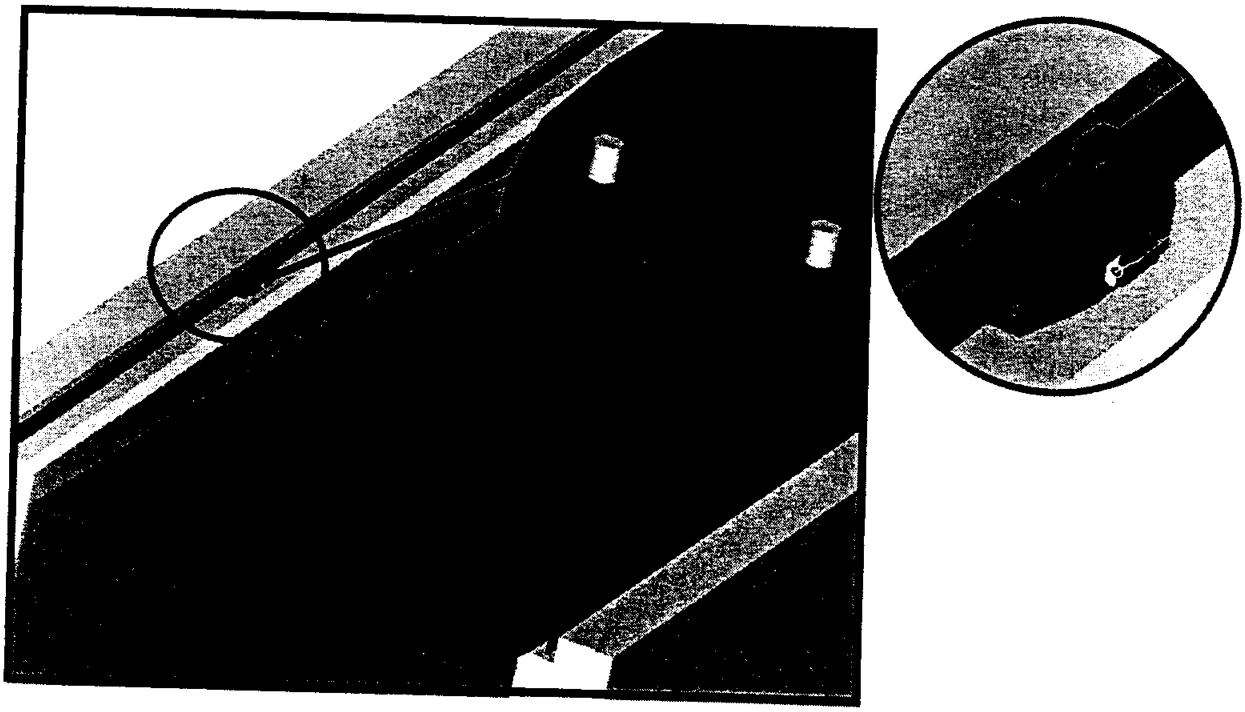


Figure 3: Sketch of the Automated Winch System

System capabilities

The system is capable of handling all types of vessels. The transit of the vessels can be achieved with minimal human interaction under all the weather conditions encountered in the lock. Attachment of the connecting cable is aided by the use of cranes at the entrance of the lock.

Operational Description

Pilot Interface

The pilot on board the vessel is provided a joystick for active control of both lateral and longitudinal ship positions. The pilot can control the position as well as the altitude of the ship within the lock. Feedback regarding the vessel position is provided to the pilot by means of monitors on board the vessel. The pilot has the option of switching between an automated mode and manual control mode. In the automated mode a computer with a control algorithm will dynamically control the position of the vessel throughout the lock system using sensors that provide the ship position information in real time.

Human elements in the system

The human operators involved in this system, apart from the pilot, will include deck hands on board the vessel and crane operators for transferring the cables onto the vessel. The cranes will be used as an alternate means of bringing the cables on board the vessel. The most critical element in the system is the pilot on board the vessel who will be needed to override the automated mode in case of emergencies. One pilot is required per vehicle transit and two crane operators are required per lock entrance.

Entrance (Gaining control of the vessel)

The attachment procedure is very similar to the one used now. While the vessel is approaching the lock entrance, tug boats and rubber bumpers are used to achieve the start position. Once the vessel is close to the center wall, the cables are supplied to the vessel using the cranes, one on each side of the lock wall. Then the cables are reeled in (via the pilot), to manually position the vessel in the desired reference point.

The side wall is shown extended to match the center wall (Figure 4). This will allow full control of the vessel from the entrance of the lock chamber. The entrance is shown wider to allow the tugs to assist in achieving the start reference position.

Achieving the start reference position is the critical part of the transit though locks. Once the vessel is in the desired reference position, the pilot can switch to the automated mode. In this mode the feedback system will control the position of the vessel and at the same time keep the distance between the rail cars constant. The distance between rail cars is maintained constant so as to enable a simple control system for controlling the cable length.

As shown in Figure 4, one side of the lock entrance is irregular. Because of the special shape of that side of the lock entrance, different control algorithms will be needed to control the cable length and distance between the cars.

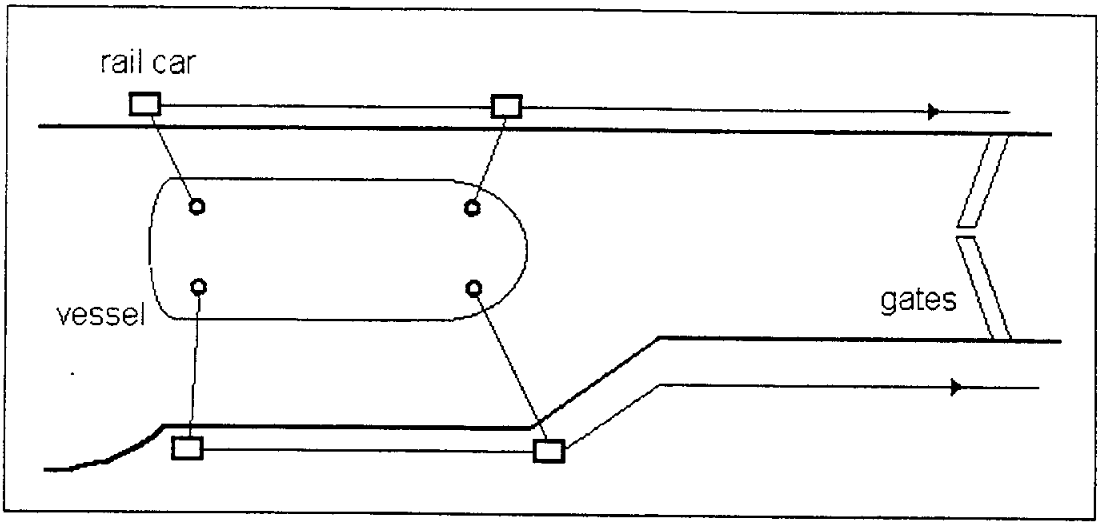


Figure 4: Lock Entrance

Forces imposed on the Ship

As in the case of the current system, pulling forces are applied to the vessel through the bits. Each rail car is designed to provide a nominal pull of 140,000 lbs. A technical description of the rail-car system can be found in the Appendix. This system could be scaled up to impart larger forces on the ship. However, the decreased response time and improved accuracy of the system will result in lower forces necessary than those required with the current system.

Centering Throughout the Transit

In order to control the ship, we need the following parameters (see Figure 5)

k_1 = distance between the mooring points in the X-axis,

k_2 = distance between the mooring points in the Y-axis,

l_1 = length of the cable attached to the mooring point A,

l_2 = length of the cable attached to the mooring point B,

d = distance between the rail cars,

θ_Z = angle between the cable and the Z-axis (for points C_1 and C_2),

θ_{XY} = the angle between the projection of the cable in the X-Y plane with the Y-axis (for points C_1 and C_2).

Note that the lengths of the cables, l_1 and l_2, are required to be controlled for only one side of the ship, the lengths of the other side being maintained at a constant value.

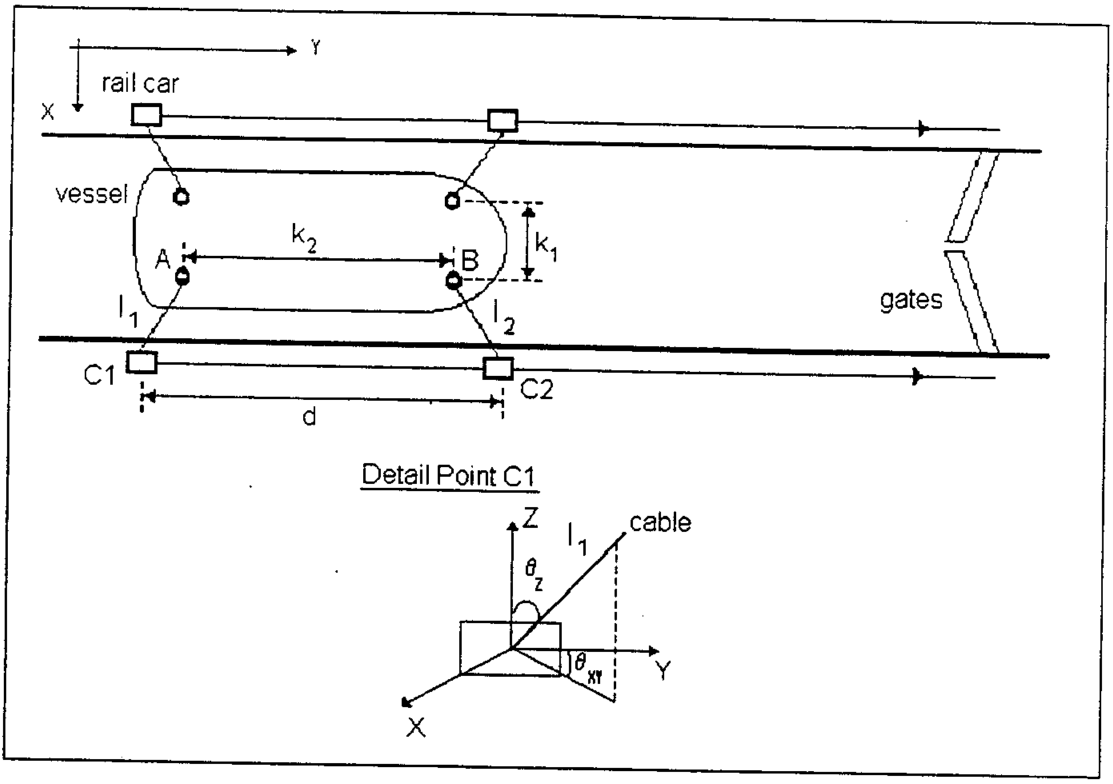


Figure 5: Vessel Parameters

The block diagram of the feedback control system used for centering is indicated in Figure 6. There are two control loops. The measurements required for these control loops are carried out using electrical and optical sensors. A detailed discussion of sensors is provided under "System requirements".

The main control loop measures the length of the cables and the angles and uses this information to compute the position of the mooring points A and B with respect to the X-axis. These positions are compared with the reference signals (r_1 and r_2) which specify the distance that is desired between the vessel hull and the lock wall. The controller uses the deviation between the reference and the actual position in order to produce a corrective signal. This corrective signal is fed to the winch, which reels the cable in or out depending on the requirement.

The second control loop keeps the distance between the cars a constant. The distance is maintained a constant in order to simplify the algorithms used in the main control loop. A PI (Proportional Integral) controller is used to make the deviation between a preset reference and the actual distance between the cars zero.

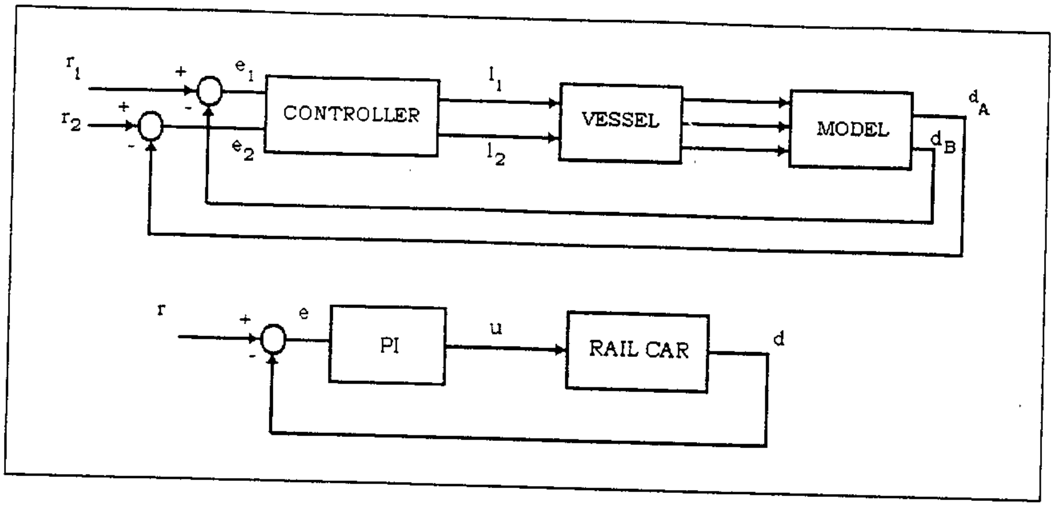


Figure 6: Block Diagram of the Feedback Control System

The controller should be designed using the elements from robust control theory, in order to tolerate external disturbances such as wind, tides etc. The control system gains can be reset in order to accommodate vessels of different sizes. For each vessel a reference position is set, depending on its size.

Accommodating the Elevation Changes

The system can accommodate elevation changes, using the control algorithm described above. During elevation changes the rail cars are stationary. But the distance between the mooring point and the winch changes along with the elevation of the vessel.

The control system aims towards maintaining the distance between the vessel hull and wall at a constant preset value. The lengths of the cables are adjusted to maintain this preset distance between the lock wall and the vessel hull. In order to obtain this, the controller will automatically reel out the cables when the vessel is being lifted and will reel in the cables when the vessel is being lowered.

By doing the reeling in and out of the cable in a controlled manner, control of the vessel position is not lost during the elevation changes. This is a definite improvement over the existing locomotive system in which the cables are slackened before the elevation changes are carried out.

Stopping

For stopping, the two aft rail cars will supply the negative longitudinal force required. In the automated mode, a photoelectric sensor is used to detect when the vessel is close to the lock gates. The feedback control system then stops the vessel over a minimum distance given the initial velocity of the vessel and a maximum stopping force that cannot be exceeded.

We performed a sample calculation to estimate the stopping forces required on a 70,000-ton vessel moving at 3 mph with a required stopping distance of 100 ft. In the actual scenario, the water drag and the piston effect aid the stopping forces. In order to obtain a highly conservative estimate, we ignored the water drag and piston effect on the vessel. The resulting stopping force was obtained to 420,000 lbs.

These stopping forces can be applied by the robot winches through the cables attached to ship structure. The control system can automatically initiate the stopping forces by sensing the distance of the ship from the lock gates using photoelectric sensors. However, as in the previous cases, the pilot has the option to override the controller and manually control the rail cars and execute the stopping procedure using the joystick and the monitors installed on board the vessel.

Towing

For towing, the two fore railcars will supply the positive longitudinal force required. During forward motion, the cars are always on a steady inclination either uphill or downhill. As a result, the required length of the cable in order to maintain a constant distance between the hull and lock wall is linearly changing. The actual length of the cable required to obtain a preset distance between vessel hull and the lock wall is calculated by the controller and the winches are automatically reeled in or released to achieve the same.

System Requirements

Power Requirements

In the case that each rail car provides 70,000 lbs. of force at 3 mph, the power output for each car is 560 horsepower or 0.42 MW. The total system output (for 4 cars) would then be 2240 horsepower or 1.67 MW.

We propose the use of Liner Induction Motors (LIMs) to obtain the propulsion of the railcars. LIMs operate by means of magnetic propulsion. A LIM consists of an array of coils, which on application of an AC current will cause a moving magnetic field. This moving magnetic field can be used to propel a mass of magnetic material, which is capable of sliding over the coils. The velocity of the mass is directly proportional to the frequency of the alternating current that is applied to the coils.

With the model of the linear induction motor used in the feasibility calculations for this system the total power requirement of the system would then be 3,280 horsepower or 2.45 MW.

Maintenance

As mentioned in the previous section, linear induction motors (LIMs) can be used to propel the rail cars. LIMs operate by means of magnetic propulsion and have no moving parts such as gears, drive shafts and reducers. All these elements constitute the major items requiring regular service in conventional electric motor driven transport systems. This lack of moving parts within the LIM reduces both the need for regular maintenance and for emergency repairs. The main items requiring regular maintenance would be the rolling elements in the cars (i.e. wheels and bearings) and the winches. The maintenance requirements of these items would be comparable to similar items in the current system. In the case of a failure of one of the cars, the car could be removed from the track via a crane.

Discussion of the Sensors

As shown in Figure 5 the feedback control system needs to measure several parameters in order to dynamically control the position of the vessel. A critical component of this system is the ability to determine the position of the mooring points with respect to the rail car throughout the lock traverse. In order to do this the following optical position sensing system is proposed: (see Figure 5)

Laser Source: An infrared semiconductor laser diode can be used. This type of a laser has been used extensively in ship docking systems. It is completely eye safe and meets the FDA Class 1 specifications1. It calculates the distance between the cart and the vessel hull by measuring the time of flight of very short pulses of infrared light. A precision crystal-controlled time base can be used to measure the time.

Laser Retro-Reflectors: Retro-reflectors or corner cubes as they are sometimes called, have the property that light incident on the face of the prism is deviated by 180 degrees (i.e. any light incident on the surface will be reflected back along the same path that it came from) independent of its angle of incidence. They are constructed of three first surface mirrors assembled into a corner cube. This produces a "hollow corner cube" that is totally insensitive to position and movement. The retro-reflectors are extremely precise providing an exact 180 degree deviation within 2 arcsec tolerances. The reflector can be magnetically attached to the vessel hull close to the chuck, or alternatively can be clamped on. They can be provided with cushion mounting to provide resistance to shock. The purpose of this reflector is to reflect the laser beam back to the rail car.

Photoelectric Sensor: The photoelectric sensor is mounted on the rail car next to the laser source. The sensor continuously tracks the retro-reflector by rastering (dithering). The sensor is provided with a coder which is preset to allow only a specific wavelength of light. This prevents the sensor from being misled by the surrounding noise.

The retro reflectors can be carried onboard when the pilot boards the vessel and can be clamped on (or magnetically attached) close to the chuck on the vessel hull by the deck hands. They do not require to be precisely aligned. The laser source- sensor system locks on to the reflector as the vessel approaches the lock. The sensor continually tracks the reflector by dithering. The distance can be measured by calculating the time of flight. The angle can be measured by using tilt sensors mounted on the photoelectric sensor.

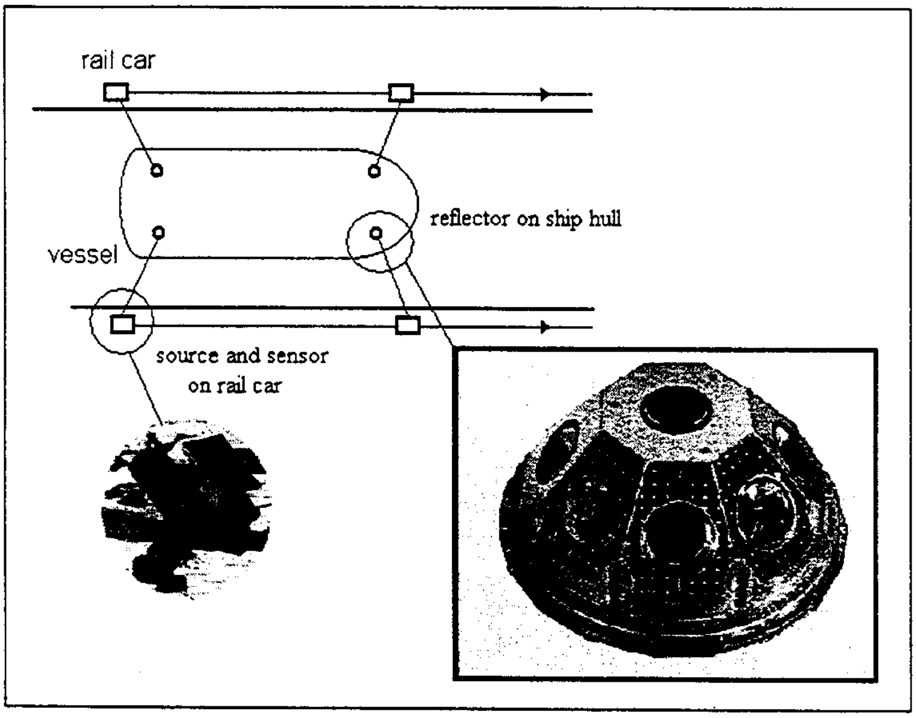


Figure 7: Laser retro-reflector (left) and corner reflector (right)

Modifications to Existing Infrastructure

New rails must be built to accommodate the rail car proposed in the Appendix. The new design will allow autonomous operation of the system and high efficiency through the use of linear induction motors.

The lock walls must be modified so they exhibit a slope of 0.025 (which corresponds to an angle of 1.43°) as shown in the Appendix. This will give the rail cars a direct traveling path with no jumps or step shaped transitions.

Modifications to Vessels

No modifications to the vessel characteristics are needed. The pilot can take aboard a controller module including a monitor and a joystick.

System Robustness

The winching system is similar to the current system and hence is as reliable as the current system and could be designed with hydraulic or similarly compliant couplings to reduce the shock loads. The loads seen by the track and the car will inherently be smaller in magnitude and less instantaneous than those in the current system because of the greater accuracy and speed of initiation of control.

The extensive use of electronics in the system is one aspect that deserves special attention. However, systems of this nature can be found in many engineering applications. One of the examples for the use of electronics in extreme environments is downhole drilling. Design concepts from such applications can be adopted for implementation in the proposed system.

Comparative analysis of the design

The proposed idea is an automated version of the current system used in the canal. Towing and stopping forces are still being applied to the vessel through steel cables. Rail cars are used to pull, brake, steer, and center and hold vessels in position as they enter or exit the locks and are raised or lowered inside the lock chambers. However, the new rail car design minimizes the shear loads by using improved rail designs and provides a way to automate the transit of the vessel by using a feedback control system. The use of linear induction motors reduces the need for regular maintenance and provides a non-polluting, efficient propulsion source for the rail cars. Different sensors installed throughout the lock system (laser sensors, photoelectric sensors, etc.) allow the system to measure critical parameters of the transit process. These measurements are then used to make a decision either in an autonomous fashion or by means of the pilot on board the vessel.

Conclusions

This system includes a robot rail system designed for minimal shear loads, optical and mechanical sensing mechanisms and induction motors to provide forward pull. Some of the desirable features of this system are closed loop control with instantaneous response, accurate position measurement, user-friendly pilot interface, automated as well as manual operation options and an optimized response protocol.

The operation of this system is similar in nature to that of the current system. The use of linear induction motors will increase the reliability and decrease the overall maintenance of the system. The estimate average power requirement for the system is 2240 horsepower or 1.67 MW and the maximum power requirement is 3280 horsepower or 2.45 MW. The system will require input of several vessel parameters and the monitoring of 6 control variables. These variables will be monitored by electrical and optical sensors and will allow an autonomous operation of the system under the supervision of the pilot on board the vessel. The technology required for this system exists today, although no linear induction motors for the specified requirements have been located. The system would reduce the number of personnel intimately involved in vessel transit but would increase the reliance on electronic equipment.

TRAVELING BIT

Summary

The system works by attaching the cables of fixed length to the vessel and to bits that are propelled by a mechanical drive system based on linear induction motors. Two bits are used at each mooring point. Instead of using just one cable per mooring point, the traveling bit uses a system of three cables as shown in Figure 8. The bits are equipped with winches to set the initial cable length, which will remain fixed during the transit. Since the cables are of fixed length, there is no possibility in the absence of a mechanical failure that the vessel will contact the wall. The bits travel along a rail that is mounted to a vertical concrete structure. This system incorporates the usage of a constant-angled lock wall structure instead of the steps used currently. Therefore, as the bits travel down the lock their elevation either increases or decreases depending on the direction of travel. Since the rail the bits travel on is not parallel with the surface of the water and there is a need to accommodate changes in elevation, the effective distance between the mooring boot and the traveling bits must be altered. This is achieved by modifying the distance between the two bits

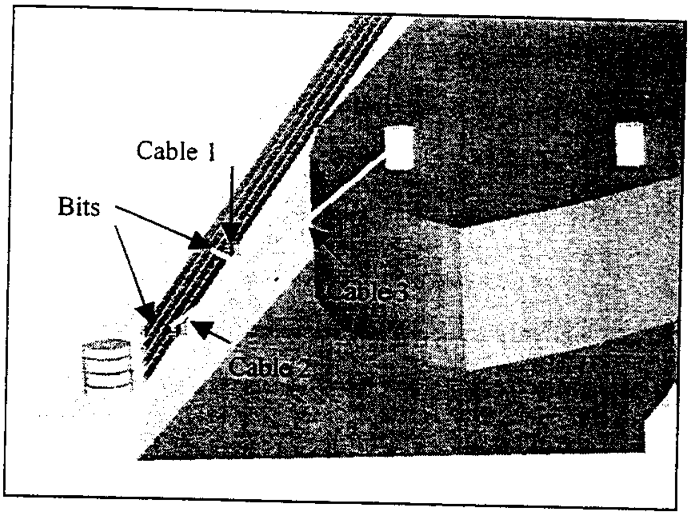


Figure 8: Sketch of the Traveling Bit System.

System capabilities

The traveling bit will be able to provide safe passage to all types of vessels through the lock. The capacity of the drive mechanism and the strength of the track and bit can be sized to handle post-panamax vessels. Once the cables are attached to the travelling bit and the cable lengths are "locked" in position, the system performs the lateral control without reeling in or out the cables. Therefore, the lateral control does not have to be done actively by the pilot. The pilot has the capability to stop and start the vessel. The system could be used in conjunction with a more complex control system, giving the pilot active lateral control of the vessel. but this would take away from the simplicity of this design.

Operational Description

Pilot Interface

The pilot on board the vessel is provided with a joystick for active longitudinal control of the vessel position within the lock. Feedback regarding the vessel position is provided to the pilot by means of monitors on board the vessel, which gather data from the laser positioning system. In the event of an emergency, this information will allow the pilot to override the system. However, during normal operations, the lateral position of the vessel within the lock is held constant by the fixed cable lengths, so there will be no need for control in this direction.

Human elements in the system

The human operators involved in this system, apart from the pilots and the deck hands on board the vessel, will be crane operators for transferring the cables onto the vessel; a person in charge of setting the predetermined length of the cables; and two to four persons to visually inspect the cable settings. Note that the lengths of the cables are determined by using the size and the geometry of the ship. The formula to establish the length can be found in the Appendix. The crane operators will be used in properly positioning the cables on board the vessel is as the ship enters the lock structure. The most critical element in the system is the pilot on board the vessel who will be needed to override the automated mode in case of emergencies.

Entrance (Gaining control of the vessel)

The lock approach will be very similar to that of the Integrated Robot Winch. The vessel is brought close to the lock entrance under its own power, assisted by tugs. Enough cable is released from the bits to allow the cables to be attached to the vessel. The front four bits, two on each side, would then be positioned correctly for the transit. As the vessel travels into the lock, the four rearward bits would be positioned and attached similar to the forward bits. Figure 9 shows the schematic of the entrance.

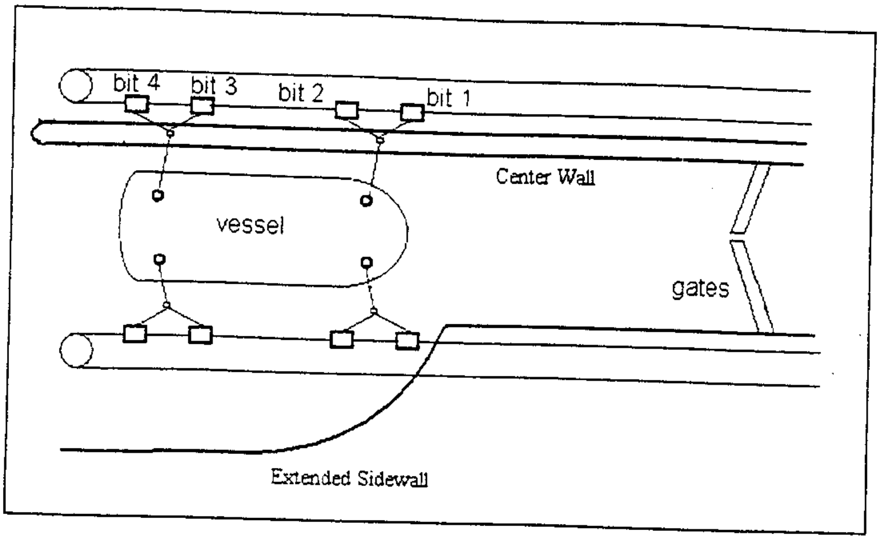


Figure 9: Schematic of the lock entrance.

Forces imposed on the Vessel

Pulling forces are applied to the vessel through the forward and backward motion of the bits. As there are eight bits per ship, each bit is designed to provide a nominal pull of 70,000 lbs. This system could be scaled up to impart larger forces on the vessel.

Centering Throughout the Transit

The system relies on the fixed length of the cables to control the vessel laterally. Hence, no active centering operation is required in this system. During normal operations, all the cables are kept in tension to maintain the vessel at the center of the lock. Therefore the vessel never gains lateral momentum. Thus, the required centering forces will be of smaller magnitude than those in the current system. The energy used in this system is directed towards starting and stopping the vessel.

Accommodating the Elevation Changes

The distance between the angled rail and the mooring points changes as the vessel travels down the lock. To accommodate this change without releasing more cable from the winch, the pair of bits is brought closer or farther apart. Therefore, the bits have a relative velocity that is dependent upon their position in the lock and the initial length of the cables. This results in three drive systems as shown in Figure 8. One drive system for the forward bits (depicted in black), another drive system for the backward bits (depicted in gray) and finally a drive system for the middle front bits. Notice that the forward bits have a different elevation than the backward bits since induction motors of different speeds cannot act on the same rail.

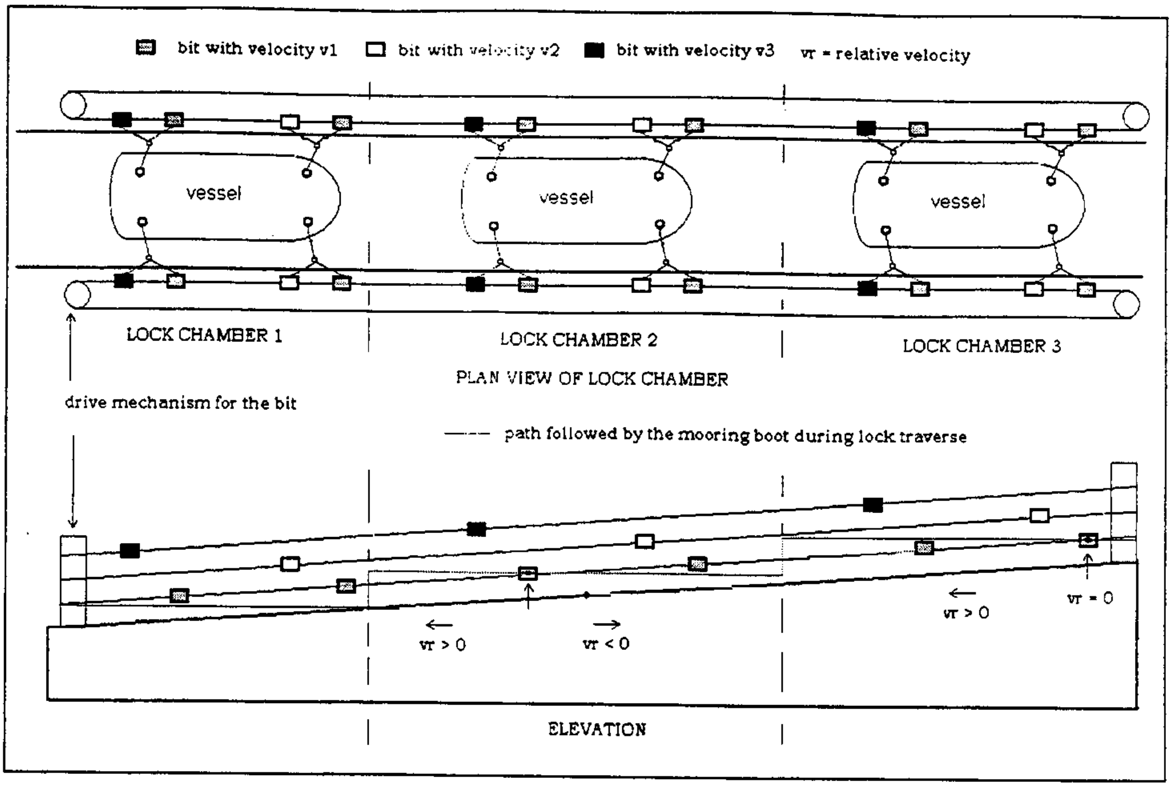


Figure 10: Schematic of Lock Traverse Using Travelling Bits

The above figure shows the path of the mooring points represented by the step line and the path of the bits in white, gray and black. As can be seen in the figure, when the distance between rails and the mooring points is decreasing, the distance between the bits in a pair will be increasing to reduce the effective distance from the sidewall in order to keep the ship at the center of the lock. Conversely, if the distance between the rails and the mooring points is increasing, then the distance between the bits in a pair must decrease to increase the effective distance from the sidewall.

Towing

When towing the vessel through the lock chamber, the longitudinal force is provided by the drive mechanism on which the bits travel. The system is capable of providing a nominal force of 70,000lbs per bit. For example, if the towing angle is 30 degrees, then effective force in the longitudinal direction is 52,500 lbs.

There is no active control in the lateral direction; the system depends on the fixed cable lengths to prevent the vessel from hitting the lock wall. As mentioned earlier, the relative velocity between the bits associated to a mooring point change in order to accommodate the change in the lengths of the cables. Notice that only the forward bits (bits in gray color in fig. 8) are providing the towing force, while the rest of the bits are follower bits. The parameters needed to determine this relative velocity are: (see Figure 11)

k_1 = distance between the mooring points in the X-axis,

k_2 = distance between the mooring points in the Y-axis,

l_1 = length of the cable associated to the mooring point A,

l_2 = length of the cable associated to the mooring point A,

l_3 = length of the cable attached to the mooring point A,

d = distance between the rail cars,

h_f = free board height (front and back of the vessel)

$^{\Delta}V$ = relative velocity between the bits associated to mooring point A.

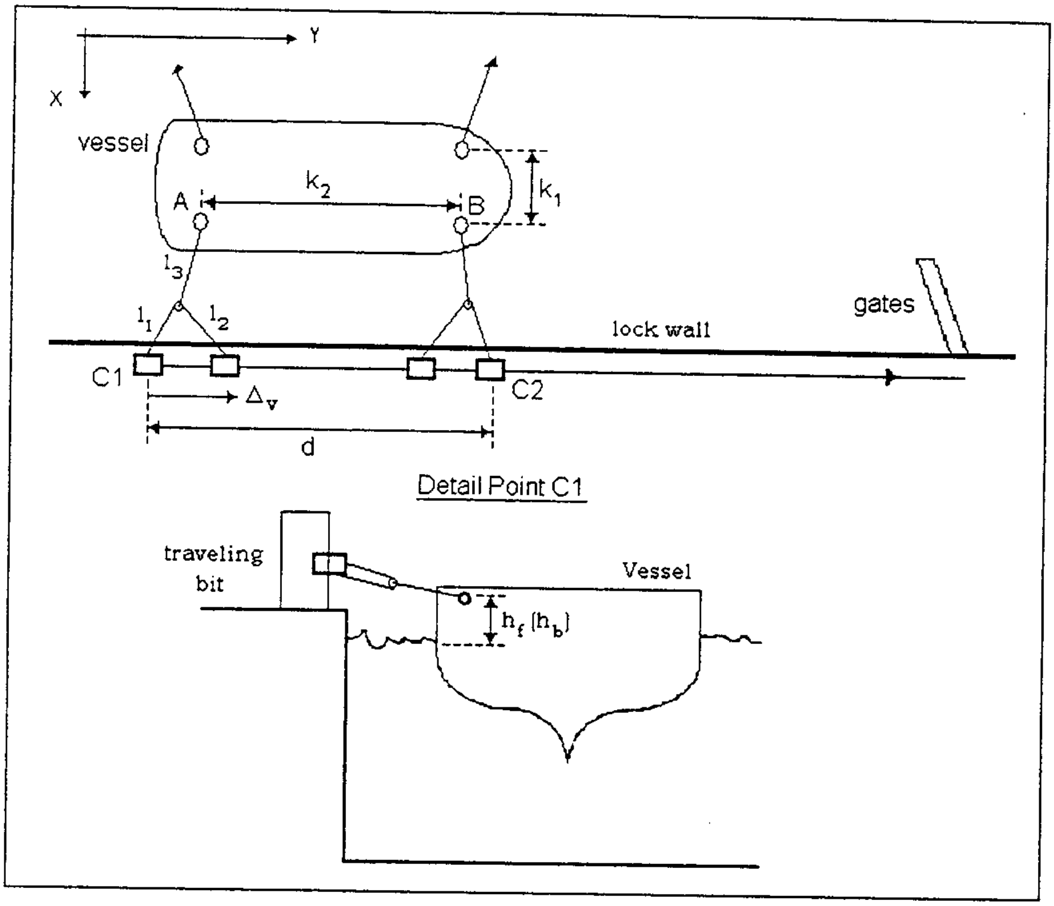


Figure 11: Vessel Parameters.

All these parameters are used in the Appendix to derive the equation that determines the length of the cables for a given ship.

Stopping

The proposed system is designed to stop the vessel over a minimum distance given the initial velocity of the vessel and a maximum stopping force that cannot be exceeded. For example ignoring water drag, if the minimum stopping distance for a 70,000-ton vessel is set to 100 ft. and the vessel has an initial velocity of 3 mph. a total force of 420,000 lbs. will be required to stop the vessel. If needed, the ship could supply part of this force by inverting the propellers. As in the case of towing the vessel, the pilot manually controls the bits and executes the stopping procedure using the joystick and the monitors installed on board the vessel.

System Requirements

Several conceptual drawings are included in the Appendix to illustrate the general concept of the traveling bit. The concept is to construct three parallel rail systems on both lock walls (one dedicated to each of the three independently controlled bits). Once the cables are locked down, secured, and tightened to the traveling bit (Figure B5), the bits themselves are driven by linear induction motors. Corresponding to one ship, four traveling bits on each lock wall will communicate with three drive systems to provide the necessary bit separation, and longitudinal positioning.

Power Requirements

In the case that each forward bit provides 70,000 lbs of force at 3 mph, the power output for each bit is 700 horsepower or 0.52 MW. The total system output (for 4 towing bits) would then be 2800 horsepower or 2.10 MW. See the appendix for details on these power requirements.

Maintenance

The main items requiring regular maintenance would be the rolling elements in the bits (i.e. wheels and bearings) and the winches. Also the driving mechanism located inside the vertical concrete structures (see Figure 8) would need regular maintenance. The maintenance requirements of these items would be comparable to similar items in the current system. In the case of a failure of one of the bits, the bit could be removed from the track via a crane.

Modifications to Existing Infrastructure

The system will require three linear induction motors to be installed on both sides of the lock wall for the travelling bits.

Both the center wall and the sidewall need to be length (see Figure 9). This modification will allow the system to gain control of the vessel earlier than it is possible now.

As in the case of the Integrated Robot Winch System, the lock walls must be modified so they exhibit a slope of 0.025 (which corresponds to an angle of 1.43°) as shown in the Appendix. This will give the rail cars a direct traveling path with no jumps or step shaped transitions. The step shaped transitions are undesirable because they increase the complexity of the control algorithm and they result in obtuse angles that decrease the longitudinal forces.

Modifications to Vessels

This system does not require any modification to be done to the vessels.

System Robustness

This system is robust and reliable. The winching system is as reliable as the current system and could be designed with hydraulic or similarly compliant couplings to reduce the shock loads. The loads seen by the track and the bits will inherently be smaller in magnitude and less instantaneous than those in the current system. As in the case of the Integrated Robot Winch system, a feedback system can be designed to dynamically control the position and the relative velocity of the bits, thus providing an autonomous mode of operation. Figure 10 shows the block diagram of the proposed control system.

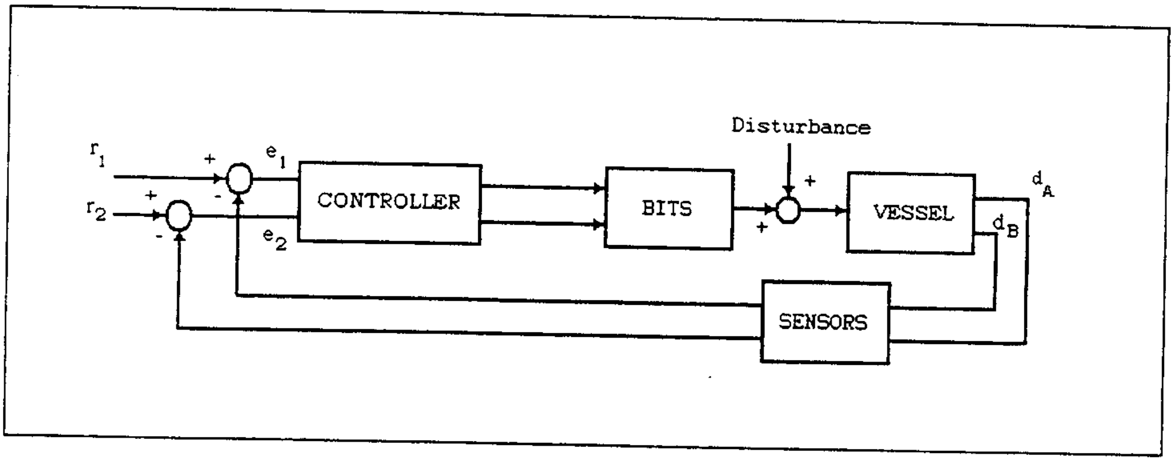


Figure 12 Block Diagram of the Control System

Comparative analysis of the design

This system is better than the current system in terms of its simplicity and the lack of a need for active lateral positioning control. Towing and braking forces are provided with steel cables, as in the current system. The most critical aspect of the design is the fact that the relative velocity of the bits associated to a mooring boot must be regulated in order to keep a minimum separation between the lock wall and the hull of the vessel.

Conclusions

The above system uses a simple concept of fixed cable lengths for maintaining lateral position. Two bits are used at each mooring point. Instead of using just one cable per mooring point, as in the current system, the traveling bit uses a system of three cables. The necessity of constantly reeling in the cable to accommodate elevation change is overcome by adjusting the distance between the two bits. By eliminating the shear loads upon the tracks and automating the traveling bits, this system is an improvement on the current system in terms of maintenance and ease of operation.

COUNTERWEIGHTS

Summary

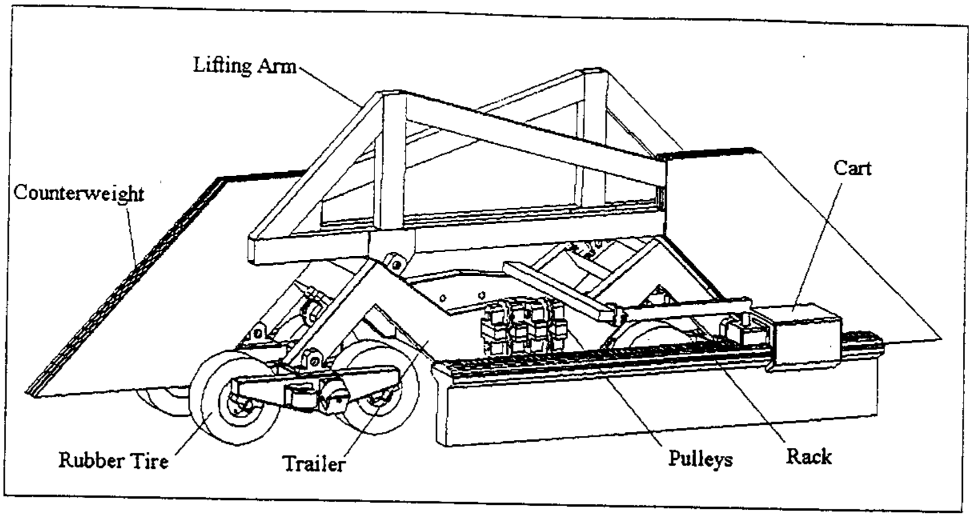


Figure 13: Counterweight mechanism and cart

This idea employs gravity acting on counter weights to apply the centering forces. Cables connect the ship to the counter weight mechanism through a set of pulleys. These connections occur at the front and back mooring locations on each side of the ship with two cables from each cart to the mooring point (for a total of eight connections for lateral position). These pulleys convert any deviation in the lateral position of the ship to a vertical movement of the counter weights. Thus, counterweights on one side of the ship are lifted for any lateral displacement of the ship in the opposite direction. This lifting of counter weights generates a restoring force and hence the transverse position of the ship is corrected. Therefore, centering of the ship within the lock structure is obtained without the use of active control.

The counterweight system is mounted on a trailer that is pulled along the sides of the lock. The cart uses electric motor that drives a pinion gear that engages the rack on top of the rail support wall. The trailer also has rollers that engage the rail support wall which prevents the trailer from being pulled into the lock. There is also a set of roller that prevent the trailer from being lifted off of the ground when the mooring points of the ship are above the level of the cart.

Longitudinal forces are applied using the powered carts that run along the lock wall (Figure 1). Towing/braking cables connect the carts to the mooring points at mid ship (four cables total). The carts are attached at mid ship to ensure that the towing and braking angles are as small as possible. This ensures that the towing and braking forces are applied in as efficient manner as possible. Two carts are used on each side of the ship, one in the front for towing and the other in the back for stopping the ship. The counter weight mechanism is mounted on a trailer that runs on rubber tire wheels. The powered carts also tow the trailer. Since the lateral forces correcting the ship position are applied directly to the trailer, the cart has to take only the longitudinal forces. This helps reduce the wear of the rack that is mounted on top of the support wall.

System capabilities

This system is capable of enabling a safe transit of vessels of all sizes including the Panamax without causing damage to the vessels and the lock structure. The vessels, however, need to have mooring bits on the deck, capable of handling the restoring forces.

The system can be incorporated on the current lock structure with a minimum amount of modification. The design presented here can provide a maximum lateral correcting force of 280,000 lbs. and a maximum longitudinal force of 200,000 lbs. These magnitudes were chosen because they are the capabilities of the current system, however this can be scaled up to larger ships and a new lock structure if required.

The system has an inherent redundancy to reduce the risk of total failure. This is achieved by using two counter weight arms on each of the trailers, each one attached to the same mooring point using its own cable. The longitudinal position of the ship is controlled in an active manner. This is accomplished by controlling the electric motors providing the towing and braking forces. The lateral position control is achieved passively i.e. without controller or human intervention. The system completely decouples the longitudinal and lateral forces thereby reducing the complexity of the system.

The system can be operated under all weather conditions. The self-centering nature of the mechanism ensures that night operations can be performed safely.

Operational Description

Pilot Interface

During lock approach the pilot has control of the ship just like in the current locomotive system. Once the cables are attached, there are two possible roles for the pilot. If the system is fully automated the pilot will monitor the progress of the system making corrections only when absolutely required or when an emergency takes place. If, on the other hand, the system is not fully automated the pilot could have control of the different carts using a controller (via a joystick or similar device) that could send radio signals to the different carts. Note that this would give the pilot stopping and accelerating capabilities only, because the lateral control is performed without the need for any control signals.

Human elements in the system

Human operators are required to attach the cable onto the mooring points on the deck. The attachment procedure has to be completed before the vessel enters the lock completely. Assuming two operators per mooring point, a minimum of 16 operators is required on the vessel. In addition, one pilot is also required on the bridge. On land, no operators are necessary on the cart since the carts do not require any human intervention. However, during the elevation changes, the cables have to be coiled in or coiled out. This is accomplished using a winch that operates only during attachment to the ship when it takes out the slack from the system and during elevation changes. This operation can be fully automated in a fashion that enables each counterweight system to perform the cable management independently. The manpower required on land is much less than the existing locomotive system.

Attaching the cable is a critical procedure that has to be performed in a timely manner. This is important in order to gain control of the vessel before it enters the lock.

Entrance (Gaining control of the vessel)

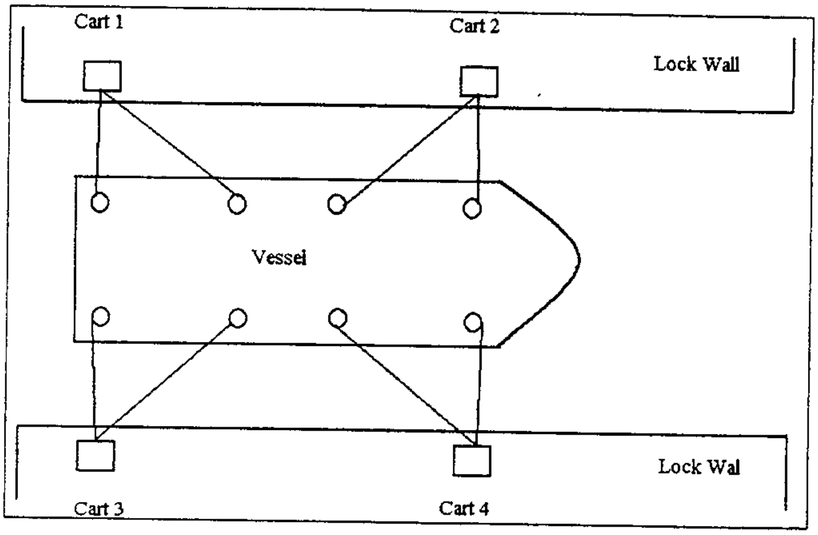


Figure 14: Ship attached to four counterweight mechanisms and their carts.

The attachment procedures for this system can be similar to the one currently used. However, the rowboats can be replaced by a swiveling arm at the approach wall. This arm can be used to extend the attachment cables to the deck as the ship approaches the lock. After the cables are attached to the mooring points, they are coiled in using the winches and locked in position. From this point onwards, cable lengths remain unchanged except during elevation changes.

Full control of the ship is achieved when all four trailers are attached to the ship (Figure 2). The system is currently designed so that four trailers are sufficient to guide any ship up to the Panamax vessels through the locks.

Forces imposed on the Ship

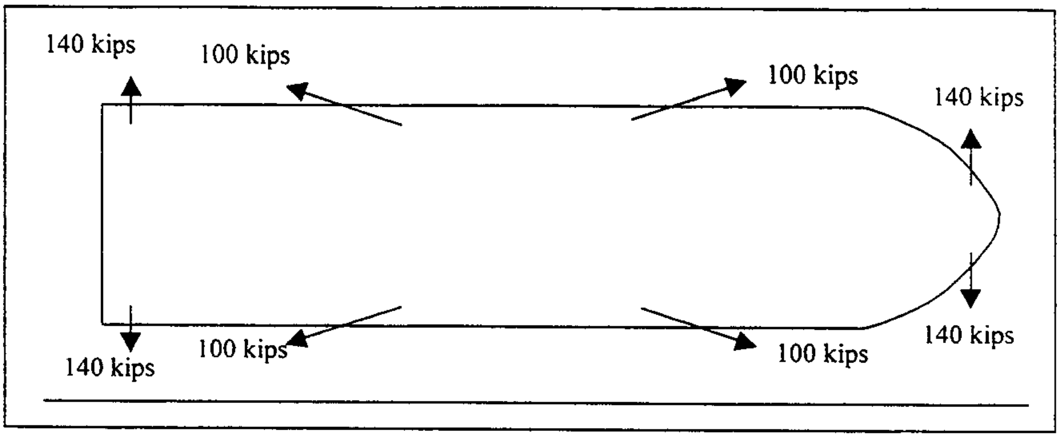


Figure 15: Location and direction of force capabilities of the counterweight system

Centering Throughout the Transit

The centering of the vessel is achieved passively using the counterweight mechanism. As the vessel tries to deviate from the initial lateral position, the pulley-cable mechanism causes the attached counter weights to lift. The lifting of counter weights provide the restoring forces that bring the vessel back to its initial lateral position. The counterweights and associated moments about the truss pivots are designed to correct deviations on a fully loaded ship throughout the possible range of lateral motion. Also, since each of the trailers has two counterweight lifting arms with separate pulley-cable mechanisms, there is redundancy in the system. This ensures that, even if one of the lifting arms fails, complete loss of control of the vessel does not occur. This also allows the connection of only one counterweight to a vessel halving the forces that are applied. This may be useful when working with smaller vessels.

This mechanism works equally well for ships of varying widths and lengths. However, the ships are required to have at least six mooring points on the deck, two in the front and two in the back of the ship two at mid ship.

Accommodating the Elevation Changes

During elevation changes, the length of the attached cables has to be varied. This can be achieved by actively controlling the winches to coil in or coil out proportional to the elevation changes.

The trailer is also designed to accommodate the change in elevation. Its wheel chassis is attached to the main chassis using a pivot to provide compliance while going up the ramp (Figure 4).

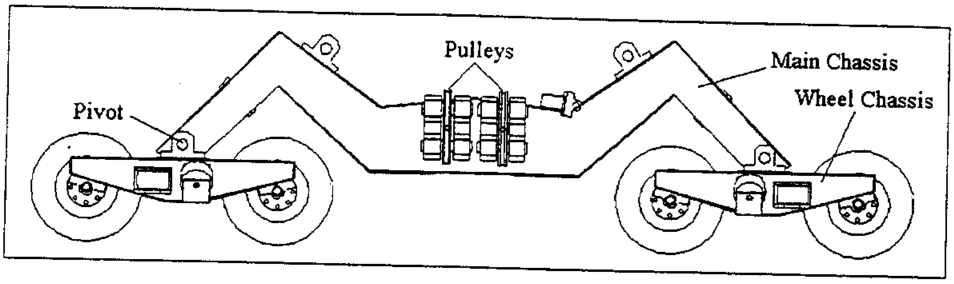


Figure 16: Trailer chassis showing the wheel attachment mechanism

Stopping

The carts that move on the lock wall provide the longitudinal forces. There are four carts attached to each ship, two on the back and two on the front. The two carts in the back provide the stopping forces. These carts are attached to the mid ship in order to obtain a small braking angle so that the majority of the energy provides a braking force. If the angle becomes too large the majority of the energy provides a lateral force, therefore a small angle is the most efficient way to obtain a braking force.

Unlike the existing locomotive system, the back end carts are always in the "stopping position". This ensures a faster response to a stop command. Therefore, stopping or slowing down can be accomplished just by braking or reducing the speed of the carts. Once initiated, the duration of the stopping procedure depends on the momentum of the ship. The carts obtain traction using a pinion wheel, which meshes with the rack on the lock wall

Towing

As explained in the previous section, there are four carts attached to each ship, two on the back and two on the front. The two carts in front provide the towing forces. These carts are attached to the mid ship using cables. These mooring points are chosen in order to obtain the small angle that is most efficient for providing the longitudinal forces.

The front-end carts are always maintained in the "towing position" which ensures a fast response to the tow command. The carts obtain traction using a pinion wheel, which meshes with the rack on the lock wall. Drive is provided to the pinion using an electric motor.

System Requirements

Power Requirements

Each counterweight system will have one 50-hp electric motor for longitudinal positioning (one for each cart) and one 40-hp motor for hydraulic systems power used to provide power for the winches. This indicates that the maximum energy usage is 270 kW per ship. The average power consumption should be less than half of this value.

Maintenance

The components of the system are designed considering the specific loading pattern present in the system. The lateral forces are taken by the trailer and transmitted to the track support structure through the rollers. This is an improvement over the current system which experiences shear stresses on the rack and rails. The longitudinal forces are taken directly by the cart. The cart transmits these forces to the structure through the rack and pinion. The forces on the rack are aligned normal to the rack teeth. This ensures that the loading pattern of the rack is optimized to reduce wear.

Through design the forces on the system are handled in such a way as to reduce the wear and therefore, minimize the maintenance costs of the system. The system is built with mutually independent components. In case of a trailer fault, the trailer can be towed out of its position with at tractor and a new one can be put in place. The carts are smaller and lighter compared to the locomotives of the current system. Hence replacement of the carts in case of a failure is easier compared to the existing system.

Modifications to Existing Infrastructure

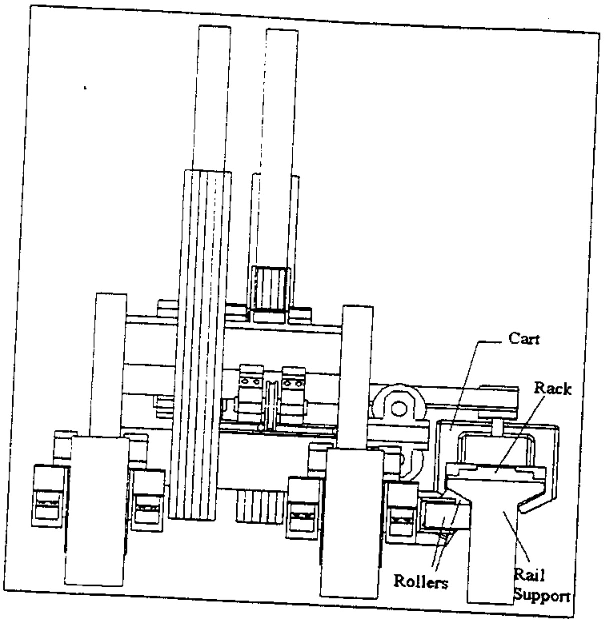


Figure 17: Front View of Counter Weight Mechanism

The tracks used in the present system needs to be completely replaced for implementing the proposed design. Figure 4 shows the proposed track structure design and the components required to attach the cart and the trailer to the track structure.

The current track system suffers from excessive wear and tear due to the nature of loading pattern. The proposed system greatly reduces wear by improving the loading pattern. This is accomplished by using rollers to resist the lateral forces and designing the system such that the rack and pinion systems are not subjected these lateral forces. These design improvements increase the durability of the system and reduce maintenance costs.

Modifications to Vessels

No modifications are required on the vessels since the attachment procedure required is similar to that of the current locomotive system.

System Robustness

Due to the inherent self-centering nature of the system, the control system required for operation is highly simplified. This adds to the robustness of the system and its ability to operate under extreme conditions.

Redundancy is also an inherent part of the system. Each of the trailers has two counterweight lifting arms with separate pulley-cable mechanisms. This ensures that, even if one of the lifting arms fails, the system can continue to operate with one-half of the original system capacity. Also, since the longitudinal and the lateral control systems are de-coupled, if one of them fails the other one still works, i.e. if the lifting arms fail, longitudinal control can still be enforced. In case of a failure of the trailer, the trailer can be disconnected from the cart. A tractor can then remove it and install a new one quickly during the traverse of the vessel.

Comparative analysis of the design

The system proposed in this design has many advantages compared to the existing locomotive system. The proposed system performs the lateral control passively. This eliminates possibilities of human error and measurement errors that are critical to the existing system. In the event of a total power failure, lateral positioning is unaffected. Full control of the ship is not lost at any instant during the transit.

The forces applied on the ship are well aligned compared to the locomotive system. The longitudinal forces are taken directly by the carts and the lateral forces are taken directly by the counterweight lifting arms. Therefore the lateral and longitudinal forces are de-coupled and each component has been designed specifically to take the kind of forces acting on them. This also implies that in case of a cable failure, only control in one direction is lost.

This de-coupling of forces results in less wear on the system and hence the maintenance required is less. The track can be replaced modularly using bolted connections. The trailer design ensures that maintenance can be performed relatively quickly and cheaply. The trailer can be connected and disconnected from the system with ease, even during a lock transit. The trailer is on rubber tires and not on rail tracks, and hence can be hauled away by a tractor in case of a breakdown, and a new one can be placed in its position.

Conclusions

The proposed counterweight system provides passive lateral position control and de-coupled active towing and stopping actuation in a robust and cost effective manner. Unlike the current locomotive system, once the initial cable lengths are set, it is impossible to actuate forces in an opposing direction. and therefore improves efficiency. Maintenance costs can be reduced since the transfer of loading from the vessel to the lock wall is performed in a manner which improves the loading patterns the components experience. Automation and passiveness of the system enables transit of all sizes of vessels regardless of visibility conditions.

TELESCOPING TRUSS

Summary

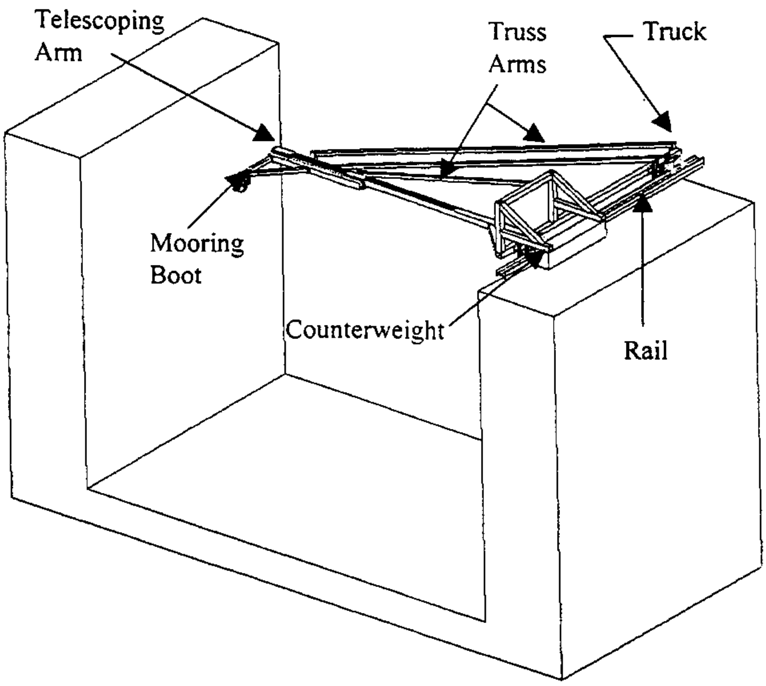


Figure 18: Telescoping truss positioned on the lock wall

This concept evolved from a desire to obtain a rigid connection to the ship and hence obtain full control of the position of the ship throughout the transit. The design challenge here is to provide sufficient strength without undue size and also provide adequate compliance to accommodate shock loads. Two truss arms extend from the lock wall and attach to the ship, one in front and one in back. The arms "lock" and maintain the lateral position of the ship using a mooring boot and a cable. The connection is through rigid elements however, the hydraulic cylinder that actuates the telescoping arm will provide some compliance in the system to reduce shock loading through the use of accumulators within the hydraulic systems.

The attachment procedure is facilitated by the use of the chock bit mechanism. The truss system will also be able to extend its telescoping arm to place the cable on the deck of the vessels, thereby eliminating the need for the rowboat and associated personnel. The cable runs through the mooring boot so that when the cable is reeled in, the mooring boot automatically lines itself up with the chock and is inserted. The mooring boot then extends three clamping devices that lock it into the modified chock. The cable can then be loosened without influencing the mechanical integrity of the connection. The truss can then transfer force in any direction to the ship through the mooring boot.

Each telescoping truss can provide both lateral and longitudinal positioning forces. Both arms act together to provide the stopping and towing forces. The truss arms are mounted on trucks that are driven on rails mounted to the lock walls. A rack and pinion is the current choice for this function, however, linear induction drive technology could offer a reliable alternative. The rack is bolted on the inside of the rail as opposed to being cemented into place such that replacement and maintenance is made easier.

During elevation changes, the lengths of these arms are modified using the telescoping mechanism. This telescoping mechanism is hydraulically actuated and allows the system to maintain control of the ship while going up the slope between locks and during fill/drain operations while in the locks. This process is to be automated. The horizontal position of the chock location within the lock which maintains the vessel in the center of the lock is used to calculate the required amount of telescoping action to maintain the desired lateral position as a function of the angle made by the truss with horizontal.

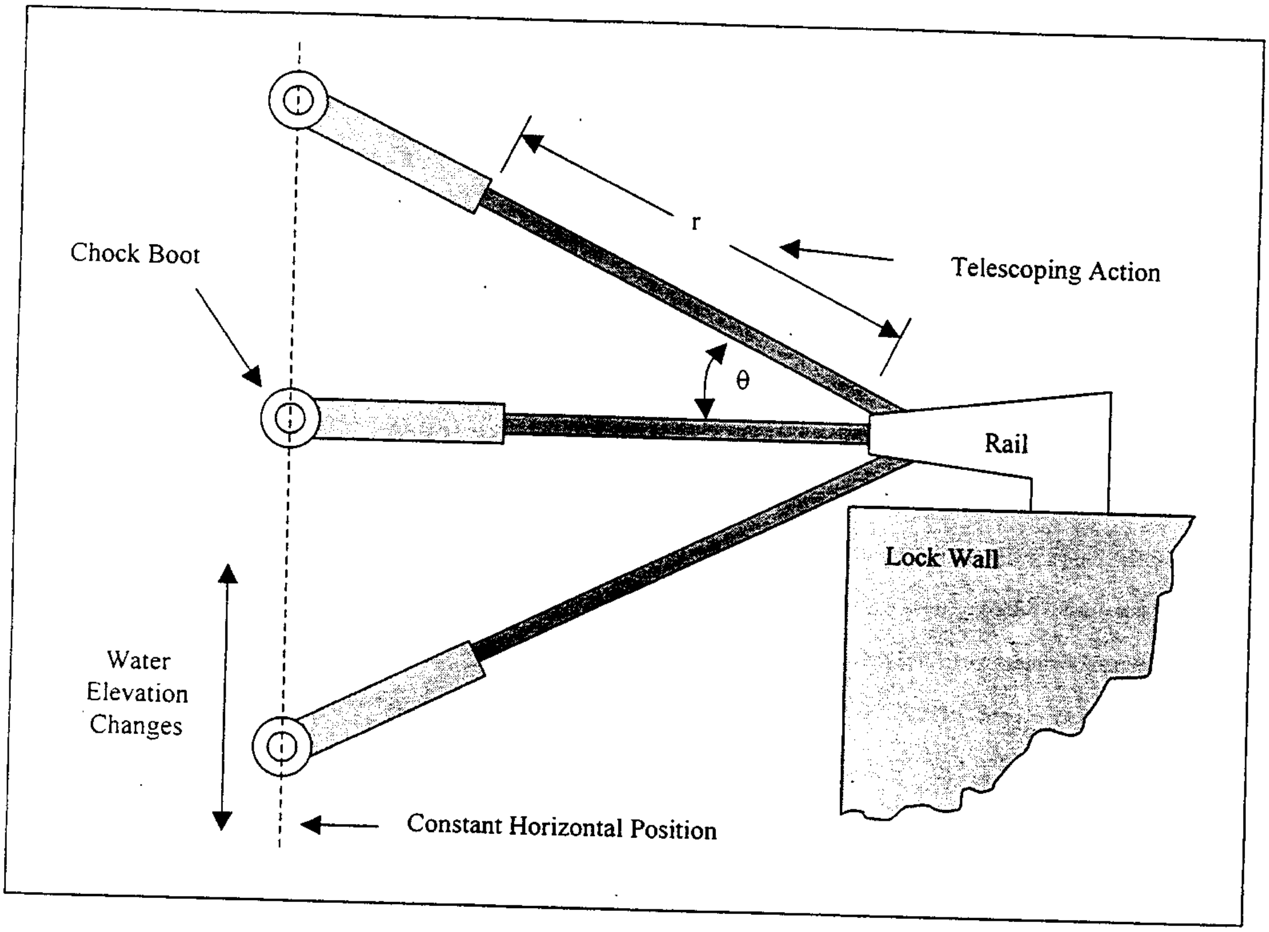
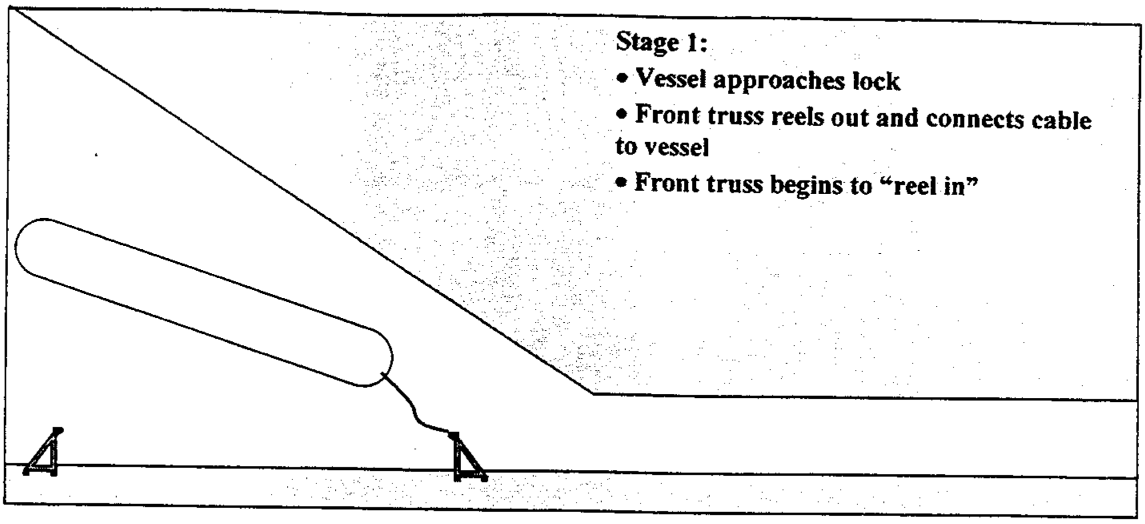


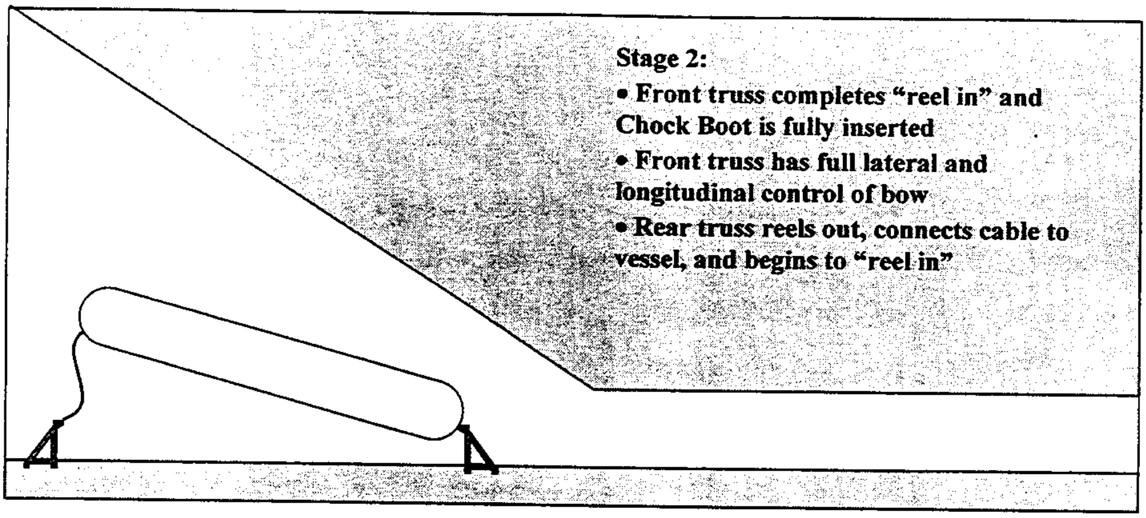
Figure 19 Telescoping Action

The sequence of events performed to gain and impose control on a vessel is shown below.



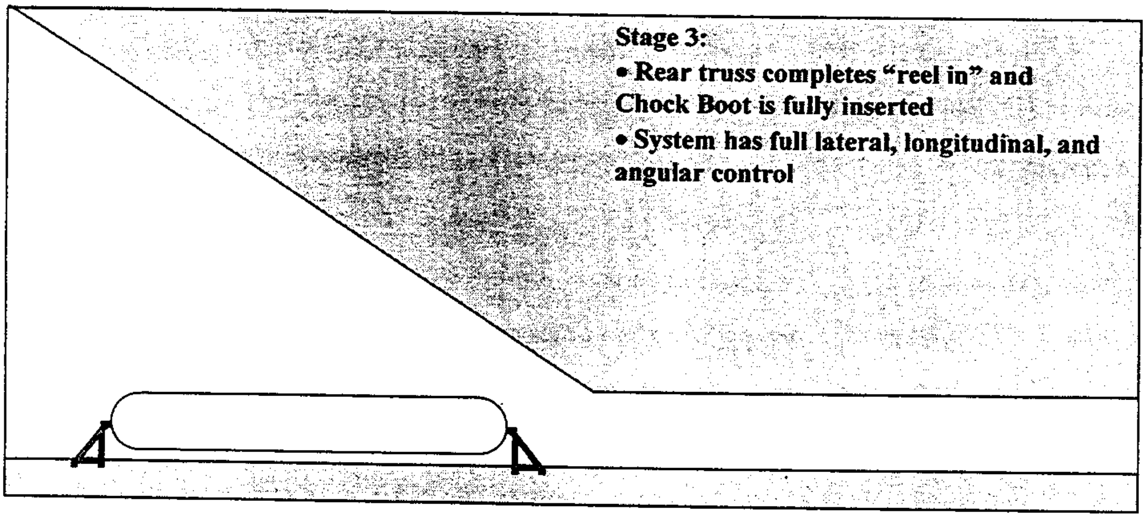
Stage 1:

- **Vessel approaches lock**
- **Front truss reels out and connects cable to vessel**
- **Front truss begins to "reel in"**



Stage 2:

- **Front truss completes "reel in" and Chock Boot is fully inserted**
- **Front truss has full lateral and longitudinal control of bow**
- **Rear truss reels out, connects cable to vessel, and begins to "reel in"**



Stage 3:

- **Rear truss completes "reel in" and Chock Boot is fully inserted**
- **System has full lateral, longitudinal, and angular control**

The rigid nature of the attachment provides excellent longitudinal and lateral control and eliminates the possibility of conflicts in control effort. Also, attachments are required only on one side of the vessel, thus reducing the amount of equipment and attachment points on land.

System capabilities

This system is capable of providing a safe transit of vessels of varying sizes through the locks without damage to the vessel or the lock system. The requirements of the system include mooring points on deck and chocks on the hull in the front and the back of the vessel. Also, both chock and mooring points have to be capable of withstanding the positional correcting forces. This will likely involve some modifications to the chocks such that they are capable of withstanding the load levels required for position control.

This design can provide a maximum operating lateral correcting force of 280,000 lbs. It can also provide operating longitudinal forces up to a maximum of 200,000 lbs. However, the loading capabilities are scalable for use with Post-Panamax vessels.

The system can be incorporated on the current lock structure with minimal modifications. It can be operated under all weather conditions. The robustness of the mechanism ensures that night operations can also be performed safely. The position measurement system will consist of position sensors to indicate the position of the telescoping arm and the angular position of the truss. These two pieces of information along with ship dimensions allow the control system the ability to determine the position of the ship at all times. These measurement devices are not adversely affected by weather or visibility, therefore there should not be any restrictions on operation due to these factors.

Operational Description

Pilot Interface

The pilot will be responsible for getting the vessel into its initial position necessary for connection to the truss system. However, after that is completed the pilot will only be responsible for the controlling the vessel's engines. In the event of control system failure or unusual circumstances the pilot will have the ability to override the system and take manual control of the vessel using a "joystick interface." The pilot will then be responsible for the departure from the lock and disconnecting the system from the vessel. The pilot will also be responsible for overseeing the entire process and ensuring that a quick and safe transit occurs.

Human elements in the system

The attachment procedure is facilitated by the mooring boot mechanism. This reduces the manpower required in completing the attachment procedure. Two operators are required per mooring point to complete the attachment, although three operators are recommended for redundancy reasons. The role of the rowing boat in the current locomotive system is replaced by the telescoping arm on the truss, which extends a cable to the deck for initiating the attachment. Line handlers are required to receive the cable from the telescoping arm and attach it to the mooring point. Thus, we estimate that 12 line handlers are needed per ship. Additionally one pilot is still required at the bridge.

No personnel will be required on the lock walls during a transit. This is the result of the control system automation and the elimination of the locomotive operators. However, personnel might be useful in the case of a system fault.

Entrance (Gaining control of the vessel)

As the ship approaches the locks, the telescoping arm extends and takes the cable to the deck. The human operators on the deck receive this cable and attach it through the chock onto the mooring bit.

Once the cables are tied to the mooring bit, the truss starts reeling the cable in. This causes the vessel to drift towards the truss mechanism. Along with this, the mooring boot moves along the cable towards the chock of the ship.

At the end of the reel in procedure, the mooring boot comes into contact with the chock. The mooring boot then clamps itself onto the chock using three radially positioned clamping devices. From this point onward, the mooring boot acts as an interface between the truss arm and the ship structure, and it is responsible for transmitting the positional correcting forces. This procedure occurs first at the bow of the ship then as the ship proceeds the back truss will be attached to the vessel.

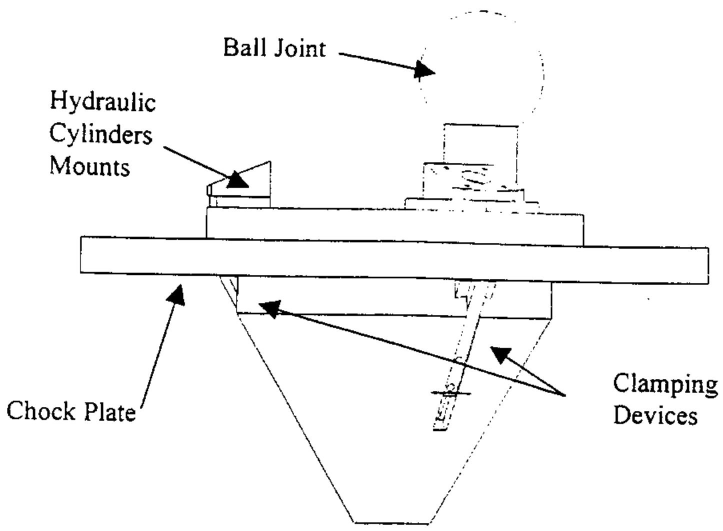


Figure 3: Mooring boot with clamping devices extended

Once both the arms are attached, the ship is in full control and cannot undergo any lateral positional deviation and longitudinal forces can then be applied.

Forces imposed on the Ship

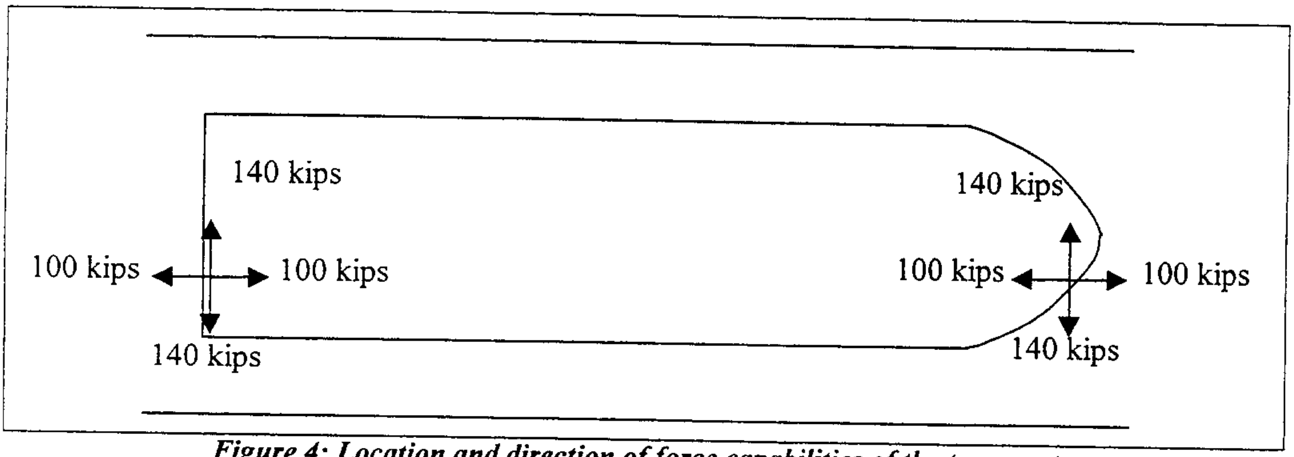


Figure 4: Location and direction of force capabilities of the truss system

Centering Throughout the Transit

The semi-rigid nature of the attachment does not allow for large lateral deviation in the vessel's position. This semi-rigid nature is accomplished using a hydraulic accumulator on the telescoping arm to provide a shock absorbing effect. The centering is automatic without any control actuation hence it is very effective throughout the transit of the vessel.

The cables are used only to bring the ship to the truss before connection occurs. After the connection process is completed the cable will not transmit any forces to the ship. Therefore, the reliability of the system during a transit is improved because the boot system is much more reliable than a cable.

Accommodating the Elevation Changes

Modifying the length of the attaching trusses using telescoping arms accommodates elevation changes. Also, the system has enough compliance to accommodate the roll and pitch and the changes in the cart orientation while moving up the ramp. Note that the carts that attach the truss to the rail have being designed in order to accommodate all those changes in vehicle position. They also greatly reduce the amount of wear and tear on both the track and the rollers since they have being specifically designed to properly withstand all the forces it needs to deal with.

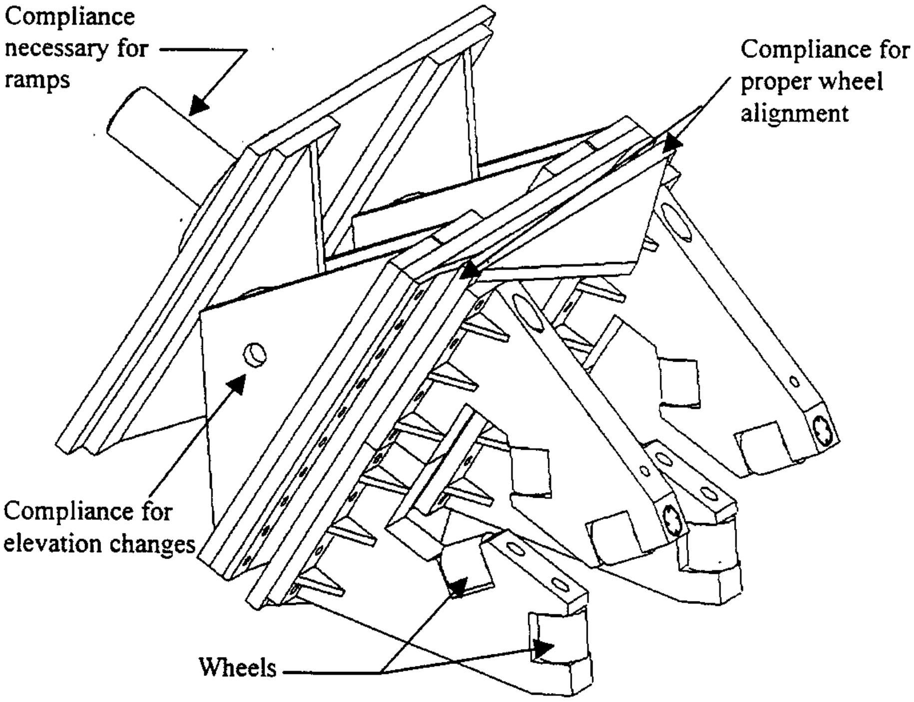


Figure 5: Truck

A controlled extension of the arms using hydraulic actuators ensures that complete control of the ship is maintained during elevation changes. The telescoping procedure is controlled by a system that detects the angle of truss with the horizontal this coupled with the vessel's dimensions allows it to calculate the required length of the telescoping arms. The actuation is achieved using a hydraulic piston-cylinder mechanism. This mechanism is also used to maintain the lateral position while the cart goes up the ramp, by extending the arms to the required length.

Since the extension of arms is done in a controlled manner, the system never loses the ability to apply the controlling forces even during the elevation changes. This gives this system a definite advantage over the current locomotive system.

Stopping

Stopping is achieved by braking the front and back carts at the same time. Therefore, both trusses apply stopping forces on the ship. Since a change in position of the carts is not required for initiating the stopping procedure, a fast response to the stopping command is enabled.

The tracks are designed such that the trusses can apply the stopping forces even while the carts go up or down the ramp. The magnitude of the braking forces and distance to full stop will depend on the size of the ship. However, the system is designed to bring even a fully loaded Panamax vessel to a complete stop.

Towing

Towing is achieved by increasing the speed of the front and back carts simultaneously. Therefore, both trusses apply towing forces on the ship. Since a change in position of the carts is not required for initiating the towing procedure, a fast response to towing command is ensured.

The tracks are designed such that the trusses can apply the towing forces even while the carts go up or down the ramp. The magnitude of the towing forces depends on the size of the ship. However, the system is designed to tow even a fully loaded Panamax vessel.

System Requirements

Power Requirements

Each truss system will have two 100-hp electric motors for longitudinal positioning and one 100-hp motor for hydraulic systems power. This indicates that the maximum energy usage is 450 kW per ship. The average power consumption should be less than half of this.

Maintenance

The system is designed specifically for the loads experienced during a transit, therefore, the maintenance costs should be much lower than the current system. The lateral forces are transmitted to the wall structure through the angular roller wheels of the cart. The longitudinal forces are transmitted through the rack and pinion mechanism. One of the main sources of wear on any gear system is improper clearances and alignment. To alleviate the wear associated with the current system, the truss system will have rollers that contact the rail on each side of the rack to ensure that the proper gap is maintained. This system also increases the life of the individual components by reducing the shock loading of the system be using hydraulic accumulators as shock absorbers.

One of the major maintenance issues of the existing locomotive system is the maintenance of rails. Replacement of rails in the current system is difficult and requires a large amount of time. The proposed system removes this burden from the maintenance operations. The I-shaped steel tracks are rolled sections bolted onto the steel support structure. The modularity of this design allows ease of replacement and repair and decreases down time due to rail failure or rail maintenance. The wheels which contact the rail can be replaced by removing one bolt on the trucks. The track could also have wear surfaces bolted onto the main rail body to eliminate the need to replace the entire rail system.

The steel support structure is embedded in the concrete lock walls. The design of the joint between the steel support structure and the concrete walls is important because the loading pattern on the concrete should always remain in tension. Thus the life of concrete structure is increased.

The carts and the truss structures are also built with modular sections. This facilitates the replacement procedures and reduces costs of replacing components.

Modifications to Existing Infrastructure

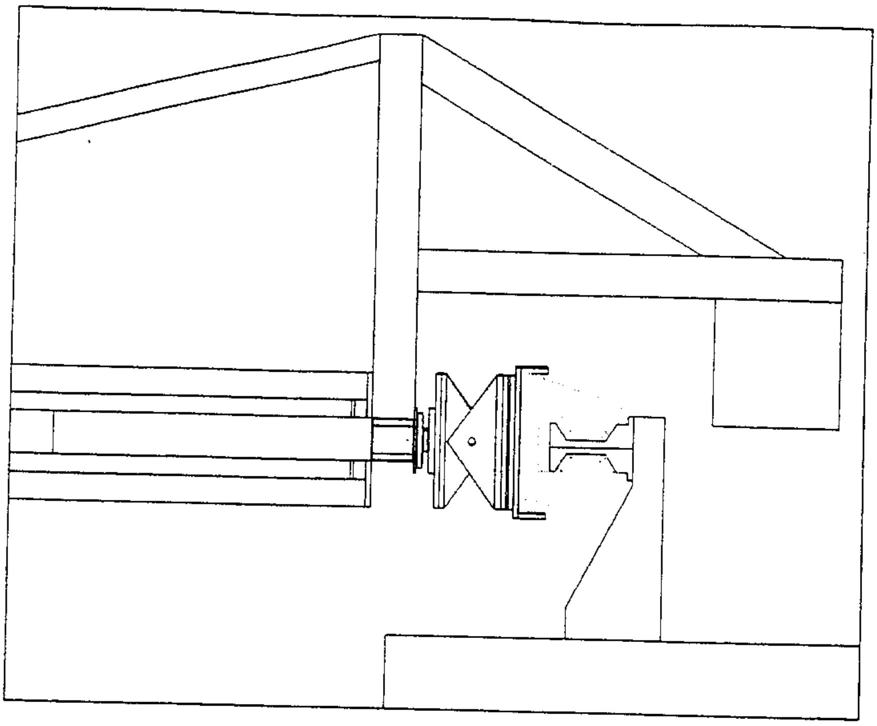


Figure 6: Side view showing telescoping truss connected to rail

This system can be incorporated onto the current lock structure without major structural modifications. The rails system proposed is completely different from the existing rail system. Hence a new rail system has to be built along the lock structure.

The proposed tracks are designed specifically to take the kind of loads that are present in the system. The wear rate of these tracks is estimated to be much lower than the existing rails. Also, these tracks are built in modular sections and are attached together using bolted joints. This enables easy replacement of components and a cheaper and quicker maintenance procedure. The concrete curing time, which is a key factor in the current rail maintenance, is completely eliminated by the bolted steel assembly.

Modifications to Vessels

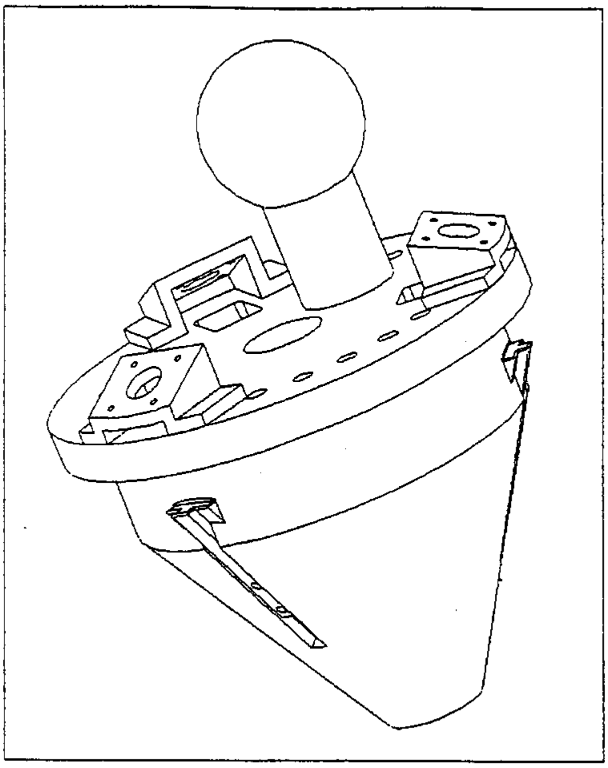


Figure 7: Mooring boot

Since most of the positional correcting forces are applied at the chock, it becomes a critical member of the whole system. A reinforcement of the chock might be required in order to take forces of the order of 200,000 lbs. for a Panamax ship.

The modification of the chock is necessary to implement the proposed connecting procedure. Using the chock-cable combination, the attachment to the ship becomes simpler and more efficient. Also, the manpower required on deck is reduced. A fast and easy connection procedure of this nature reduces the transit time per ship and hence increases the throughput of the locks.

System Robustness

The semi-rigid nature of the connections speaks for the robustness of the system. This system's automatic nature implies that the chances for human error are minimal once the connection between the truss and the ship is established.

The mechanism does not have any form of delicate instrumentation. This makes the system inherently robust and capable of operating under extreme conditions.

Comparative analysis of the design

The telescoping truss system is a rugged and easily maintained system. The rugged nature of the system arises from the fact that no cables or other high maintenance components are being used. The entire design of the system takes into consideration ease of maintenance. To this end, components are bolted together instead of welded to make the replacement of parts quick and easy. The rail system is also a modular system to reduce the downtime associated with rail replacement. This reduction occurs because the rail system will be bolted to a structure that adequately distributes the loads to the concrete. The rail can also have sacrificial wear surfaces that can be replaced without replacing the entire rail.

Compared to the existing locomotive system, the proposed system has many advantages. The control on the lateral position is better due to the rigid attachment. The stopping and towing forces can be applied at the front and the back and this force is de-coupled from the lateral force application. In the current system a braking or towing force applied by a locomotive tends to pull the vessel to the lock wall. The truss system does not have this problem. Also, the response of the system to the "stop" and "tow" commands is faster since the trusses don't have to move from "towing position" to "braking position". Only two attachments are required on the vessel unlike the four to eight attachments of the current system.

The proposed system simplifies the initial attachment procedure. This eliminates the need for a rowboat, and reduces the manpower required on deck due to the reduced weight of cable that the line handlers must work with. The attachment procedure should increase the throughput of the system by reducing connection times.

The only modification that may be required on the vessels is a reinforcement of the existing chock. This reinforcement can be done easily and at a low cost because the chocks are near the mooring bits which are already designed to take the required loads. The reinforcement procedure could be as simple as bracing the chock up using the bit as a backing.

During elevation changes and while the trucks go up the ramp, the lengths of the truss arms are varied in a controlled manner. This enables full control on the lateral and longitudinal vessel position during the elevation changes and while the carts go up the ramp.

The truss system has many advantages over the current system because it addresses the changes in the vessel size that has occurred since the canal was built. These advantages include lower maintenance costs, reduced down time, and an ability to operate on any vessel during any type of weather and visibility conditions.

Conclusions

The proposed telescoping truss system uses readily available components to solve the unique problem of ship position control in the Panama Canal. The truss system was designed by using the current system as a baseline. This baseline allowed the identification of many problems that were avoided by proper use of the design process. These problems included items such as high maintenance costs, labor-intensive processes, and poor loading of the rail system. The telescoping truss system lowers maintenance costs. reduces down time, and allows vessel transits during all weather and visibility conditions.

FLOATING LOCK

Summary

The purpose of this design is to facilitate the easy transit of ships through the Panama Canal locks. This system won't replace the existing system of locks or the gates. It will serve as a tool for the pilot to help maneuver the ship through its transit. The major problem of the current system, which uses locomotives, is the limited control over the ship dynamics and the highly non-linear loads. During the transit forces act upon the ship, which makes the job of centering difficult. It's the incoherent action of the forces aggravated by the unsynchronized forces of the locomotives, which makes the problem worse. The aim of this design is to study the use of the concept of floating lock as a replacement to current locomotives.

System capabilities

As designed, this system is restricted to ships having a beam of less than 98 foot in the present locks. This is because the floating lock walls are 3 ft wide and they need 2-3 ft of clearance. However, the concept can be scaled up to facilitate Panamax and Post-Panamax vessels in a new lock system. The system provides all maneuvering capabilities (longitudinal and transverse) to the ship while it's in the transit. The floating lock can be viewed as a vessel that can perform the functions of a tug and a dynamic positioning vessel.

Operational Description

Pilot Interface

A pilot on board the ship controls the thrusters on the floating lock prior to initiation of control and once the floating lock is connected to the ship. Sensors on the floating lock provide precise position information to the pilot.

Human elements in the system

Two floating lock operators are needed to guide the floating lock to the ship in open water and to facilitate mooring of the vessel. These operators control the azimuth thrusters remotely and controls the floating lock. The mooring has to be done from the ship's bollards. These operators take the lock to the ship embark the ship using a ladder and assist in mooring. After the mooring the floating lock is controlled remotely through out its transit. After the transit they disembark the ship and get back on the floating lock.

Entrance (Gaining Control of the Vessel)

The Floating Lock will have the capability to cruise out to meet the ship before it reaches the lock area. It then assists in steering the ship through the lock system from the entrance to the exit. The Floating Lock meets the ship within 1/4-mile of entering the locks. The ship is secured to the mooring positions on the floating lock. These mooring points are similar to the bollards on the ships. The thrusters on the floating lock helps the lock in entrance, performing necessary yaw, surge and sway operations. Once the ships reach the lock the floating lock is taken to the ship and it is stationed so that tethering to the mooring points is easy. The mooring points of the ship are used to tether. When the ship is secured to the floating lock then the thrusters on the floating lock is operated to position the lock. The thrusters on the floating lock are vertical axis omni-directional azimuthing thrusters, which can rotate on their axes for 360 degrees. These thrusters provide sufficient power for towing the ship through the locks. If there are some disturbances caused by mixing currents, winds etc. the thrusters can be controlled to compensate for them.

Forces imposed on the Ship

The ship will be "statically" moored to the floating lock via the mid-ship bollards. These mooring lines will transfer the thruster forces to the ship. The nature of application of the forces, like the phase lag has to be studied by model tests.

Azimuth Thruster:

The basic idea behind an azimuth thruster is that the propeller can be rotated 360 degrees around a vertical axis providing an omni-directional controlled thrust resulting in excellent maneuverability. It also eliminates the need for a reverse gear and rudder, which facilitates the easier control of the yaw of the ship. It is also a very good mechanism for stopping.

Centering Throughout the Transit

The most important feature of the current system is that it can help in centering while transiting the lock. This is done with the help of locomotives. In the case of the floating lock this centering is done with the help of azimuthing thrusters which can provide necessary forces so as to overcome the disturbances. The pilot can read the disturbances on the ship like the yaw and he can control the thrusters and thus control the ship. To aid the pilot, position sensors indicate the position of the floating lock wrt the lock walls.. The pilot can read this data and operate the thruster control via a joystick and rectify the disturbance. There is no self-centering mechanism for this system in the sense that the operation is not automatic since it requires pilot action. This system can be used for centering with the help of proper use of the thruster angles.

Accommodating the Elevation Changes

The Floating Lock concept inherently accommodates changes in elevation while within the lock. The Floating Lock is completely compatible with elevation changes.

Stopping

In the current system stopping is performed using the locomotives. This creates excessive wear on the rails thereby requiring more maintenance. The floating lock uses the thruster power to stop the ship. When the thrusters are rotated 180 degree the thrust acts opposite to the direction of the motion of the ship and stops the ship. From the resistance calculations it is seen that it takes around 180 ft for a Panamax ship to stop from a speed of 3 mph with the aid of the four thrusters. An added advantage of using the floating lock is that during the stopping sequence the thrusters are facing the lock gates and this will increase the piston effect and thereby helping the stopping action. With the help of the floating lock, a Panamax ship can be stopped with a safe distance of 30 ft from the gates in approximately 3 minutes starting at 210 ft from the gates.

Towing

The towing capability of the floating lock is better compared to the existing system. In the existing system only around 40% of the tension (depending on the water level) is used for the towing. This because of the bad angle between the mooring points and the locomotive guides. In case of the floating lock this elevation problem can be alleviated by proper ballast. The ballast tanks on the floating lock can be flooded or drained by operating the ballast pump. For instance flooding the ballast tank increases the draft and thus improves the handing of a low freeboard ship. The power required for towing the ship through the transit is provided by the thruster. A speed of 3-4 mph can be achieved inside the lock whereas a speed of 6-7 mph can be achieved outside the lock when the thrusters are at full power. This significant speed reduction is owing to the added resistance created by the presence of the walls. This also better compared to the current system. The thrust created by the thruster is indirectly applied on the ship using the four mooring lines.

System Requirements

Power Requirements

The floating lock requires around 3 tons of diesel per week. This diesel is used to operate the engines for the thruster propeller and for the thruster azimuth controller.

Maintenance

The life of the floating lock is considered much better compared to the current system as there are no rails or other friction producing parts. Primary maintenance involves the thrusters and the hull of the floating lock. Damage due to flooding of the floating lock can be critical, so an emergency pump is required for de-watering. A damage due to flooding will cause substantial draft change (trim also possible) and thus reducing the efficiency of the thrusters. Serious repair to the hull can be done only in a dry dock or on a slipway.

The thrusters must be maintained every 4000 operational hours (about 6 months).

The thrusters must be overhauled every 20000 operational hours (about 2 1/2 years).

The floating locks must be dry-docked for structural maintenance and repainting every 4 years.

Modifications to Existing Infrastructure

No modifications are necessary to the existing infrastructure.

Modifications to Vessels

No modifications to the ships are required.

System Robustness

The floating lock is quite failsafe once the ship is engaged. Several possible failure modes exist, however, in the initiation of the ship. Skilled operators are needed to maneuver the floating lock around the ship. If the floating lock approaches the ship at an angle, a danger exists in the protruding bow of the ship damaging the operator control house on the floating lock. Responsible and adept operators must handle this in conjunction with an alert pilot. If the thruster fails then the ship should use its power to stop the lock. Another possibility could be to use high power thrusters and operate them at a lower power. This will ensure that the lock can be operated with the help of 2 thrusters. The disadvantage of this is that the cost of the floating lock will escalate.

Comparative analysis of the design

The floating lock represents a radically different way to aid ships transit through the Panama Canal locks. The system does require skilled operators to navigate the floating locks. The personnel required for the transit is reduced, as compared to the current system, as there are no tugs required for pre-entrance assistance and there is no reliance on external systems while in the lock. The maintenance costs should be less than the current cost of locomotive repairs. The up-front cost of building the floating locks is quite large, though. At least two floating locks are required for each set of Panama Canal locks, plus a backup at each facility.

Conclusions

The floating lock assists safe transit of ships of all sizes through the Panama Canal locks. Its primary strength is that it makes all transits uniform while eliminating the possibility of collision between the ship and the stationary lock walls. Additionally, its thrusters reduce the piston effect (the forward thrusters suck water in front of the floating lock). It also can improve the night time transit as the visibility can be enhanced by installing strong bow, side and stern lights on the floating lock. Finally, it initiates control outside of the confines of the lock chamber. The floating lock increases the throughput of the locks due to increased speed as compared to the current system.

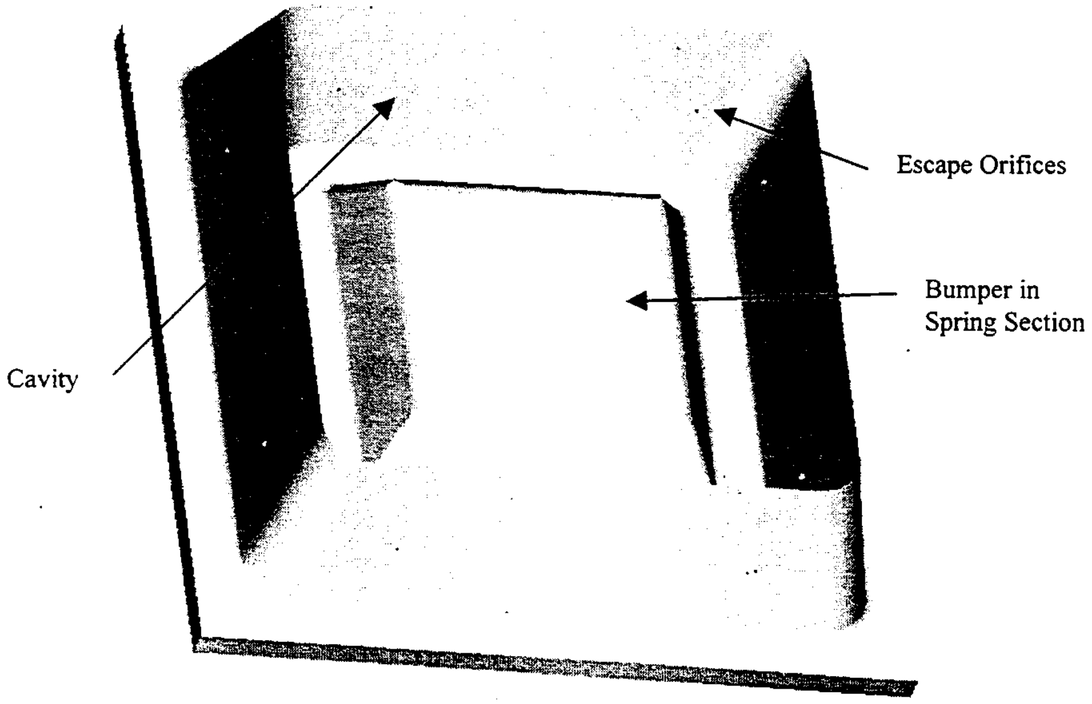
VISCOUS CELLS

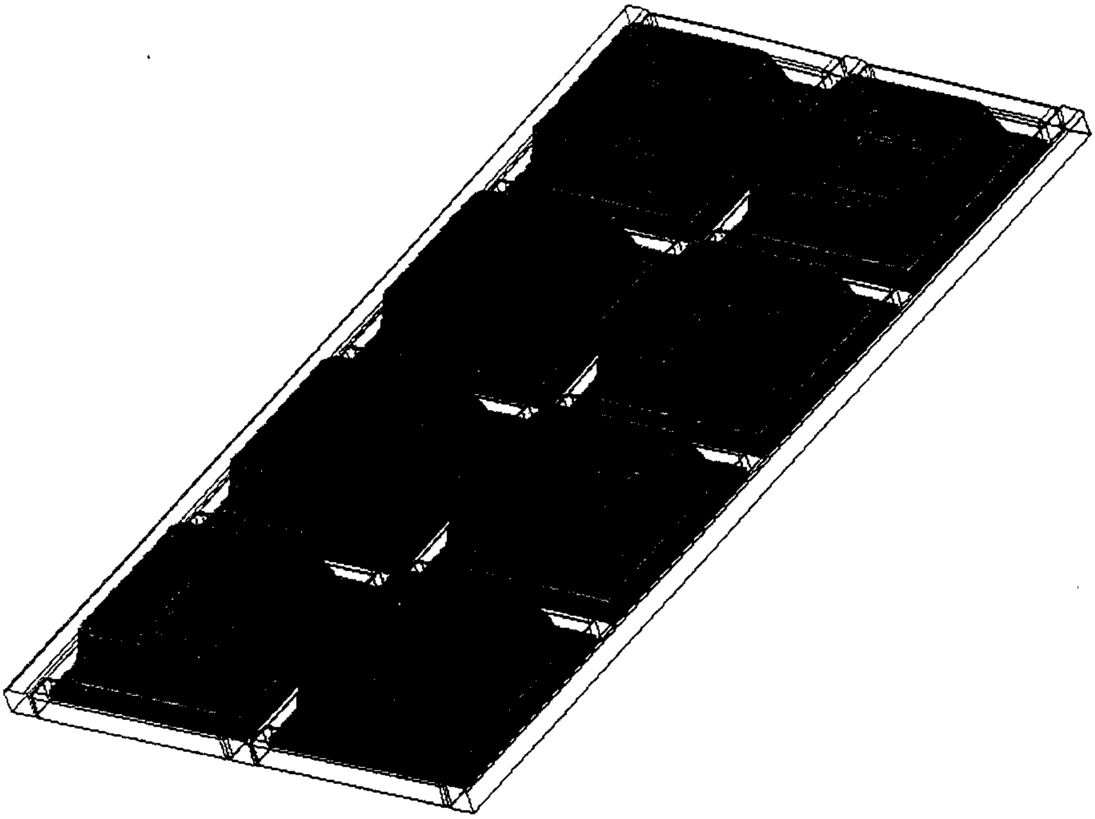
Summary

This concept is the result of the pursuit to embody a bumper system of some form. Such a system has many inherent benefits such as being a completely passive solution to the centering aspects of the task of vessel position control within the locks, requiring little or no operating power, and offering a low cost and low maintenance solution. Along with the many benefits, come accompanying drawbacks. For instance, a bumper system has no means by which to guide a vessel into a lock or provide towing and stopping forces.

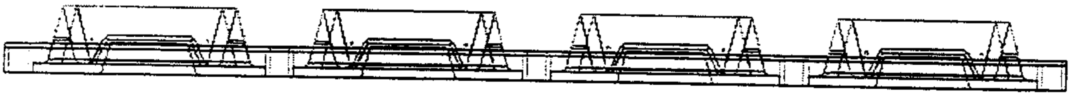
This idea employs a system of four winches to provide longitudinal positioning force and both sides of the lock are lined with a bumper system that provides a lateral positioning force. As the vessel traverses the lock system, the four winches (two on each side) provide the towing and stopping forces for the ship. As the vessel moves from lock to lock, the vessel is attached to different sets of stationary winches in a "relay" type operation. The viscous cells have concave sections and an inner spring section.

Single Viscous Cell





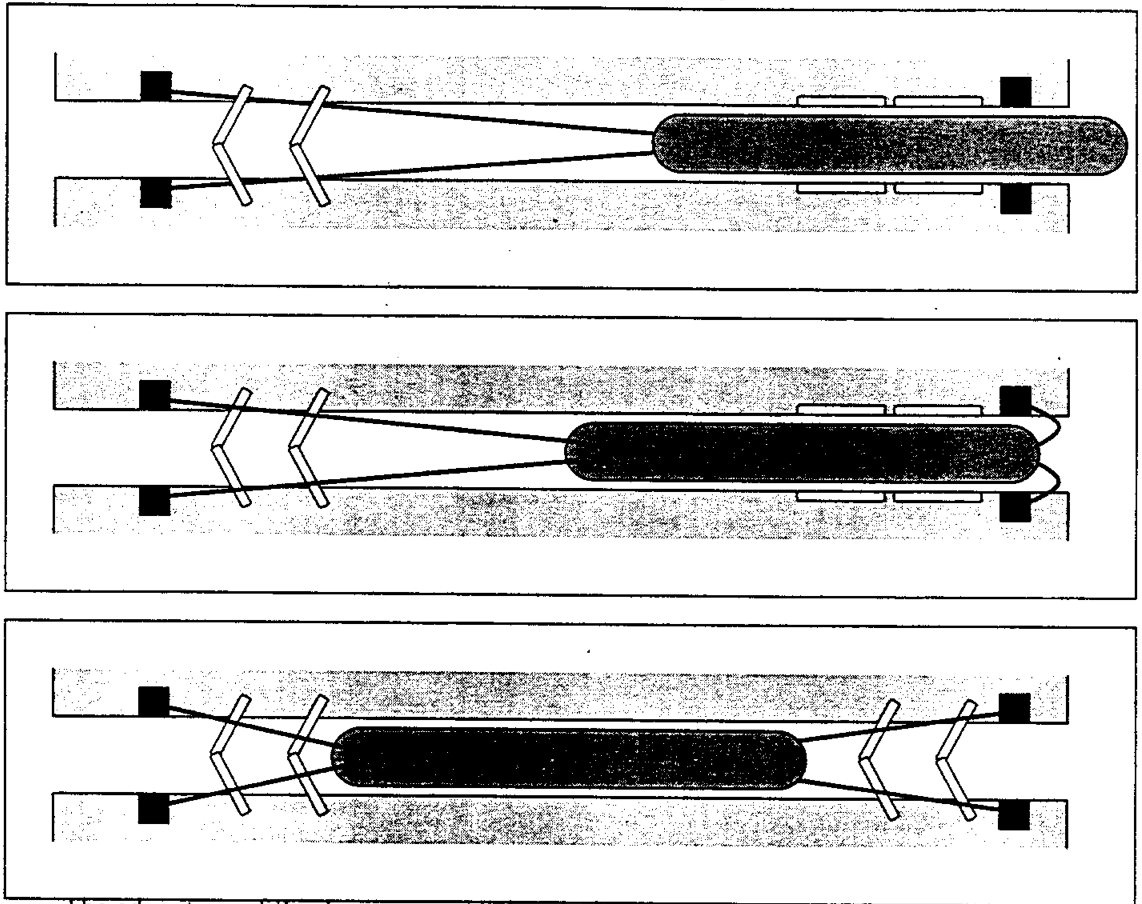
Array of Viscous Cells Mounted in Rigid Grid



Side View of Viscous Cell Array

The concave section is used to trap water between the hull of the vessel and the side of the lock. This trapped water is then expelled through eight small orifices around the perimeter of the individual bumper section. The momentum of the ship is dissipated through the viscous damping caused by the water being forced through these orifices. If the ship continues to move toward the side of the lock, the hull will then make contact with the spring portion of the viscous cells. This spring section provides a force that will help position the vessel laterally within the lock. If the ship continues to move toward the side of the lock it will contact a grid of rigid bumpers that are attached to the side walls of the lock. In normal operation, the ship will not contact the rigid bumper system; however, in order to prevent the viscous cell system from being ripped off of the side wall these rigid bumpers are necessary.

Towing and Stopping Sequence for Lock



The advantage of this bumper over other designs considered is that it manages the lateral moment of the ship in two distinct ways: viscous damping and a restoring force when the springs are contacted. The bumper system applies these forces in a distributed manner to prevent damage to the hull of the vessel.

System capabilities

This system is capable of providing a safe transit of vessels of varying sizes through the locks without damage to the vessel or the lock system. The requirements of the system include fore and aft mooring points on the deck and chocks on the hull capable of transmitting the longitudinal correcting forces.

The system could be incorporated on the current lock structure however, the bumper system would reduce the width of the lock by two feet. The design presented here can accommodate a maximum lateral correcting force of 200,000 lbs. for a vessel with relatively straight and flat sides. Longitudinal forces reach a maximum of 200,000 lbs. However, this can be scaled up to larger ships and a new lock structure if required.

The system can be operated under all weather conditions. The absence of active control for lateral positioning improves the robustness of the system ensuring that night operations can be performed safely.

Operational Description

Pilot Interface

The complexity of pilot interface is reduced tremendously by the passive nature of the lateral positioning system. Hence, the only control required is the towing and stopping of the vessel. The interface can be a signal that directly controls the stationary winches.

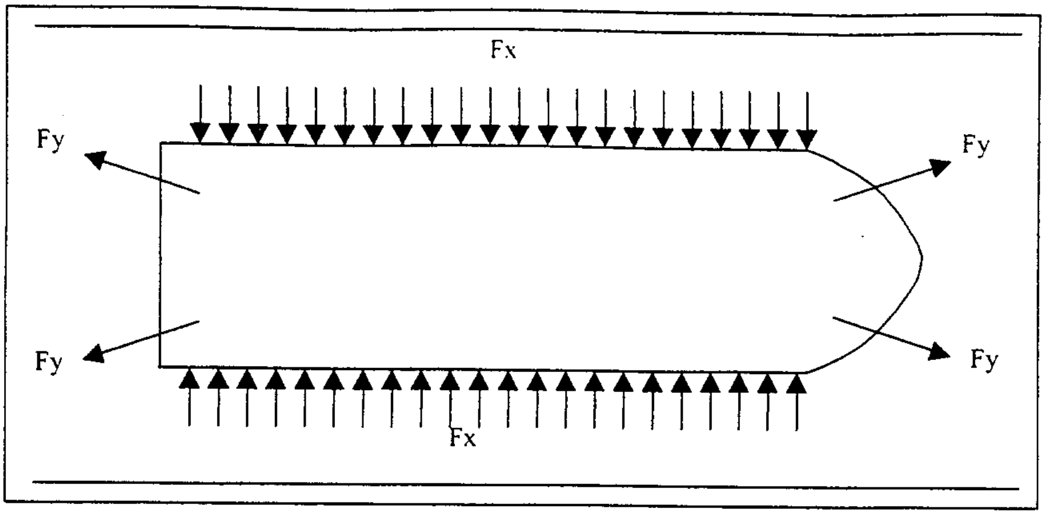
Human elements in the system

The attachment procedure will require the use of line handlers. Four cables will need to be attached to the vessel in order to provide the longitudinal positioning forces. This reduces the manpower required in completing the attachment procedure because there are four fewer attachments to the vessel required than the existing procedure. However, the relay operation will require the linehandlers to detach and reattach the cables for each lock traverse. Approximately twelve persons are needed as linehandlers per vessel with one pilot at the bridge.

Entrance (Gaining control of the vessel)

As the ship approaches the locks, the two towing cables must be attached to the front of the vessel. This can be accomplished through the use of rowboats. Once the cables are attached to the mooring bit, the winches start reeling the cables in. This causes the vessel to move into the lock. As the vessel enters the lock the back cables used to brake the ship are attached. After the attachment of the four cables, the vessel is under full control.

Forces Imposed on the Ship



The lateral positioning forces are present only if the vessel is contacting the side bumpers.

Centering Throughout the Transit

The lateral position is controlled by allowing the ships lateral position to deviate until it contacts a bumper on the side wall. When this contact occurs a correcting force is applied first due to the viscous damping as water is pushed through the eight orifices on each bumper element and then a spring force is applied if the ship continues to move toward the side wall.

Accommodating the Elevation Changes

The accommodation of elevation changes is accomplished by lining the walls of the lock from the low water line to the high water line with viscous cells. This ensures that no matter how high the water is, the ship will not contact the bare sides of the lock. The towing and braking cables will also have to take up the slack in the lines during lock raises and pay out cable during lock lowerings. The control of the vessel during rising and falling water levels is not compromised.

Stopping

The two rear stationary winches provide the stopping forces to the ship. These winches will need to be synchronized to ensure that they do not force the ship to one side. This can be accomplished by measuring the amount of cable that is being reeled in and out of the winch. The use of two winches also increases the redundancy inherent in the system. If one of the winches fails the other winch will be able to provide stopping forces. However, in this case the ship will be forced to one side of the lock which is less severe than damaging the miter gates.

Towing

The two stationary winches in front of the vessel provide the towing forces. These winches will also need to be synchronized to ensure that they do not force the ship to one side. If one of the winches fails the vessel may use its own power or a tug to get into and out of the locks.

System Requirements

Power Requirements

The viscous cell system will require no operational power as all of the motion damping is achieved through conversion of the vessel momentum into flow losses associated with the orifices described above. The stationary winch system will, however, require operating power. Assuming that the vessel uses no on-board means of propulsion and all towing and stopping forces are imparted to the vessel via the set of fore and aft stationary winches, a typical transit through a single lock can be expected to require steady operation of two 100 hp electric motors powering the winches. The relay operation can be expected to consume minimal power since only the weight of the unrolled cable is drawn the length of the lock to be connected to the next vessel.

Maintenance

As described in previous sections, the viscous cells are guarded from destructive interaction with the hull of the vessels through the use of the rigid bumpers. Eliminating such interaction should guarantee long life of the cells. Normal wear, however, is expected and a well-devised maintenance schedule should reduce the burden of costly down-time. Such a maintenance schedule would require division of the array of cells into several sets which could be either localized sections or well interspersed throughout the array. If each cell is expected to last for two years and only a given sector is replaced on a given week, the job is not only manageable, but also results in a continuously good overall condition. The primary drawback to this system in terms of both initial installation and regular maintenance is that components are positioned below the waterline. The saving factor here is that none of the parts are made of materials that can corrode or fail due to mechanical complications. The viscous cell should require about the same level of maintenance attention as a vehicle tire with the advantage that no pressurization is required.

While the winches are stationary and therefore eliminate the element of track repair, they too will require some maintenance. Regular inspection of both the mechanical elements of the winch as well as the cable itself should be performed. The configuration of the cable relaying system will have a large and positive impact on the cable life as opposed to simply dragging the cable along the concrete lock decks. The basin of this cable relaying race will have to be replaced periodically, but require only inexpensive materials (either wood or plastic sheet such as polypropylene) and relatively unskilled labor.

Modifications to Existing Infrastructure

This system can be incorporated into the current lock structure without major structural modifications. The viscous cells are designed to be surface mount with the option of creating an array of recesses in the concrete lock wall or providing cell protection via the rigid bumpers. The longitudinal action winches are surface mount units and would require only a local solid foundation capable of transmitting the required loads to the vessel; a small task for a stationary structure. The cable relaying system replaces the locomotive system and track system with a much lighter duty device requiring minimal power, minimal load capability, and less space than the current tracks.

Modifications to Vessels

The combination of the viscous cells and the stationary winch system requires no modifications to the vessels. The viscous cells act on the hull of the vessel regardless of the hull material and the cables of the stationary winches are secured on the existing bits of the vessels.

System Robustness

The passive nature of the viscous cell array and the rigid grid protection provided make this concept very robust. Operator error has no meaning within this system in terms of lateral and angular control of the vessel since these displacements are bounded by the cell arrays in a passive fashion. A disturbance such as a crosswind simply acts to bias the vessel against one side of the lock. Robustness with respect to towing and stopping forces imparted to the vessel by the stationary winches is best achieved by providing redundancy. While towing, it is not as crucial to have redundant capabilities as when stopping. Whether a particular winch system is to operate in tow or stop mode, however, depends on the direction of travel through the lock. Therefore, all winches must provide the same level of redundancy whether the option of utilizing it is exercised or not.

Comparative analysis of the design

The viscous cell system in combination with the stationary winches has several advantages over the existing system in terms of operational capability. First, it is passive in lateral and angular control. No sensors or feedback control systems, electronic or human, are required for optimal operation of this concept. In addition, the pilot or pilots is/are burdened only with the task of monitoring the longitudinal position and velocity of the vessel after entrance to the lock is achieved. Secondly, the existing system imparts forces to the vessel through cables often oriented at large angles from the intended direction of force. This can best be seen in the current system when the locomotives are in tow or stop position and the cable is making roughly a 30° angle with the longitudinal axis of the vessel as well as a significant angle with horizontal. The tensions required in the cables during operation in these least optimal configurations place more load on the vessel and the winch system than is necessary. The most important implication of operating at sub-optimal angles, however, is the coupling between longitudinal tow and stop type forces with lateral and angular position. Currently, this problem impacts the controllability of the vessel severely. This statement is supported simply by observing that the locomotives rarely reach a state in which the vessel does not require some control except when it is stationary during raising or lowering. This type of disturbance is avoided entirely by the decoupled nature of the longitudinal and lateral control.

In terms of maintenance, this system has some advantages and disadvantages in comparison with the current system. The first and most significant advantages is that the heavy load bearing tracks and costly locomotives and associated operators can be eliminated with this design. Lateral and angular control of the vessel is achieved within the lock through the viscous cell array, and winches that are stationary provide towing and stopping forces. These characteristics require no dynamic or mobile means of transferring loads placed on the vessel to the ground. Rather, the loads are transferred through stationary elements on stationary foundations which can easily be constructed for service lives that compare to that of the lock system itself. The primary disadvantage associated with all of the stationary components is that if a failure does occur that requires maintenance, the components must be removed and transported to the maintenance facility as compared to the mobility of the locomotives. This problem can be remedied to a large degree by mounting critical components on skids that can easily and quickly be removed and replaced by a standby unit. For example, each winch can be mounted in a standard fashion and an extra cable can be kept on standby. A small overhead winch can provide quick serviceability to the stationary winch systems for component removal and replacement.

Utilization of the viscous cell concept with stationary winch systems would drastically reduce the number of moving parts and tracks, reduce impact loading, and possibly decrease personnel. These factors act together to make this concept an attractive option for consideration when building new locks.

Conclusions

The viscous cell concept uses an array of cells, each containing a viscous and a linear restoring type element, to passively convert the lateral momentum of the vessels into losses associated with the flow of water through small orifices. This flow is induced once a volume of water is trapped within the cell cavity by the hull of the vessel. Further motion of the vessel towards any cells it has acted to seal off results in flow through the exit orifices of the cell. The cells are numerous, but relatively inexpensive being approximately equal in complexity to a standard automobile tire. The modular style of the array allows individual cells to be replaced as necessary. The nature of the array of cells approximates a uniformly distributed load across large sections of the hull without the immense inefficiencies of earlier concepts involving distributed hydrodynamic forces. The viscous cell concept and stationary winch system is a viable alternative for vessel positioning within the Panama Canal lock system.

CONCLUSIONS

This has been an ambitious challenging project that has been very beneficial to us in the engineering education process. It is fairly unusual for a class to have the opportunity to work as a group on a real multifaceted interdisciplinary problem that involves numerous objectives, creativity, brainstorming, design and tradeoffs, all in an international setting. The fact that the Panama Canal is one of mankind's engineering marvels that exemplifies creative design is particularly motivational. From our perspective it has been a tremendous learning experience and we are very appreciative of the opportunity.

We hope that we have been able to contribute some useful new concepts that may not have been previously considered, not only for the vessel positioning process, but also through the additional ideas that arose regarding turbulence and water conservation. Also we hope that the understanding and expression of the problems from our viewpoints have been beneficial to Panama Canal Engineers as they continually search for ways to improve the Canal operations. It is important to point out that our study has only been at the conceptual level, and that numerous issues and open questions exist before any of the concepts could ever be practical. In addition we are reluctant to prioritize the six new positioning systems that we have presented because we are not aware of all the issues that might strongly influence choices. Perhaps a hybrid version of the concepts could be the best approach.

We offer the following general conclusions.

A positioning system that uncouples longitudinal and lateral forces as much as possible is desirable from the viewpoint of minimizing wear, maintenance and component load capacities. Excessive wear and unnecessarily large forces and associated over design of components is present in the current locomotive system because of the strong coupling of forces that exists.

Automation of a positioning system requires sensing, signal processing and computing systems. These components are much more reliable presently than in the past as evidenced by their critical and extensive use in harsh environments, for example down hole drilling where there is extreme temperature and pressure, and in the outer space radiation environment. It is felt that the benefits of automation far outweigh the objections relating to complexity and potential unreliability, particularly if redundancy is used.

We feel that active positioning systems that rely on distributed hull forces, for example electromagnetic forces and water flow forces, to achieve centering are much less viable than positioning systems that rely on vessel attachments and point forces applied to bits.

All of our six ideas rely on attachments and point forces except the viscous cell idea, which is a passive, (no external power required) bumper system with point forces for longitudinal control. The attractive feature of distributed force systems is that no attachments are required, but this gain is substantially offset with problems associated with possible detrimental hull interactions, difficulty of precise control, nonlinear scaling issues, difficulty of towing and stopping, excessive power and complicated infrastructure requirements.

The rack and pinion system in use is not designed to easily withstand the shear loading that is present.

Time delay in control actuation is very detrimental to effective control and wear; every effort should be made to minimize it.

In the current system there is no feedback to Pilots regarding the amount of longitudinal and lateral force each locomotive is applying at any instant. This information could be invaluable to the current positioning operation in terms of reducing wear and more effective centering.

Finally there are a number of important tasks that remain to be undertaken. An optimal design will require a much better knowledge of the magnitudes of the disturbance and hydrodynamic forces on various classes of vessels in the restricted locks, the required longitudinal towing and stopping forces, and the lateral positioning forces that are required for a variety of vessel classes. Once a design concept is chosen for further development, this information coupled with simulation and scale models could be invaluable in design optimization. In addition there are many open issues in the design of any automated aspect of the system that requires sensing, information processing and feedback controls.

We are very interested in the next stages of the research and design processes associated with this project and would like to undertake the responsibility. There is very broad capability along these lines at Texas A&M University, and we are certain that we could develop this project to fruition.

APPENDIX

RESULTS OF BRAINSTORMING EFFORTS

Brainstorming began with generating a comprehensive list of potential ways to impose a generalized force onto a ship. No embodiment was attached with each of these methods.

MECHANISMS TO IMPOSE A FORCE:

1- Lower potential in the center of the lock (density gradient).

2- Hydraulic piston.

3- Buoyancy.

4- Hydrodynamic.

5- Springs and wheels.

6- Magnetism.

7- Wind.

8- Bumpers.

9- Wheels on the wall.

10- Cryogenic.

11- Ship lifting.

12- Induced currents.

13- Automatic wenches.

14- Rack and pinion.

15- Floating lock (use locomotives?)

16- Wheels on the boat.

17- Air cushion.

18- Beam with rollers under ship (and inflatable balloon).

19- Piezo-electric.

20- Thrusters.

21- Paddle.

22- Vacuum.

23- Overhead crane.

24- Drive ship backwards.

25- Big cable attached to the ship (fish ship in).

26- Drag net.

27- Bow thrusters.

28- Under water propellers

29- Power chain on center of the canal (like a roller coaster).

30- Chemical alterations of density of water.

31- Rubber balls with magnets inside.

32- Water curtain.

33- Water slide (strong current).

34- Pulley and counter weight system.

Considering the previous list of possible forces, we engaged in brainstorming sessions with the goal of contriving a way to embody each of the forces. The results are what we call "rough embodiments of conceptual solutions".

1.Auto-Pilot
2.Air Blanket with rollers
3.Water Pump
4.Actuated Rubber Tires
5.Buoyant Wedge
6.Continuous Rubber Bumper / Bladder
7.Fixed Roller Bearing Structure
8.High Tension "Tight-Rope"
9.Integrated "Robot-Winch" System
10.Lock Wall "Gas Jets"
11.Suction / Water Jets
12.Telescoping Truss Wall System
13.Air Bubbles
14.Rack and Pinion
15.Underwater water jets
16.Water Freeze
17.Wheel Trap
18.Hull Thruster Banks
19.Spring System with Natural Equilibrium
20.Water Displacement Using Counter Weights
21.Lateral Forces using Counter Weights
22.Hydraulic Actuated Side Cars
23.Two degree of freedom Winches
24.Non-Contact Solenoid Actuation
25.Inverted Pendulum
26.Synchrolift
27.Ship Cradle Guide
28.Wall Thrusters
29.Alternating Wall Magnets
30.Foating Bellows
31.Syringe Effect
32.Magnetic Repulsion
33.Transverse Piston Effect
34.Air Balloons
35.Hydro-Dynamic Positioning Using a Paddle Belt
36.Water Circulation
37.Rubber Fingers
38.Controlled Explosions
39.Magnetic Locomotive
40.Foating Lock
41.Conveyor

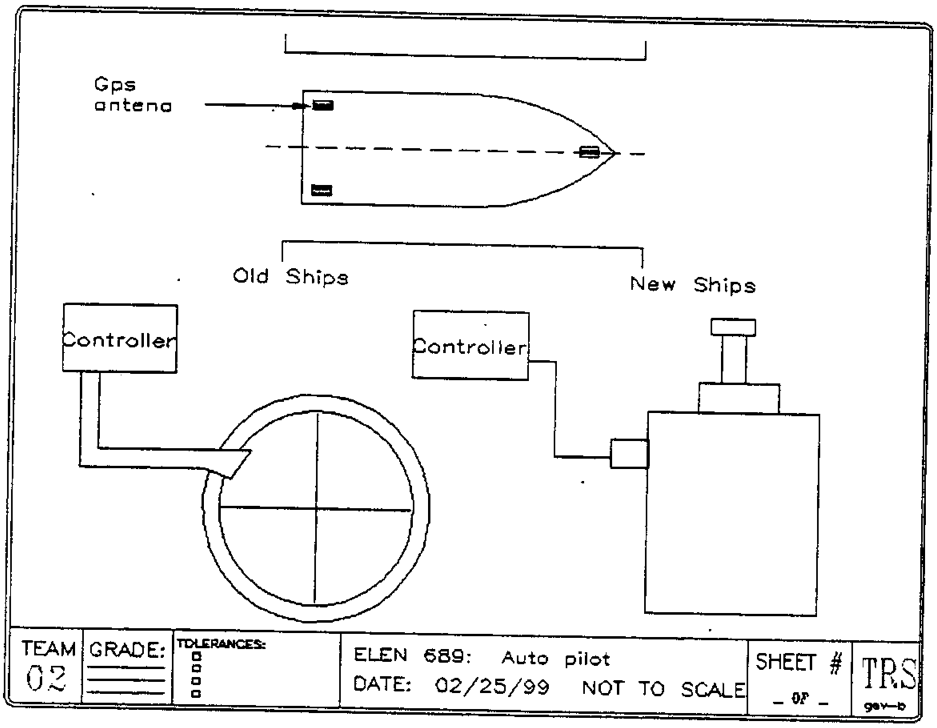
1-Auto Pilot

Description:

Many of the designs will implement a control system to assist the PCC pilots to control the position of the vessels while traversing the canal system.This recommendation utilizes GPS technology to precisely track the vessels' pitch, yaw, roll, position, and velocity. The diagram shows three sensors in the fore and aft areas of the ship, however these could be integrated into a single instrument that is temporarily installed on the ship for the duration of its stay in PCC waters.

Desirable Features of this design:

- Minimal change to current infrastructure
- Can supplement any designs proposed during this project



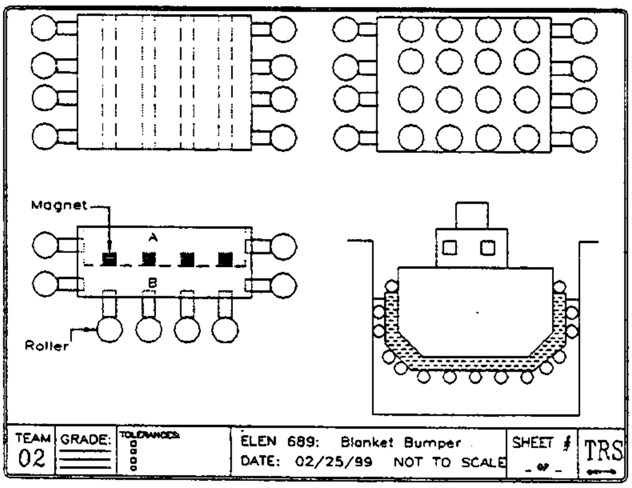
2-Air Blanket with Rollers

Description:

Resting on the bottom of the lock (or in the harbor) is a reinforced air bag with an array of rollers over its entire bottom surface. Rigid reinforcements run the length of the bag parallel with the lock walls. The air bag consists of two compartments which can be filled and emptied independently. Permanent magnets are embedded on the membrane that separates the two compartments. When the ship passes over the bag compartment B is inflated (compartment B remains empty). The bag rises to the ship and the magnets engage the hull. The bag serves as a bumper for the ship while it traverses the locks. The bag evenly distributes stresses on the hull while the rollers prevent impact damage. The bag is wider than the lock. When smaller ships pass, the excess bag area will simply float on the surface of the water. Thus restricting the yaw of the small ships. The magnets are disengaged from the hull by inflating compartment A and deflating compartment B (compartment A has insufficient buoyancy to support the weight of the bag.

Desirable Features of this design:

- Avoids localized hull stresses
- Can queue up many ships in "harbor"
- No change to infrastructure and ships
- Makes existing process safer and faster



3-Water Displacement Using Pumps

Description:

This idea uses a system of pipes and valves which transfer water from one side of the ship to the other to aid in centering. The drawing indicates pumps to facilitate the transfer of water.

Desirable features of this design:

- The vessel moves by its own power through the lock chamber
- Sensors are used to measure distance b/w lock wall and vessel side
- When a preset distance is violated, water is pumped from the side with larger clearance to the side with lesser clearance
- Pipes may also be laid along the length of the lock chamber to pump water from the front end to the back end to reduce the piston effect.

WATER DISPLACEMENT USING PUMPS

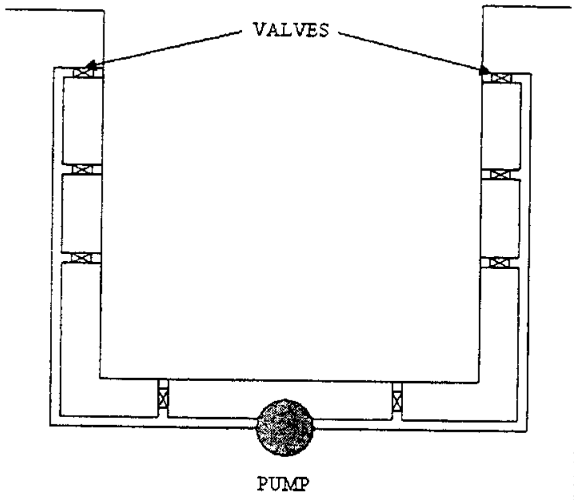


Fig 1: Cross-sectional view of lock chamber

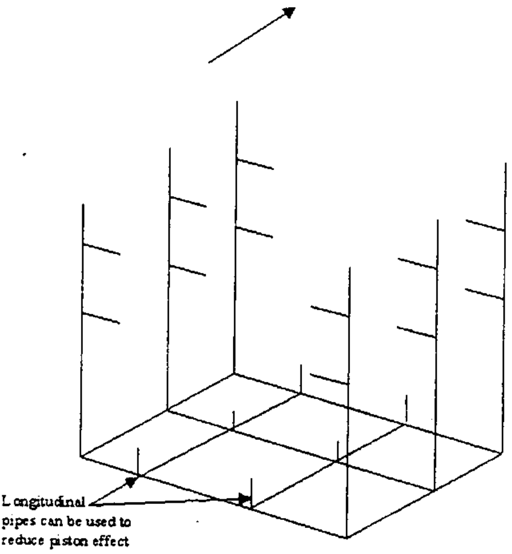


Fig 2: Line diagram showing series of pipes along the lock chamber

4-Actuated Rubber Tires

Description:

This concept focuses on direct position control only for the "Panamax" size ships. Centering forces are applied directly to the ship hull via a system of laterally actuated rubber tires. The system may be designed to provide a lateral actuation of approximately 3-5 feet on either side. The lock wall structure is modified to incorporate several independently actuated wheels to "squeeze" the ship into a centering position. Additionally, the wheels may be used to assist in providing axial acceleration (both forward and backward) via friction.

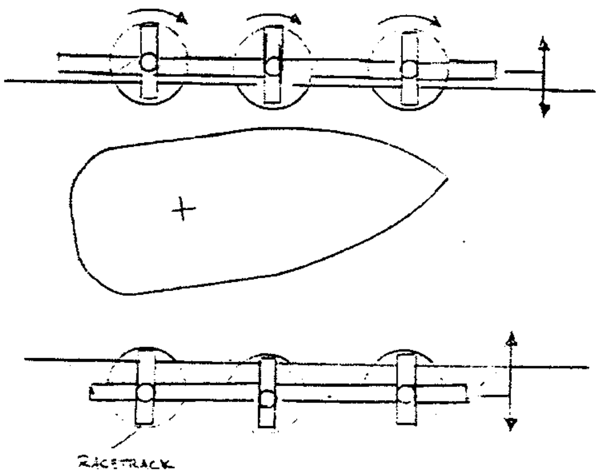
Smaller ships entering or exiting the locks are allowed to contact the tire mechanism as necessary to maintain lateral and axial position.

Desirable Features of this design:

- Fool-proof positioning
- Control of axial accelerations
- Simple mechanisms

Concept:

Actuated rubber tires



5-Buoyant Wedge

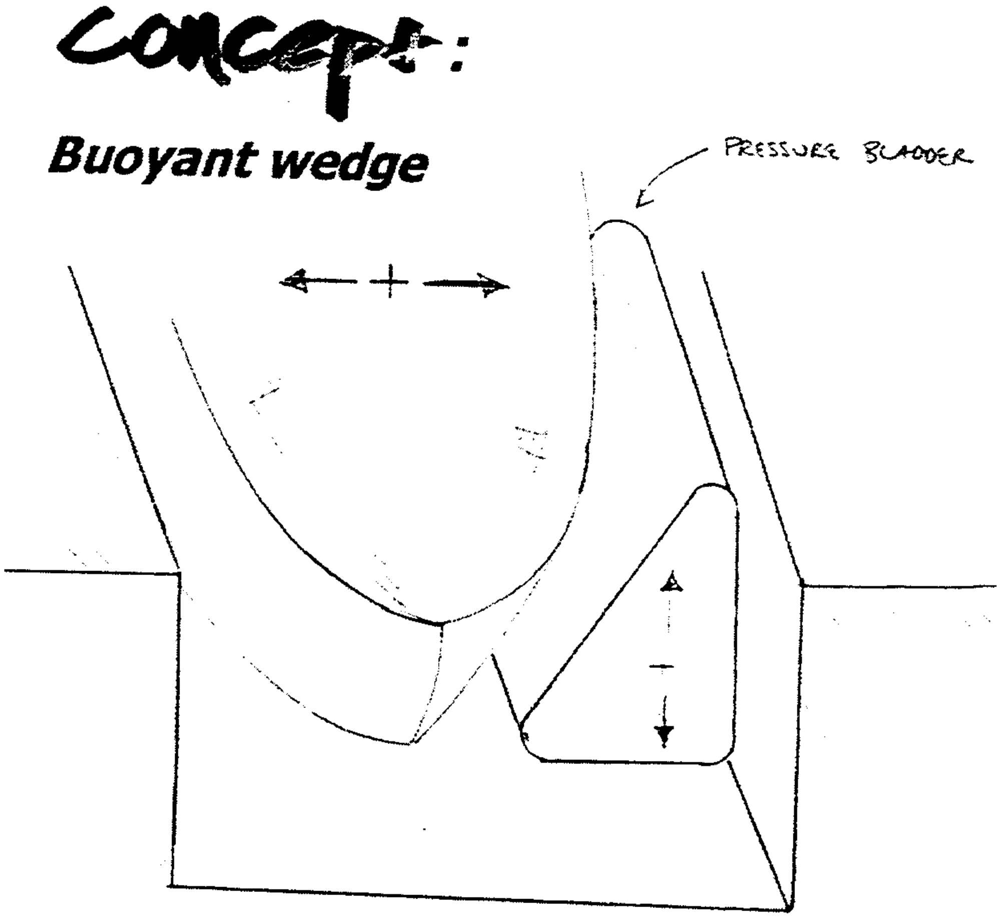
Description:

This concept makes use of buoyancy to provide positioning forces. Here, the ship is positioned against one wall, via a buoyant wedge acting from the opposite side of the ship. The vertical position of the wedge is controlled by activation / deactivation of a pressure bladder which acts as a "submarine" does to provide the desired buoyancy. The wedge can be placed at optimum elevation to provide minimal interaction with the ship's hull.

Desirable Features of this design:

Forces ship against one wall, proving "fool-proof" positioning

Minimal power requirements



6-Continuous Rubber Bumper / Bladder

Description:

This concept utilizes a rubber bumper and/or bladder continuous along the entire length of the lock walls. A ship entering or exiting the locks is allowed to contact the rubber bumper as necessary to maintain position.

Potential features include:

Let the ship bump into the walls!

Utilize viscoelastic damping material (near glass transition temperature to absorb impact energy. This is similar to the technique used to dampen vibrations in engine mounts for automobiles.

This is a passive system, requiring supplemental activity to:

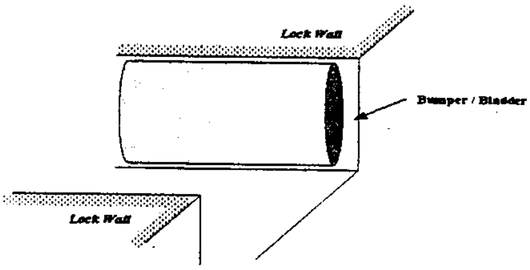
Restrain the forward motion of the ship (perhaps via air bladders / bungee cord / stretch-mesh / locomotives / rear cable...)

Supplement forward motion of the whip (via additional water displacement – to eliminate the piston effect)

Desirable Features of this design:

- Most simple, cost effective and reliable approach
- Fail-safe design
- No motorized parts

Concept: **Continuous Rubber Bumper/Bladder**



7-Fixed Roller Bearing Structure

Description:

This concept utilizes a network of bearings to provide a "roller-bumper" throughout the entire length of the lock walls. A ship entering or exiting the locks is allowed to contact the roller bearings as necessary to maintain position. Note that this is a passive system, requiring supplemental activity to:

Restrain the forward motion of the ship (perhaps via air bladders / bungee cord / stretch-mesh / locomotives / rear cable…)

Supplement forward motion of the whip (via additional water displacement – to eliminate the piston effect)

Alternatives:

Ball-bearings

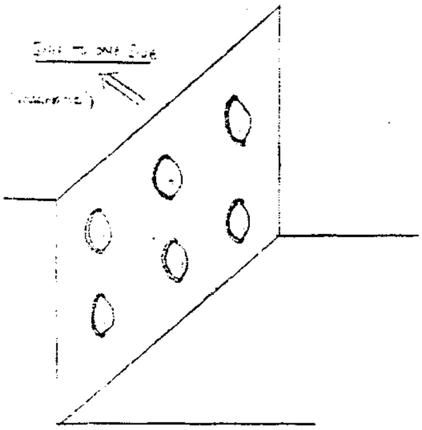
Circulating conveyer belt

Desirable Features of this design:

- Simple and reliable approach
- Fail-safe design
- No motorized parts
- Cost effective

Concept:

Fixed roller-bearing structure



8-High Tension "Tight-Rope"

Description:

Similar to the "Integrated Robot-Winch System," this concept incorporates an automated robot-winch on a rail system, carrying a "tight-rope" at the bow and stern of the ship. At the center of a tight-rope. a motorized "tight-rope walker" is attached to the mooring points of the ship, allowing lateral position control. Each robot-winch carries a clutched winch system, allowing axial control of the robot on the track. The system can be designed for closed-loop control (without human interference), or for automated response for pilot control via an operational "joy-stick", of "fly-by-wire" control. The design may include:

Robot rail system designed for minimal shear loads

Gearing mechanism allowing "position lock"

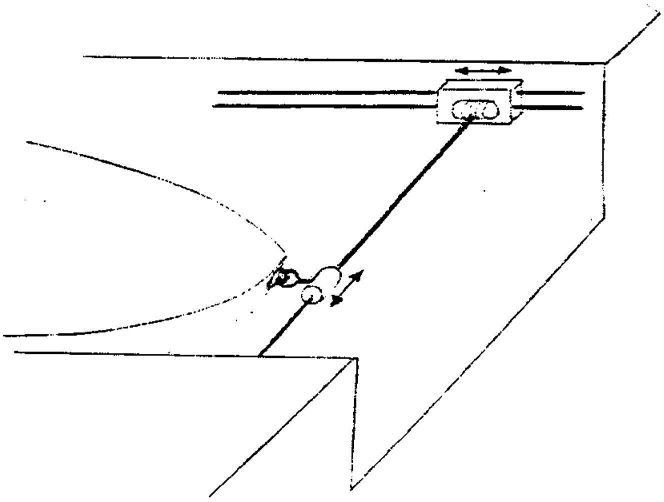
Induction motors to providing forward pull

Desirable Features of this design:

- Closed-loop control / instantaneous response
- Autonomous operation
- Optimized response protocol

concept:

High-tension cable "Tight-Rope"



9-Integrated "Robot-Winch" System

Description:

This concept incorporates an automated "robot-winch system," capable of autonomous operation. A rail system, within the lock walls, transports four automated robot winch systems (one for each corner of the ship). Each "robot" carries a clutched winch system, allowing position control of the robot on the track, and cable tension on the ship's mooring points. System can be designed for closed-loop control (without human interference), or for automated response for pilot control via an operational "joy-stick", of "fly-by-wire" control. The design may include:

Robot rail system designed for minimal shear loads

Gearing mechanism allowing "position lock"

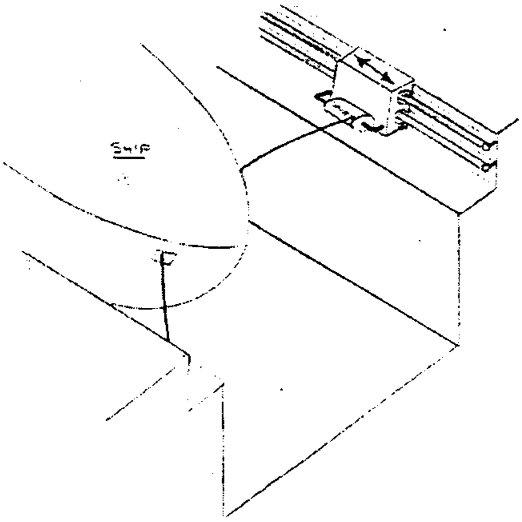
Induction motors to providing forward pull

Desirable Features of this design:

- Closed-loop control / instantaneous response
- Autonomous operation
- Optimized response protocol

concept:

Integrated robot-winch system



10-Lock Wall "Gas Jets"

Description:

This concept utilizes an embedded field of gas (air) jets within the lock walls to provide centering forces. By varying flow rates within each wall, and between opposite walls in the lock, the ship can be maintained at specified distance from either wall.

Similar to "Air-Bearing" floor

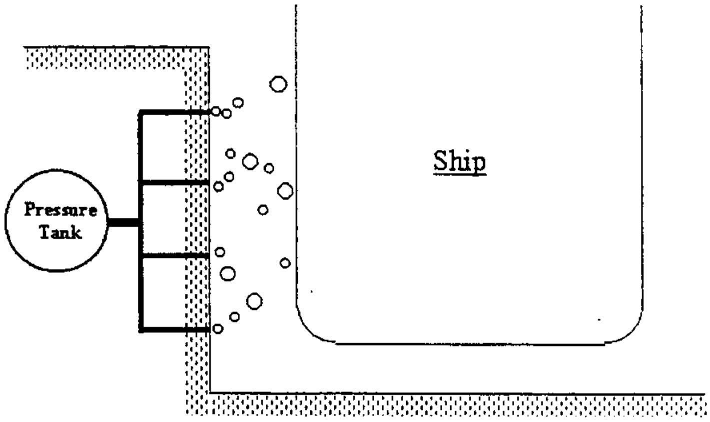
Centering force by:

1. Varying gas-flow to direct buoyancy forces
2. Direct force on ship hull in close proximity

Desirable Features of this design:

- Inexpensive medium (gas)
- Environmentally friendly

Concept: Lock Wall "Gas Jets"



11-Suction / Water Jets

Description:

This concept makes use of hydrodynamic propulsion and suction to develop ship positioning forces. Here, the ship is positioned against one wall, from which suction is provided via intake holes / valves within the lock wall. Opposite the suction, variable-controlled water jets provide the necessary propulsion to control lateral position and acceleration. The system is to be automated into a controlled network, capable of assisting in axial as well as lateral position control.

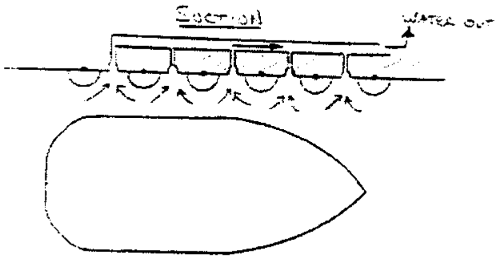
As shown, the design may incorporate wheels along the suction wall to assist in providing axial accelerations.

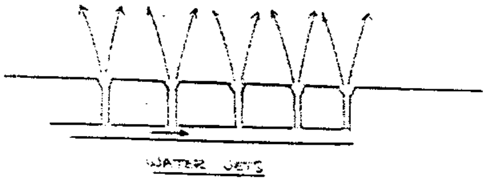
Desirable Features of this design:

- Forces ship against one wall, proving "fool-proof" positioning
- Assist in providing axial accelerations
- Accommodates all sizes of ships

Concept:

Suction / Water Jets





12-Telescoping Truss-Wall System

Description:

This concept incorporates an telescoping truss-wall system to provide ship centering forces. The lock wall structure is modified to incorporate a telescoping truss-wall with a rolling mechanism to allow axial motion with lateral position control. The wheels, roller bearings, ball bearings etc. may be used to assist in providing axial acceleration (both forward and backward) via friction.

The design may incorporate:

Both Sides – position ship in the center of the canal

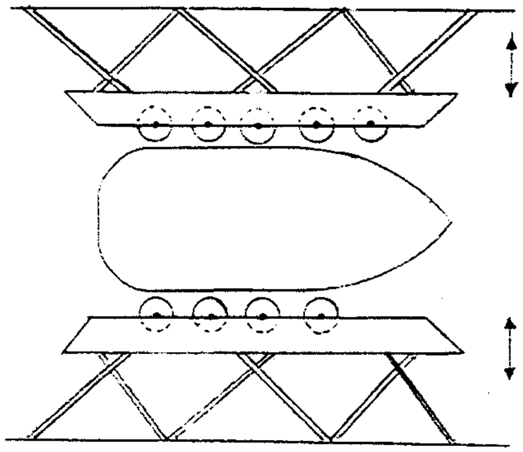
One Side – position ship against the opposite wall

Desirable Features of this design:

- Fool-proof positioning
- Control of axial accelerations
- Accommodates all sizes of ships

concept:

Telescoping truss-wall system



13-Air Bubbles

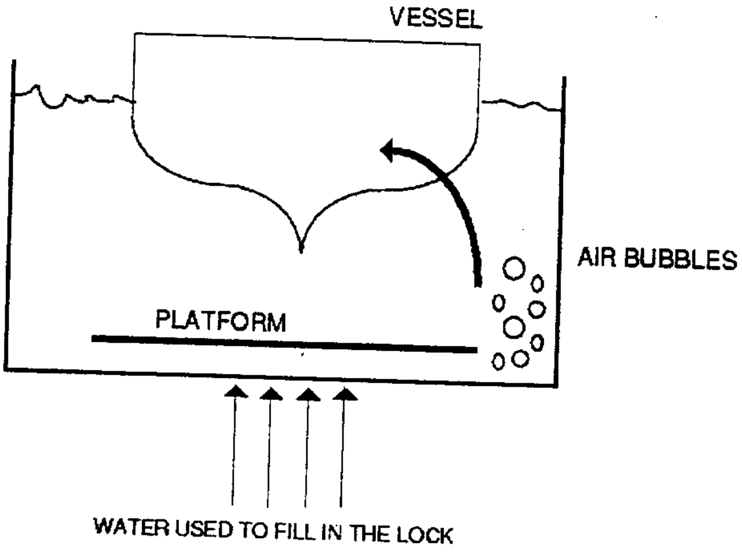
Description:

A platform is located above the bottom of the lock. Since the water used to fill the lock comes from the bottom, if air bubbles are generated in one side of the lock (see figure) then a current is generated. This induced current pushes the vessel uniformly to the wall that is opposite to the location of the air bubbles. These air bubbles can be generated in both sides of the walls. In this way, any disturbance that moves the vessel towards one wall, can be counter-acted by generating these air bubbles.

Desirable features of this design:

No need to attach any device to the vessel.

In the steady-state the vessel goes in its own power (no air bubbles are required).



14-Rack and Pinion Method

Description:

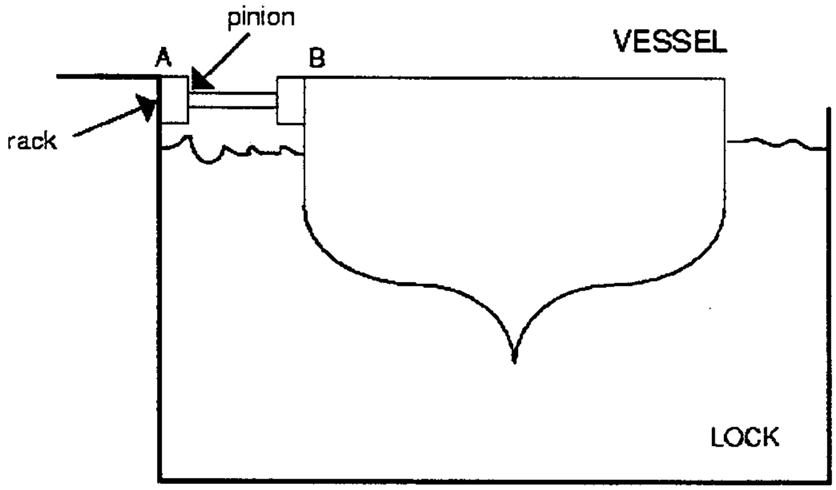
A rack is located in one of the walls of the lock. The rack can be either on the side of the wall or in the surface (where the tracks of the locomotives are now located). A pinion is mechanically connected to this rack at point A (see figure). This pinion is attached to a shaft that must be connected to the vessel at point B. This connection can be either mechanic or by ways of magnets that attach to the hull of the vessel. Once the connection is achieved, the forward movement of the vessel is regulated through the rack and pinion structure.

Desirable features of this design:

The forward movement of the vessel is controlled by the rack and pinion mechanism.

Lateral disturbances do not affect the position of the vessel.

The vessel transits the lock on its own power



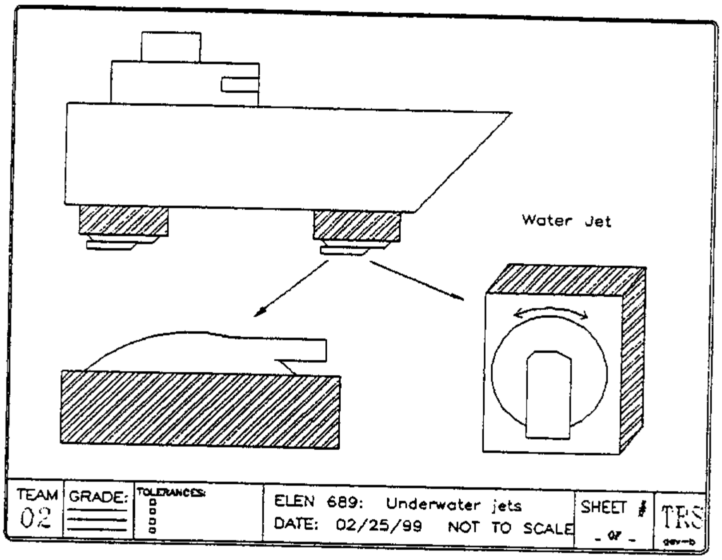
15-Underwater water jets

Description:

Small radio controlled water jet vehicles magnetically attach (or use suction cups) to the bottom of the ship. The water jets on the vehicle can rotate 360 degrees and have ballast tanks. Once attached to the ship, they can either be controlled remotely or use an automated control system. Top of the vehicles would be padded to prevent any damage to the ship. An onboard generator or an umbilical cord can power the vehicle.

Desirable Features of this design:

- The vehicles can be attached before the ship even approaches the locks



16-Water Freeze

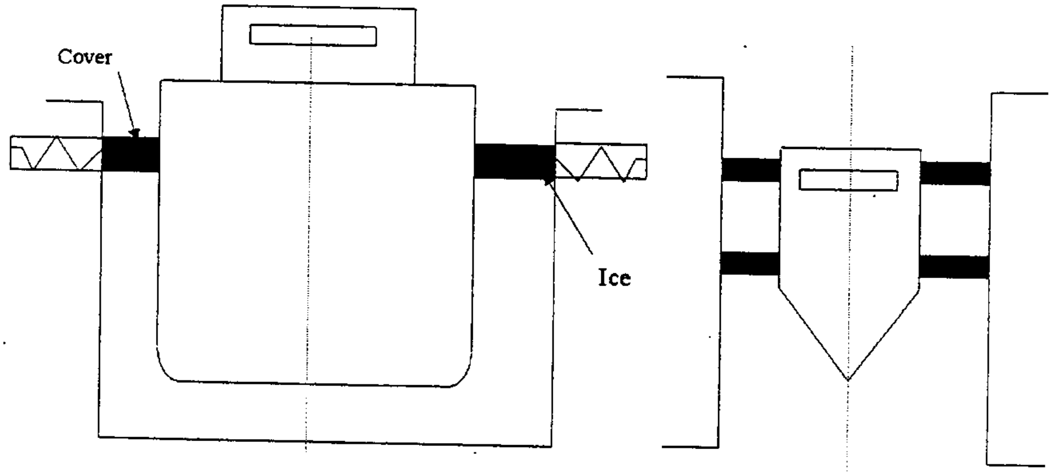
Description:

A one way permeable temperature insulated film lets water into cubic bags on the sides of the ship. A freezing agent is quickly injected into the bag as needed to produce ice as needed to form a bumper between the ship and the lock wall. The lock wall can be modified to be compliant in order to restrict the amount of force put on the ship hull when the water expands. Alternatively, instead of freezing the water, a chemical or biochemical semi-stable mixture could be used. The substance is injected to the bag. The mixture coagulates and serves the same purpose as the frozen water. After a certain amount of time, the substance precipitates to the bottom of the bag and is re-circulated for re-injection

Desirable Features of this design:

- Distributed hull stress
- No moving parts

Water Freeze



17-Wheel Trap

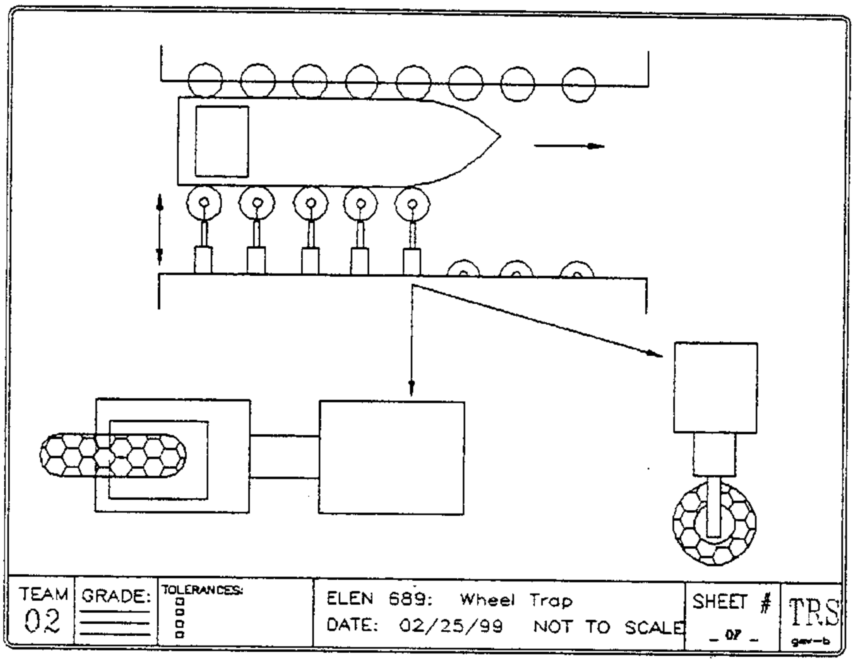
Description:

One side (1) of the lock has 3 rows of wheels at different heights to accommodate different ship sizes. The other wall (2) of the lock has a set of wheels attached to a hydraulic piston, which can extend, retract and move up and down. The ship comes as close to wall 1 as possible. Then, the piston pushes the wheels from wall 2 towards the ship. Once the wheels from wall 2 make contact with the ship, they push it against wall 1. Once the ship is trapped between the wheels in wall 1 and the wheels on the pistons, the pistons lock in place and allow the ship to navigate through the lock under its own power.

Once the ship clears the lock, the pistons return to their original position in wall 2. Note that the wheels on either side will cause no damage to the ship's haul and that wheels of the size needed are readily available.

Desirable Features of this design:

- Completely controls yaw
- Can facilitate rapid transit



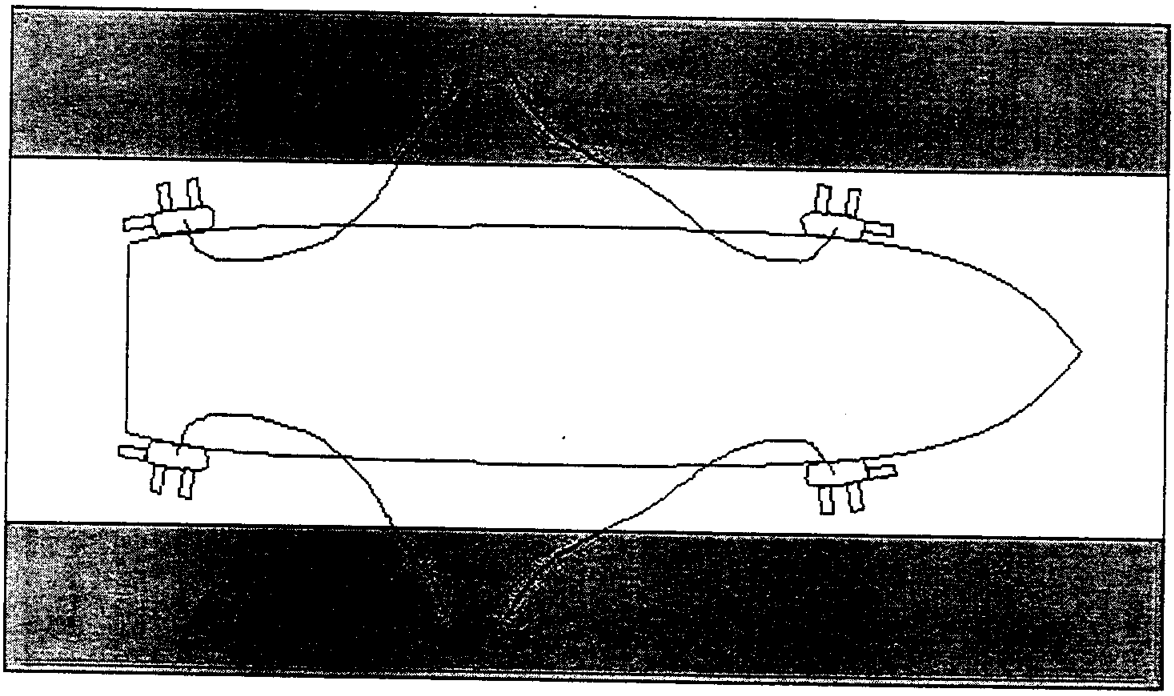
18-Solid/Liquid Fuel Thrusters

Description:

This concept utilizes banks of thrusters that are affixed to the vessel and fired in a controlled manner. Both solid and liquid fuels can be explored for this concept. This connection to the vessel can either be made magnetically or through the use of an adapter that fits into the mooring eyes. Control lines as well as current supply to the electromagnetic mounts (if employed) can be tethered along side the vessel.

Desirable features of this design:

- Lateral position and start/stop capabilities would be provided.
- No rigid connection exists between the vessel and the lock walls.



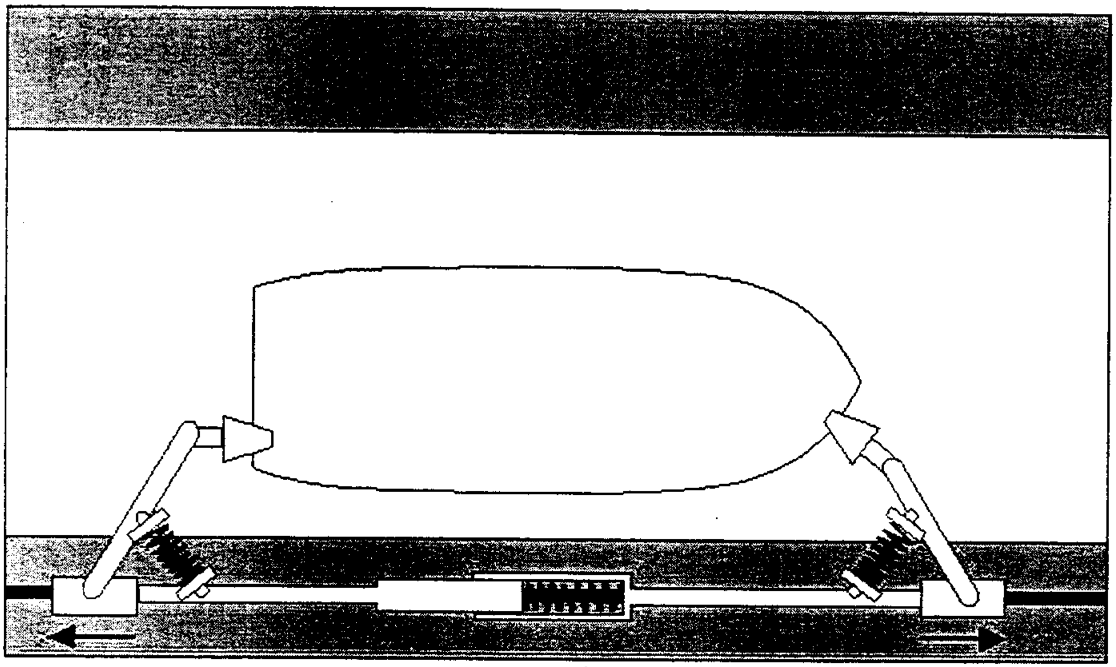
19-SPRING SYSTEM WITH NATURAL EQUILIBRIUM

Description:

This system integrates the vessel into a system of springs and rigid members. The vessel actually serves as a rigid member in this concept, and would have a natural equilibrium position. Equilibrium in both lateral and angular motions can be provided, while allowing the freedom of motion required traversing the locks. Starting and stopping forces can be provided either by a winch system or by equipping the moving spring structure with motors. Spring equilibrium points and member lengths can be set via hydraulics to accommodate various vessel sizes. An alternative design could include the replacement of the springs by hydraulic or solenoid type actuators, resulting in an actively controlled system.

Desirable features of this design:

- Both lateral and angular position is maintained at no control cost, i.e. the system is passive.
- Connection to the vessel can either be made magnetically or by the mooring eye boot.
- The design would be fail safe in the event of a power failure.
- An alternative design could include the replacement of the springs by hydraulic or solenoid type actuators, resulting in an actively controlled system.



20-Water Displacement Using Counter Weights

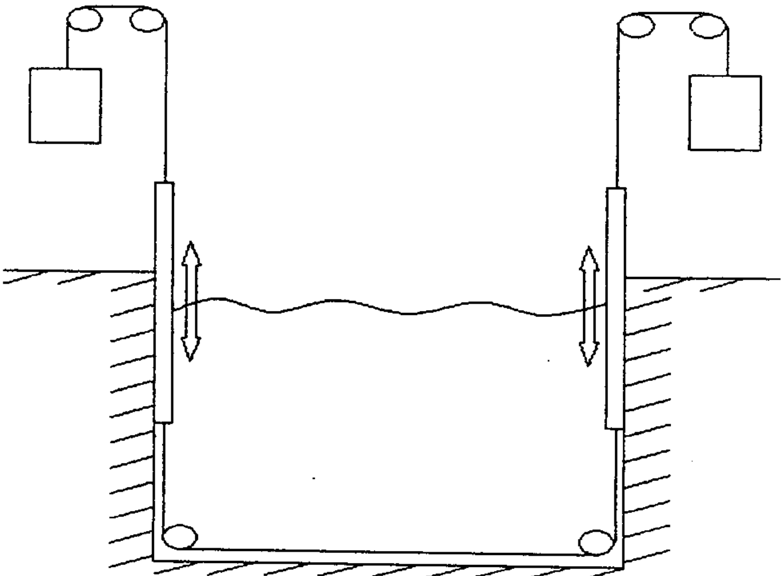
Description:

The movement of the masses up and down displaces water and performs the same function as pumping water from one side of the ship to the other.

Desirable Features of this design:

- Simple/low cost components
- Minimal lock modifications

Top View showing the system of weights distributed along the sides of the lock walls



Side View showing how the water displacement weights and counter weights will be attached

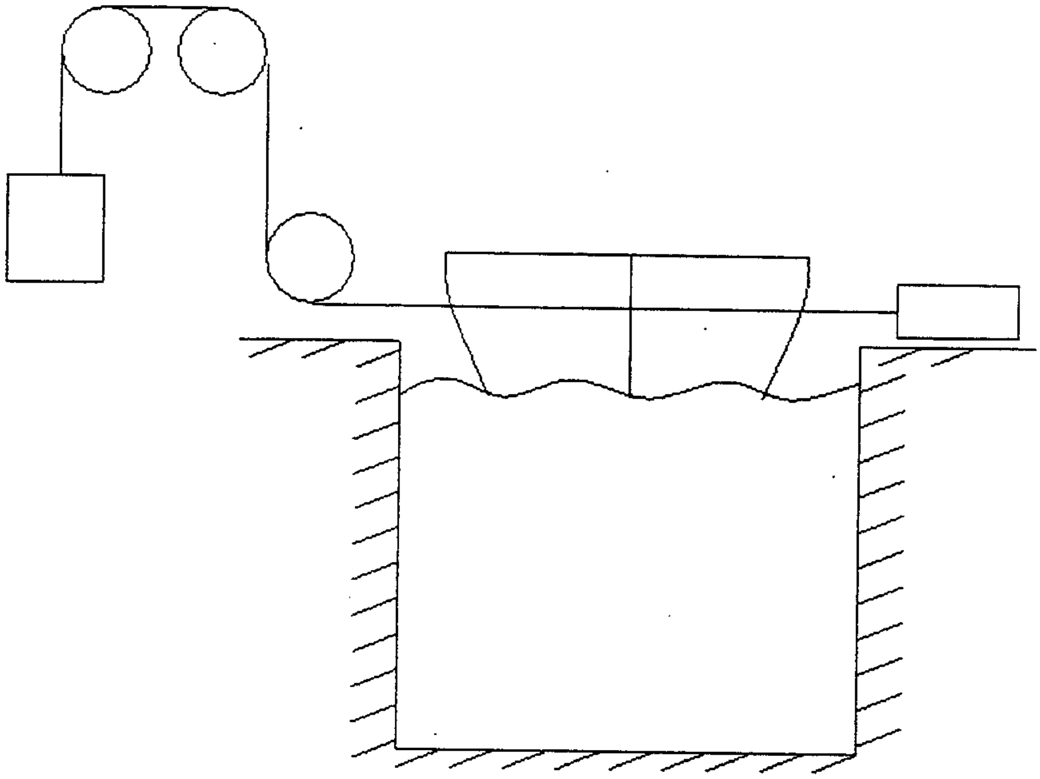
21-Lateral Forces Using Counter Weights

Description:

The counter weight is attached to two separate cables that attach to the bow and stern of the ship (i.e. two systems are required). The structure could be actuated to provide longitudinal control of the ship and the lateral motion is controlled passively. This passive control is accomplished because when the ship moves to one side the counter weight must be lifted and the cable to the far side has to support the entire weight of the counter weight.

Desirable Features of this design:

- Passive lateral control
- Passively control during lowering/raising of vessel
- Simple/low cost components



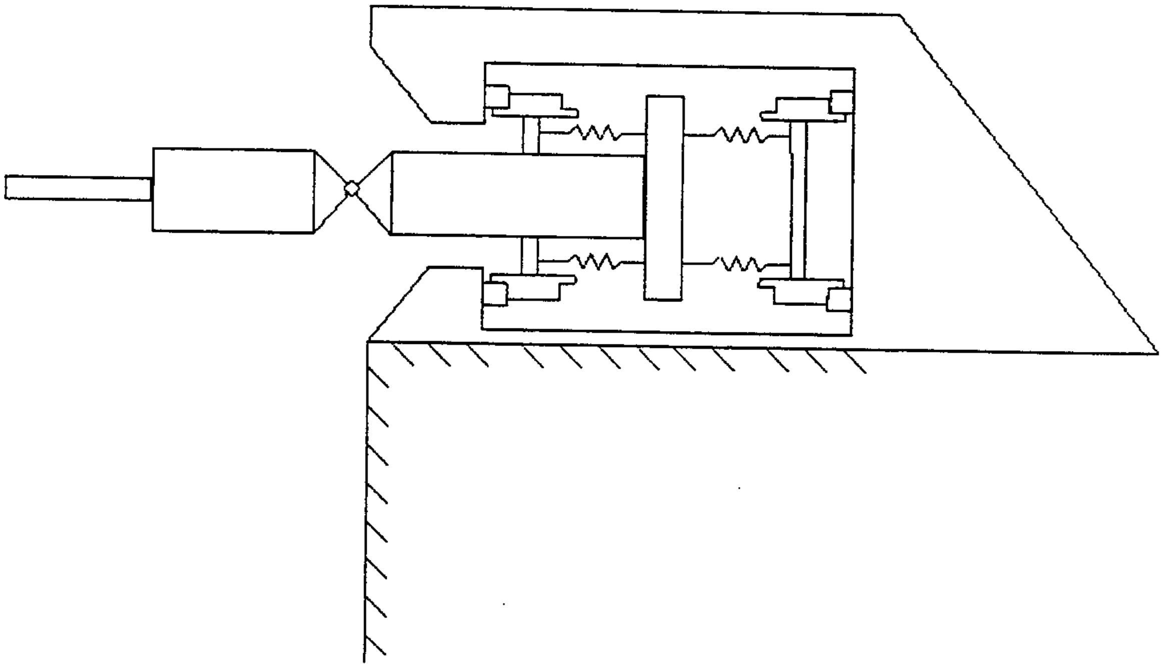
22-Hydraulic Actuated Side Cars

Description:

The figure shown below is a car that has eight wheels that engage the four tracks that run into and out of the plane of the paper. The springs that attach the main body of the car to the axles allow the system to remain compliant and thereby reduce the amount of shock loading that the rails experience. This should greatly reduce maintenance costs. The hydraulic cylinder. which provides the forces to the ship is mounted on a ball joint in order to account for the changes in elevation of the ship and to allow the car to move in front of or behind the attachment point to help control the forward motion of the ship. The piston will act in a push/pull manner through a rigid attachment to the ship's mooring points.

Desirable Features of this design:

- Simple/low cost components
- Only need to act on one side of the ship due to its ability to push or pull
- Compliance of system should reduce maintenance costs



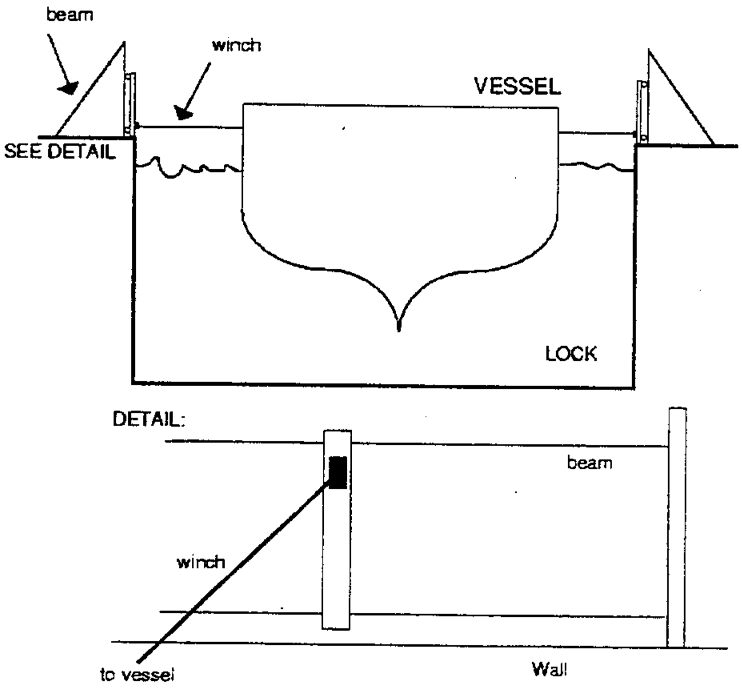
23-Two Degree-of-Freedom Controlled Winches

Description:

The fixed structure is constructed all along the lock walls on both sides; the height of the structure is determined by the maximum height of the ships' connection points. A vertical beam on rails is driven along the structure using a linear induction motor with sufficient force for towing and stopping the largest vessels. A winch that can be positioned vertically on the moving vertical beam provides the necessary centering. Automatic two degree of freedom control of the traveling winches is accomplished using a sensing system (for example a differential GPS). Four such beams and winches are employed to effect the transit, two connected to the bow and two connected to the stern similar to the current approach with locomotives.

Desirable features of this design:

- Winch cables are always horizontal improving their effectiveness and minimizing wear
- Eliminates locomotives and locomotive operators
- Minimum change to infrastructure; could be retrofitted to current locks
- Allows transits of Panamax vessels 24 hours a day.



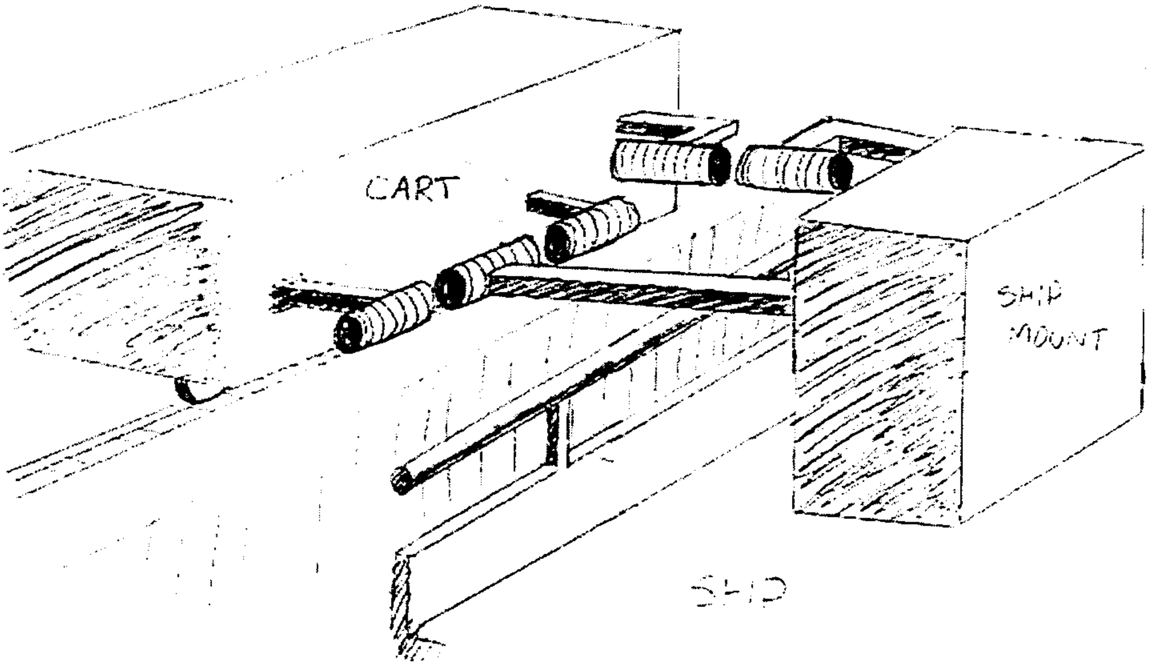
24-Non-Contact Solenoid Actuation

Description:

This solution is comprised of two rail-mounted carts and two ship-mounted modules. The two modules are coupled by solenoid electromagnets in the x and y directions to the carts. This magnetic force coupling adds compliance into the system, eliminating impulses and reducing stresses to the rails, cart, and preventing damage to the ship.

Desirable Features of this design:

- The ship's hull is not touched
- Abrupt forces are "smoothed out" by the solenoid electromagnets
- Sensing is only required in the lateral direction



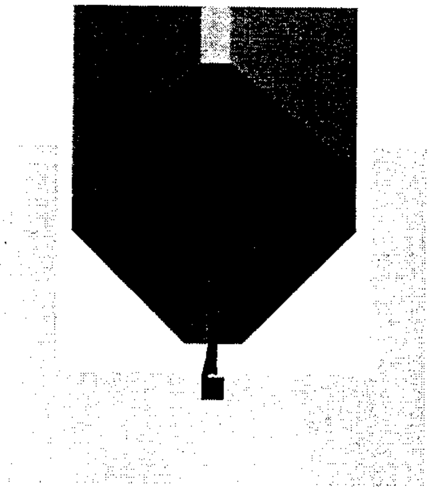
25-Inverted Pendulum

Description:

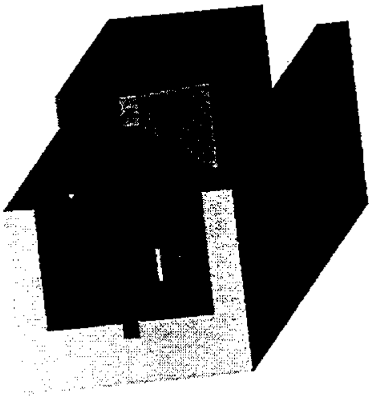
In this system the ship position and attitude is maintained by a pair of cables attached to the bottom of the ship. The cables are attached to trolleys that ride in the lock channel. Motive force is provided by the ship normally, but augmented when necessary by a set of cables, one fore and one aft. The cables providing the motive force are buoyant and connected to winches located at either end of the lock.

Desirable Features of this design:

- Use the buoyancy of the ship to provide a centering force.
- Requires little active control (self-centering).



Front View



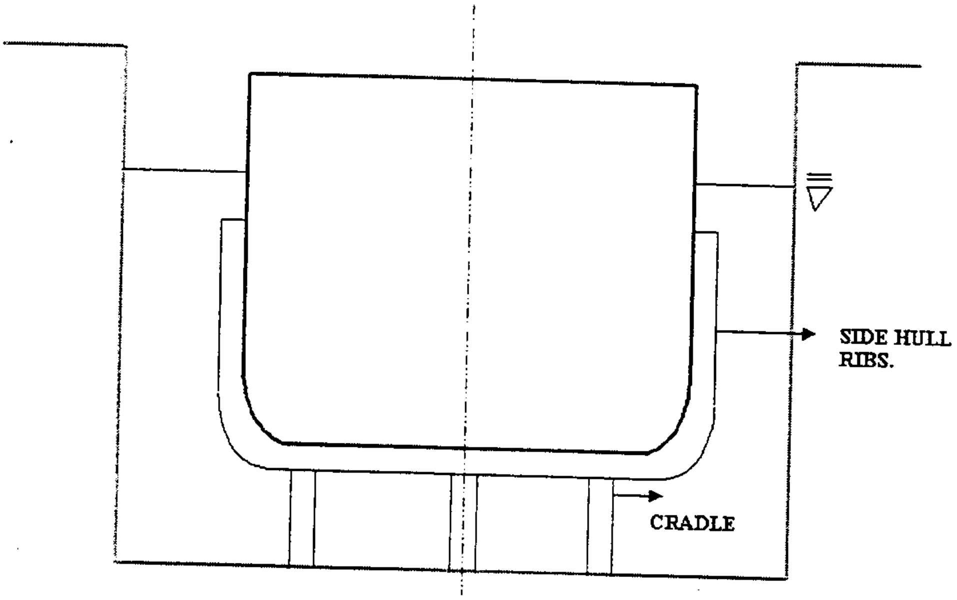
26-Synchrolift

Description:

The vessel moves forward under its own power but a rigid cradle is in place to guide the ship down the center of the lock. Though the cradle is made of rigid members, it adapts to fit various hull lines. The cradle restricts the sway,, roll, pitch and yaw motion of the vessel as the cradle moves the length of the lock with the ship.

Desirable Features of this design:

- Lesser friction at the hull contact points



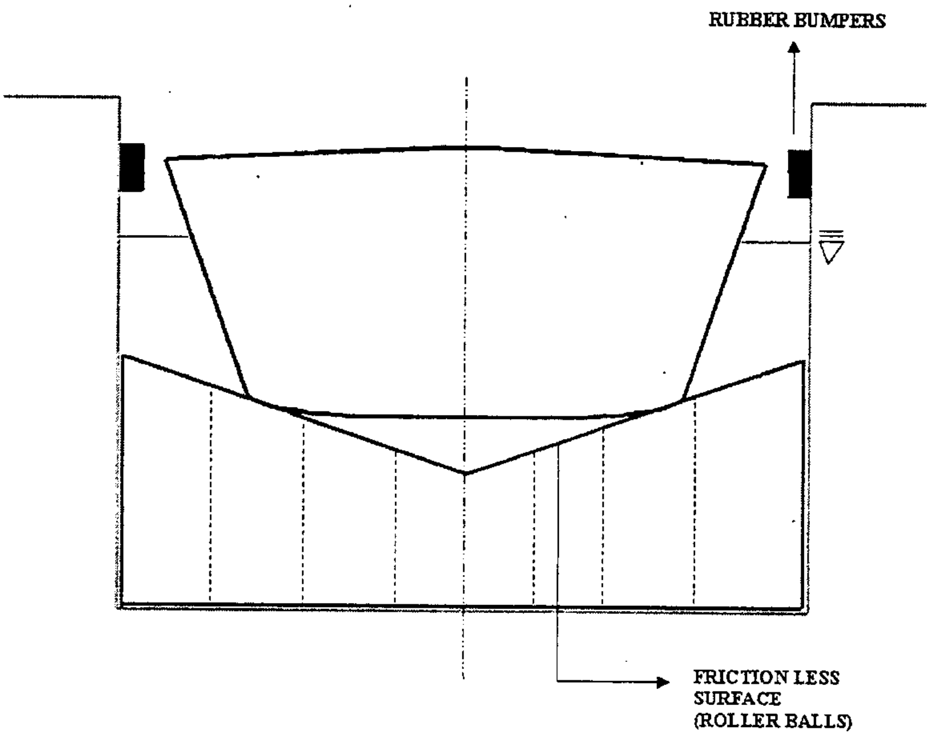
27-Ship Cradle Guide

Description:

A hollow rigid guide with a frictionless surface is the same length as the lock. Its buoyancy can be controlled with ballast. It is only slightly less wide than the lock, such that it will not roll as it is raised or lowered. Because of the v-shape, the ship contracts the guide along two lines. For the ship to go off center it must go up the incline of the guide. The resultant decrease in buoyancy will return it to center position. Rubber bumpers line the lock walls just to be sure that extreme disturbances don't cause any damage.

Desirable Features of this design:

- The roller balls could be powered wheels
- It is a passive centering mechanism
- Works for any vessel with symmetric hull lines



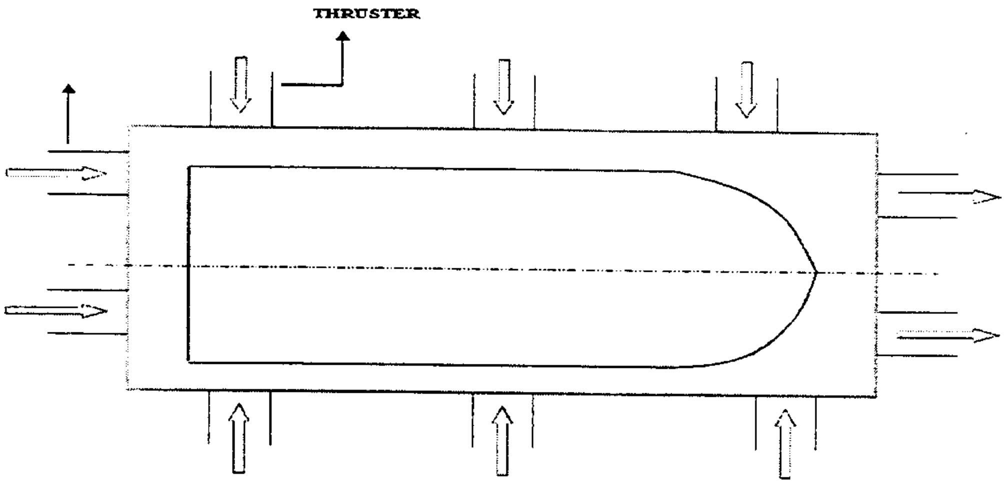
28-Wall Thrusters

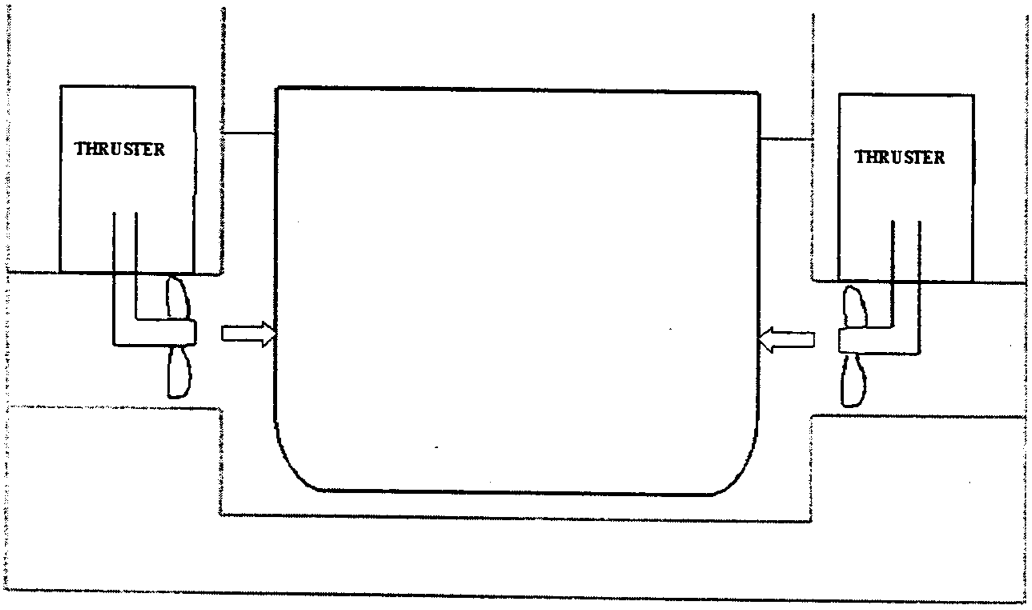
Description:

Azimuth thrusters are embedded in the lock walls to control the sway and yaw of the ship. They are independently controlled. Azimuth thrusters can give Omni-directional thrust thus enhancing the control.

Desirable Features of this design:

- The ship moves by its own power.
- Pumps are used on dock gates to annul piston effect.





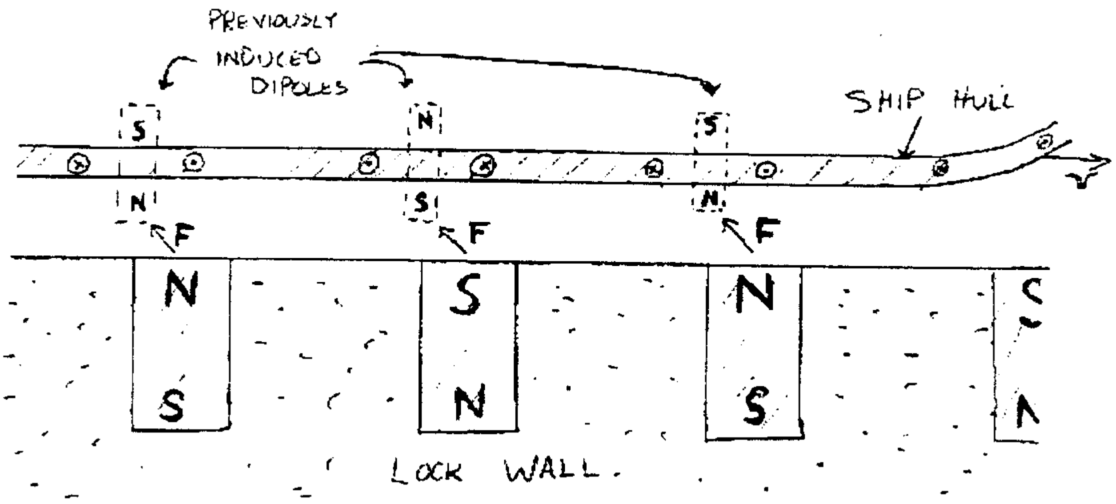
29-Alternating Wall Magnets

Description:

In this solution, magnets are placed in the wall with their poles facing outward, and alternating north and south. The magnets will induce eddy currents in the ship's hull as it passes. These eddy currents will lag the magnetic fields that create them, and as the ship continues to move, the field created by the eddy currents themselves will oppose the field of the next magnet, producing a force on the ship away from the wall.

Desirable Features of this design:

- The ship's hull is not touched
- No special equipment is required for the ship
- Induced eddy currents will not interfere with ships navigation equipment



30-Floating Bellows

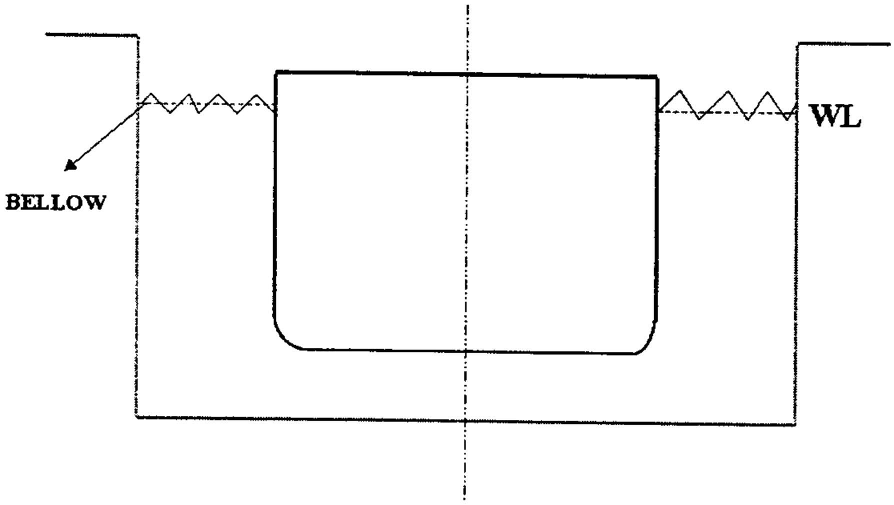
Description:

Buoyant bellows float on the surface of the water. The ship moves into the lock on its own power. The bellows displace until they near maximum compression when they act like rubber bumpers on the lock walls. The effort required to displace them can be varied by making the bellows out of flexible bladders.

Desirable Features of this design:

- The ship moves by its own power.
- As the bellows are floating it will suppress the surface waves and provide more stability.

BELLOWS FLOATING ON THE SURFACE.



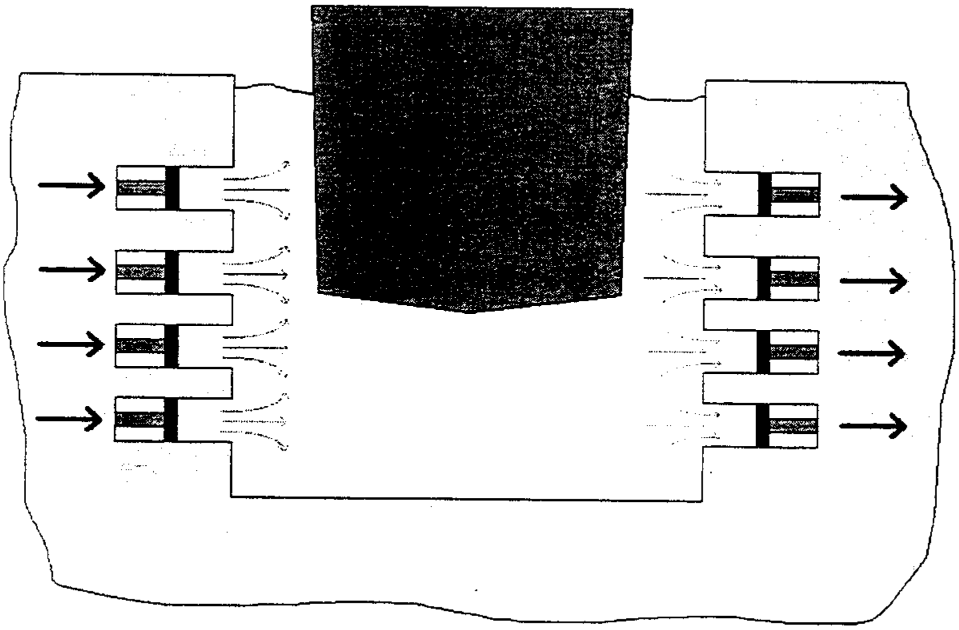
31-Syringe Effect

Description:

Circular chambers will be designed into the lock walls at various heights and along the length. A watertight plunger will be inserted into each chamber (such as a syringe). The plunger's transverse motion will be controlled via a hydraulic cylinder. The plunger will initially be placed at the mid-point of the chamber as the ship enters the lock and will be actuated according to centering needs. For example, to move the ship off the left wall, the left plungers would expel water while the right chambers would suck in water. This in effect will give a differing water head on the left side and initiate water flow toward the right side. It is expected that this will cause the ship to adjust to the right.

Desirable Features of this design:

- No direct contact with ships
- Simple design with few complex components
- Low power requirements



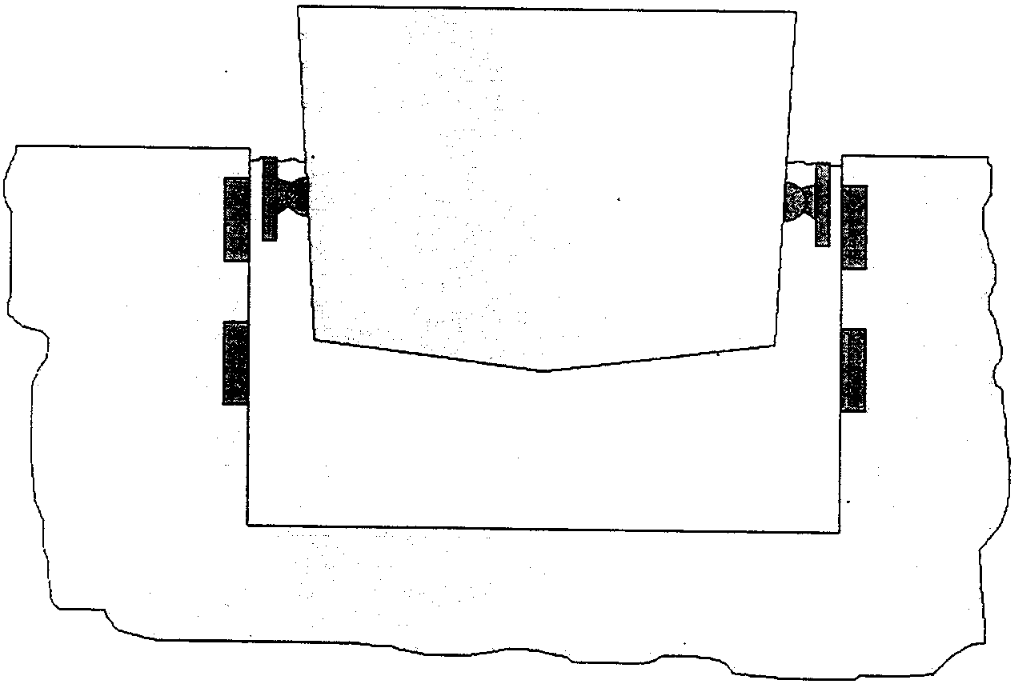
32-Magnetic Repulsion

Description:

Electromagnetic strips will be designed into the sides of the lock walls. As the ship comes under PCC control, "portable" electromagnetic hubs will be attached to the ships. The magnets will be controlled such that like poles are facing each other, and thus repelling each other. As the ship enters the lock, it will be held off the walls due to the repelling force of the electromagnets. The larger ships will be centered, while the smaller vessels will use the repulsion forces as bumpers on the wall.

Desirable Features of this design:

- No destructive interaction between ship hull and wall
- Self centering mechanism
- Increased force as distance between magnets shrinks



33-Transverse Piston Effect Using Movable Separator Curtains

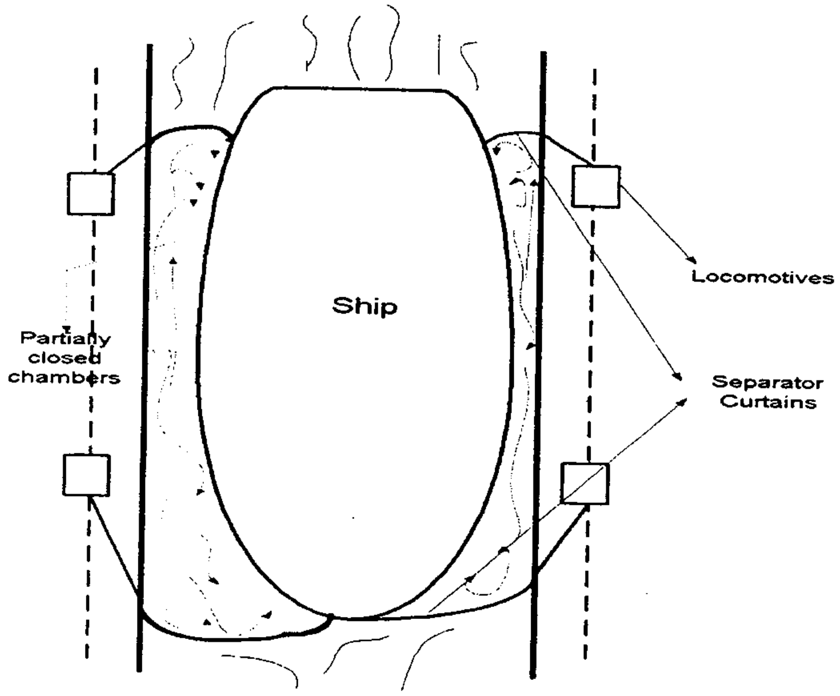
Description:

Four curtains are attached to the sides of the ship, two on each side. These curtains separate the water on either side of them. They sweep along the wall of the locks and are held tight to the hull. This creates partially closed chambers of water on the left and right side of the ship. Thus a transverse piston effect is obtained.

As the ship moves to the right, water will try to escape from the right side "chamber". The "chambers" created are not necessarily "water-tight". The opening of the chamber on the sides are restricted by the separator curtains. Thus any water, which has to escape from the right chamber, will have to flow through this restricted opening and will involve more time delay than the case in which the chambers were fully open. This restriction of flow causes a pressure build up on the right side of the ship and this pressure difference exerts a force on the hull opposing the transverse drift. However, this design has a very large blocking ratio.

Desirable features of this design

- No local stresses on the hull
- No localized stress on the hull



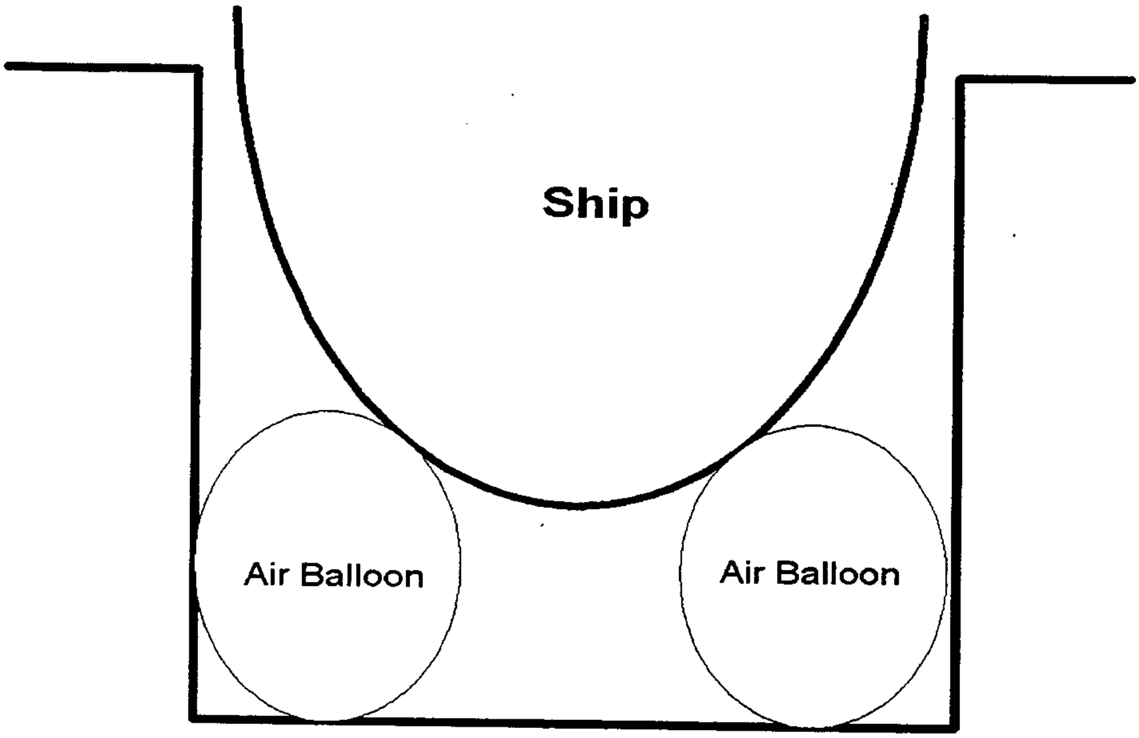
34-Centering Using Air Balloons

Description:

Inflated air balloons at the bottom of the lock are used to exert a physical force on the hull. These air balloons roll on the lock walls and move along with the ship.

Desirable features of this design:

- No localized stress on the hull
- No physical attachments onto the ship



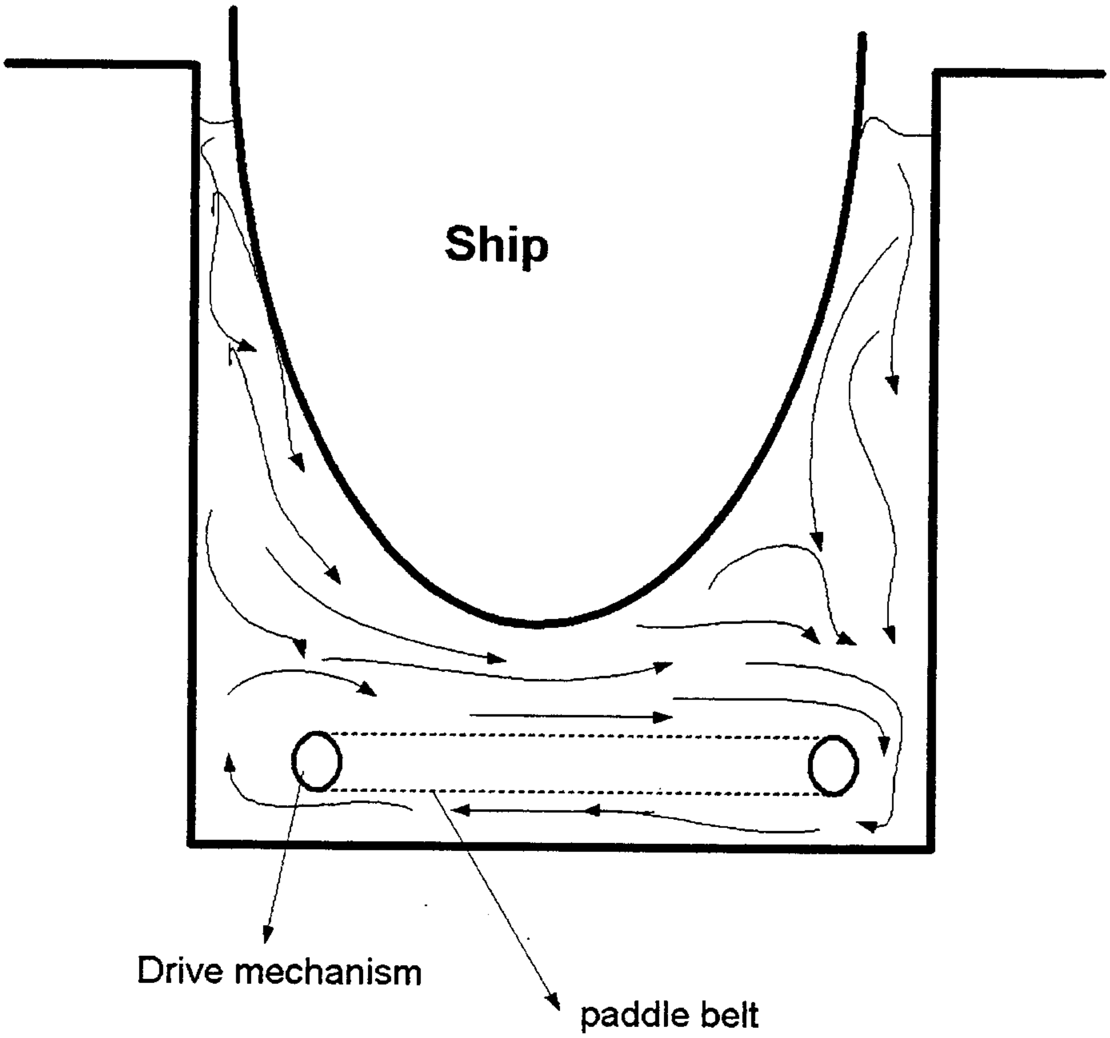
35-Hydro-Dynamic Positioning Using a Paddle Belt

Description:

Artificially generated underwater currents are used to exert a force on the ship hull and push the vessel in the desired direction. Water currents are created using a paddle belt with a drive mechanism that can move the belt from either left to right or vice versa. Feed back of the vessel position and drift can be used to decide the speed and direction of the paddle belt motion.

Desirable features of this design:

- No localized stress on the hull
- No physical attachments onto the ship



36-Hydro-dynamic Centering Using Water Circulation

Description:

A water pump is used to circulate water, drawing water from the center of the bottom of the lock and pumping it back in through the lock walls. This creates a net flow towards the center of the lock floor. The currents due to this flow exert a force on the ship hull. This force is directed towards the center of the lock floor. Thus centering of the vessel is achieved.

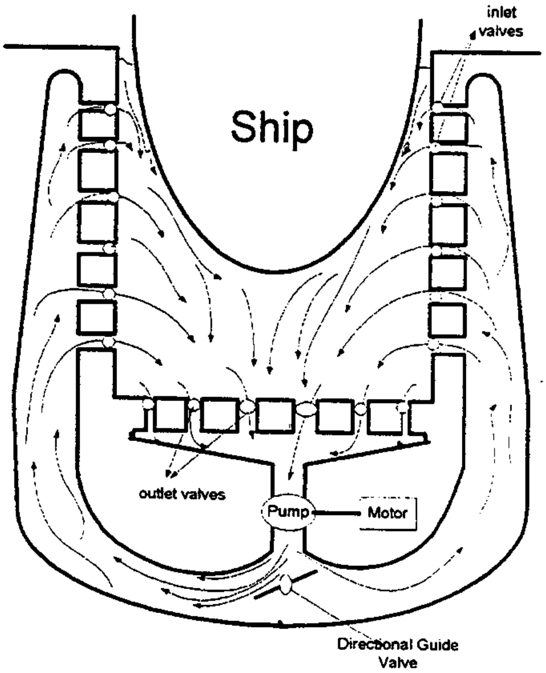
The effect is the same as that caused when water is drained off through an opening at the bottom of a tank.

The bi-directional guide valve enables a variable flow on both sides without effecting the flow rate of the pump. The inlet and outlet valves are also used to control the direction of the net flow.

The valve is controlled using a closed-loop control system, which obtains the position and drift of the vessel as its feedback.

Desirable features of this design:

- No local stress on the hull.
- No physical connection to the ship required.



37-Rubber Fingers

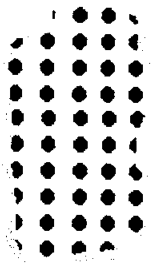
Description:

An array of rubber cylinders is embedded in the lock walls. Each cylinder is buoyant and has a one-way joint at its base. The joint allows the cylinder to fall freely, but prevents it from floating higher than the base of the cylinder. So, if the lock was completely full of water, the cylinders would be positioned as shown in the "Front View". The cylinders are of varying length so that larger ships (higher beam) have more control action than smaller ships. The stiffness of the cylinders will be dependent on the material and geometry of the cylinders.

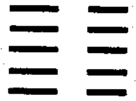
Desirable Features of this design:

- Passive centering
- Increased control action as ship nears the wall

Top View



Side View
Cutout



Front View

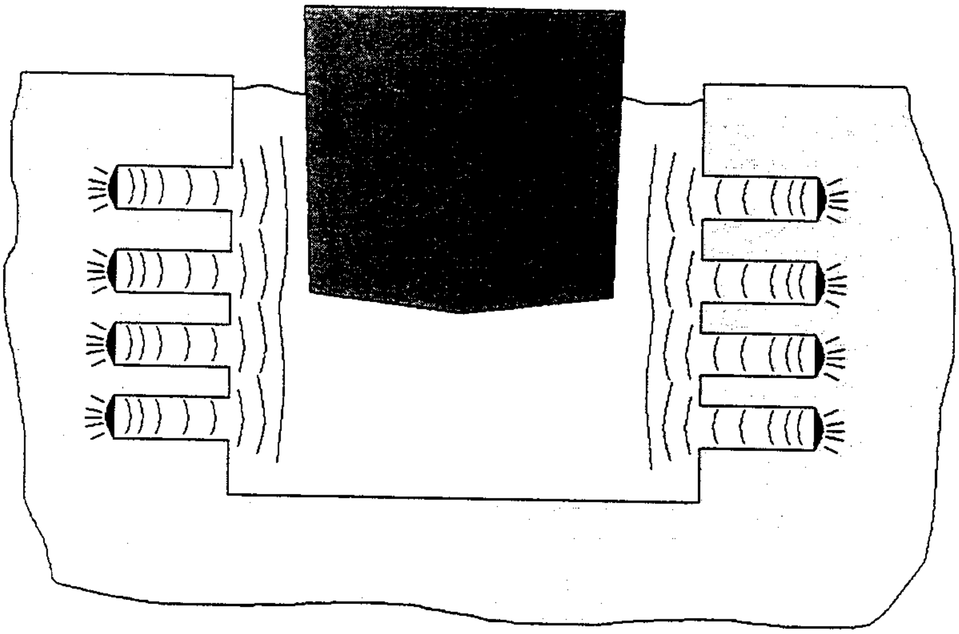
38-Controlled Explosions

Description:

Chambers will be designed into the lock walls with an explosion cap. As an impulse is needed, small explosions will expel water from a chamber. Conceptually, this will produce an impulse wave (of varying size with explosion) to push the vessel from one side to the other.

Desirable Features of this design:

- No system saturation
- No contact with ship hull
- Explosive material would be readily available and cheap



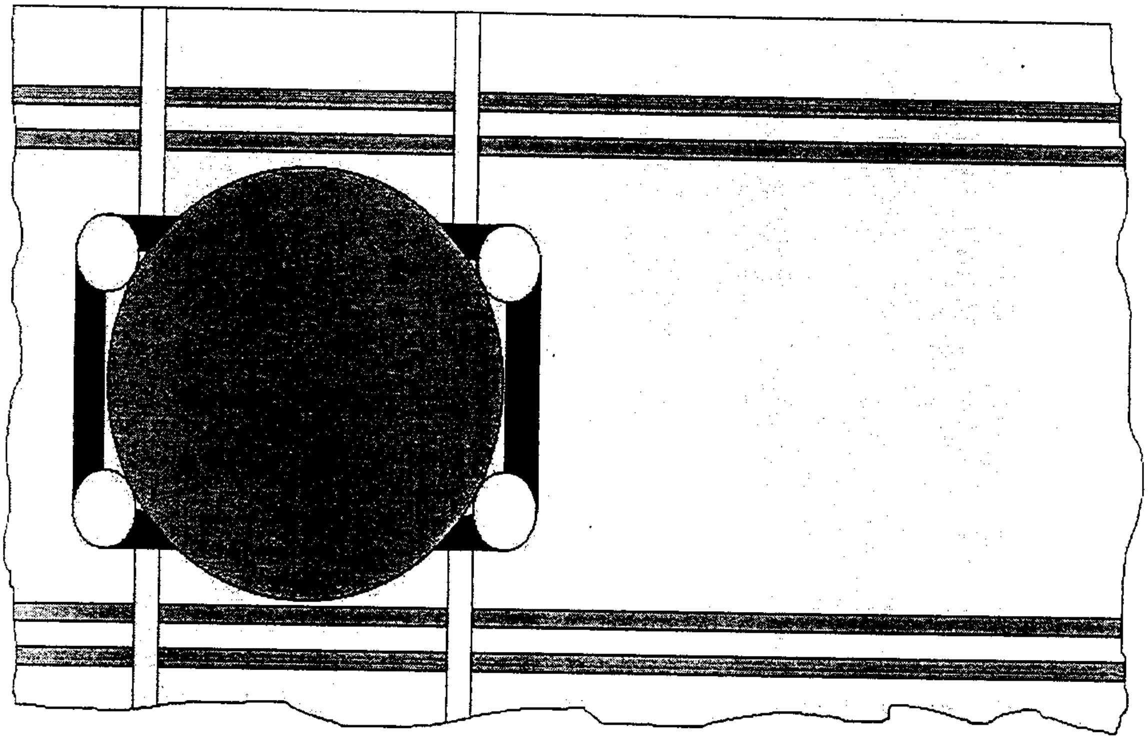
39-Magnetic Locomotive

Description:

A "magnetic locomotive" would be installed on one side of the lock walls. Vessels entering the locks would be pressed against the magnetic locomotives using the tugboats while the electromagnetic forces would hold the vessels after contact. The locomotives would have motive force to pull the vessels with them through the lock and would also have the capacity to change height with the ship.

Desirable Features of this design:

- Only need locomotives on one side
- Could accommodate varying vessel sizes easily
- Would accomplish all present locomotive functions



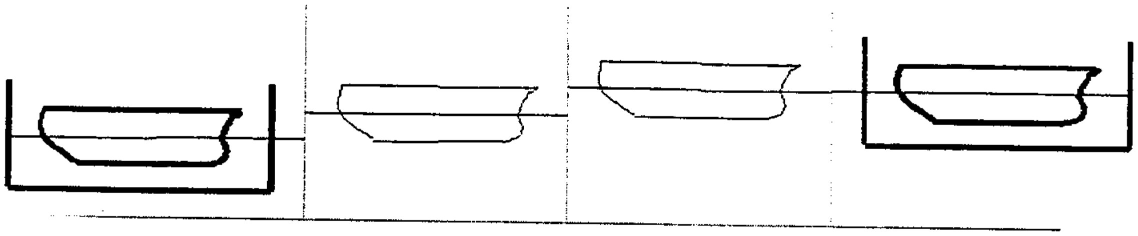
40-FLoating Lock

Description:

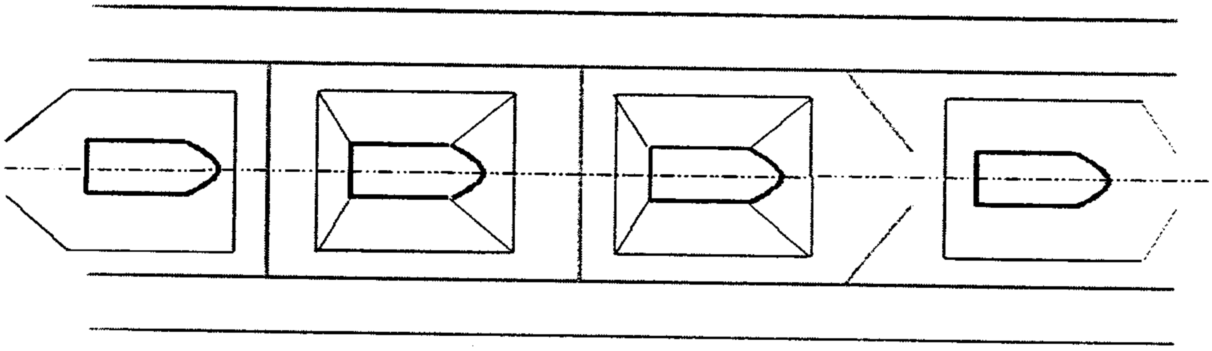
The floating lock helps the safe transit of the ship by functioning as a moving lock. The ship is moored to the lock and the lock can be raised.

Desirable Features of this design:

- The floating lock should be self-powered.
- Makes each transit predictable and similar



LOCK BEING RAISED TO THE FINAL WATERLEVEL



41-Conveyor

Description:

The conveyor guides the ship and it wards of the ship from being hitting the wall.

Conveyor can protrude and retract by itself according to the beam of the ship.

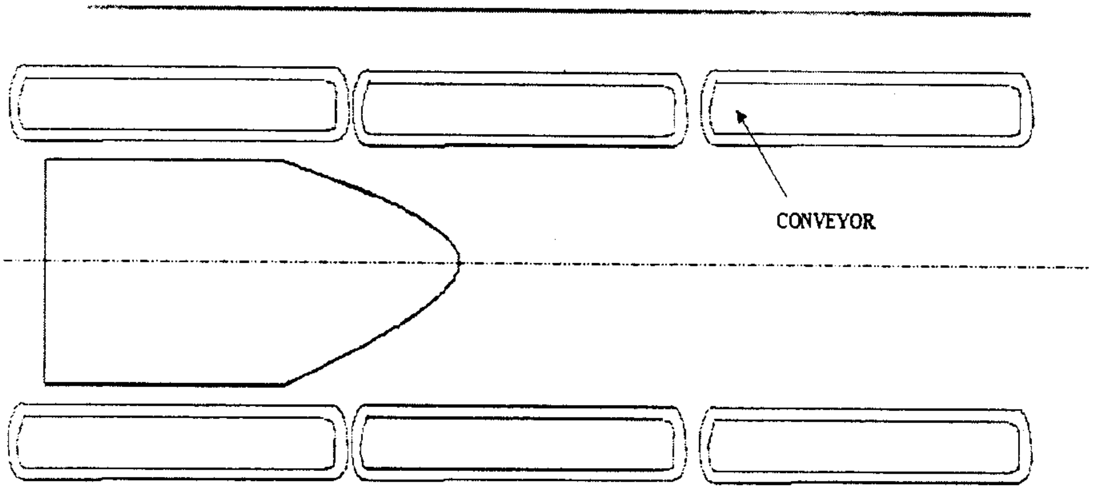
The length of the conveyor is to be more than the length of the lock in order to guide the ship at the entrance.

The vessel moves by its own power.

The conveyor belt is made of some material, which provides necessary friction and damping.

The conveyor is semi-rigidly mounted to ensure contact with the ship.

TOP VIEW OF THE CONVEYOR (NOT TO SCALE.)



RATING MATRIX

In order to quantify and evaluate all the concept ideas that the research group had explored, it was deemed necessary to write a matrix that would clearly show the weakness and strengths of each concept. The resulting matrix contains six factors, one per column, which reflect the most important steps that must be accomplished for a safe passage through the locks. The six factors are:

1. Lateral Control
2. Longitudinal Control
3. Hull Contact
4. Raise lower effectiveness
5. Ease of initiation/attachments
6. Control of transition

Each member of the research group proceeded to grade each individual concept based on the following scale: If the design performed better than the current locomotive in any particular category, it received a one in the column that represented that category. If the design behaved as well as the current system it received a zero and if the design did not perform as well as the current system, it received a minus one.

The scores for each concept were then added giving each one of the six factors equal weights except for Lateral Control and Longitudinal Control. These last two factors were deemed of most importance and therefore were worth twice as much. The results can be seen in the table bellow.

Note that the last column indicate any modifications that would need to be performed to the conceptual ideas for them to receive the recorded grade

Ranking Matrix to evaluate ideas

Note: i) Ideas with net positive evaluations are highlighted; ii) The column on the extreme right indicates modifications/additions to improve performance

	Lat. Control	Long. Control	Ease of initiation/ Attachment	Raise/Lower Effectiveness	Hull Contact	Control of Transition	Total w/Equal Weight	Total with Lat. & Long. Worth 2X	Mods.
1.Auto-Pilot							0	0	
2.Air Blanket with rollers	-6	-11	-9	12	11	-10	-13	-30	
3.Water Pump	-4	-12	10	4	12	-5	5	-11	
4.Actuated Rubber Tires	-3	-10	10	10	-10	-2	-5	-18	floating
5.Buoyant Wedge	-1	-9	-5	-11	-11	-10	-47	-57	
6.Continuous Rubber Bumper / Bladder	2	-12	10	9	-11	-9	-11	-21	floating
7.Fixed Roller Bearing Structure	-4	-12	10	-9	-10	-9	-34	-50	
8.High Tension "Tight-Rope"	6	4	5	8	0	10	33	43	pulley w/angle
9.Integrated "Robot-Winch" System	8	10	0	9	0	0	27	45	
10.Lock Wall "Gas Jets"	-10	-12	10	4	12	-10	-6	-28	
11.Suction / Water Jets	-2	-8	10	0	-10	1	-9	-19	
12.Telescoping Truss Wall System	3	-6	10	6	-10	1	4	1	
13.Air Bubbles	-10	-12	10	-10	12	-10	-20	-42	
14.Rack and Pinion	-2	8	-10	5	0	2	3	9	floating rack
15.Underwater water jets	-1	4	-9	5	-10	9	-2	1	
16.Water Freeze	-8	-12	-7	1	-11	-10	-47	-67	
17.Wheel Trap	2	-3	10	4	-11	3	5	4	
18.Solid/Liquid Fuel Thrusters	-6	1	-8	8	0	8	3	-2	
19.Spring System with Natural Equilibrium	9	10	3	3	0	6	31	50	
20.Water Displacement Using Counter Weights	-12	-12	10	-10	12	-9	-21	-45	
21.Lateral Forces using Counter Weights	6	-4	5	9	0	10	26	28	
22.Hydraulic Actuated Side Cars	8	7	3	4	0	10	32	47	two pistons
23.Two degree of freedom Winches	12	9	0	12	0	1	34	55	counterweight
24.Non-Contact Solenoid Actuation	2	5	-10	-1	0	3	-1	6	floating
25.Inverted Pendulum	5	-2	-10	-11	-11	8	-21	-18	
26.Synchrolift	12	1	-5	10	2	10	30	43	
27.Ship Cradle Guide	1	-11	-2	8	-10	-5	-19	-29	
28.Wall Thrusters	-10	-10	10	6	12	2	10	-10	floating w/seal
29.Alternating Wall Magnets	8	-2	10	0	6	-6	16	22	
30.Foating Bellows	1	-11	9	12	-11	1	1	-9	
31.Syringe Effect	-13	-12	10	-4	12	-8	-15	-40	
32.Magnetic Repulsion	7	-12	-10	3	0	-3	-15	-20	
33.Transverse Piston Effect	3	-12	-10	-9	6	-7	-29	-38	flour quadrants
34.Air Balloons	-10	-12	-7	-10	-7	-9	-55	-77	
35.Hydro-Dynamic Positioning Using a Paddle Belt	-12	-12	10	-3	12	-9	-14	-38	floating
36.Water Circulation	-6	-11	10	-5	12	-8	-8	-25	
37.Rubber Fingers	-2	-12	10	5	-1	-4	-4	-18	wheels on ends
38.Controlled Explosions	-12	-12	10	1	-10	-9	-32	-56	
39.Magnetic Locomotive	12	-9	1	9	-10	1	4	7	mag. Buoy thrusters
40.Foating Lock	10	11	-3	12	0	10	40	61	
41.Conveyor	8	-3	10	5	-6	0	14	19	
42.Truss							0	0	
43.Mechanical Water Lift							0	0	
44.Traveling Boat Trailer							0	0	

SIMULINK MODEL USED TO SIMULATE THE BEHAVIOR OF VESSELS IN THE PANAMA CANAL

Dynamic models are often used to determine the minimum number of parameters, which need to be considered in order to arrive at a reasonable model. A reasonable model is one that reasonable approximates the behavior of the actual system. When the minimum number of parameters are identified the designer can then use this information to arrive at worst case scenarios and what types of conditions need to be considered for the design.

The model that was developed here is based on simple Newton's equations. Three separate motions were considered: longitudinal (y-dir), lateral (x-dir), and rotational (yaw, theta-dir). The forces that were considered in each of these directions is shown in the table below.

y direction	**x direction**	**theta direction**
viscous forces	Viscous forces	viscous forces
control forces	Control forces	control forces
water velocity due to the piston effect	Wind forces	wind forces

Table 1 Forces considered

Several vessel parameters were deemed to be important. Those are mass, beam, length, draft, blocking ratio, and freeboard height. The lock parameters that were used were the lock width and water depth. The disturbance force that the wind provides was also considered.

Development of the Equations of Motion

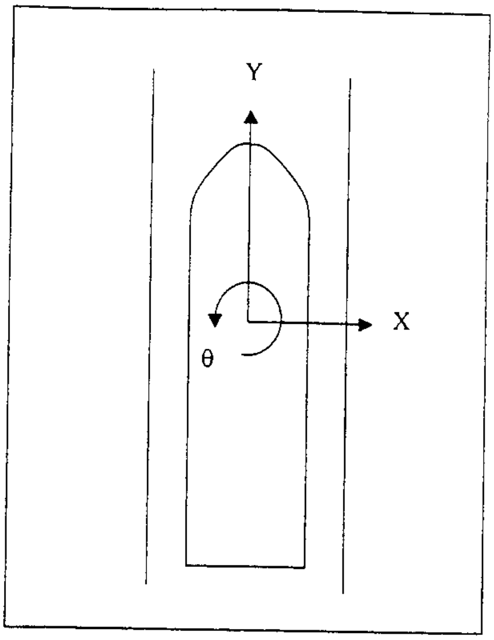


Figure 20 Coordinate Directions

Viscous Drag Forces

The drag forces that arise from movement of the ship through water and air can be approximated as a plate moving through the fluid. The drag force is usually denoted by the following formula:

$$F_D = \frac{1}{2} C_D \rho A V^2$$

where:

F_D = force of viscous drag

C_D = drag coefficient

ρ = density of the fluid

A = area of the body perpendicular to the flow

V = velocity of the body

The drag coefficient can be approximated using the following formula:

$$C_D = 1.17 + \frac{0.111b}{2h}$$

where:

b = width of the body

h = height of the body

Moment of Inertia

The moment of inertia of the ship is not known exactly therefore, the ships can be approximated as a uniform rectangular bar with the dimensions and mass properties of the ship. The moment of inertia of the ship, about its center of mass, can then be approximated by the following formula:

$$I = \frac{1}{12} m L^2$$

Summation of Forces

Newton's laws can now be applied in the three coordinate directions of interest to determine the motion of the ship.

$$\Sigma F_x = m_v \ddot{x}$$
$$\Sigma F_y = m_v \ddot{y}$$
$$\Sigma M_{cm} = I \ddot{\theta}$$

where:

ΣF_x = net force applied in the x direction

ΣF_y = net force applied in the y direction

ΣM_{cm} = net moment applied about the center of mass

Implementation of the Model Using Simulink

The equations of motion resulting from the summation of forces are solved numerically using Simulink which a graphical interface to Matlab. The general equations nonlinear ordinary differential equations with varying coefficients. Closed form solution to such equations do not exist therefore the numerical solution provided by Simulink coupled with the its graphical and control capabilities make it a powerful tool that can be used by the designer. Three separate Proportional Integral Derivative (PID) controllers are implemented to control each of the directions of interest.

The graphical implementation of this system is shown on the next page. All of the ship and canal parameters are entered on the left side of the page and the outputs are on the right side. While the model implemented is simple it gives the designer another tool to benchmark different designs and operating conditions. The time constraints of the class has limited the complexity of this model however, more work could be done that would improve model accuracy and increase the number of operating parameters that it considers.

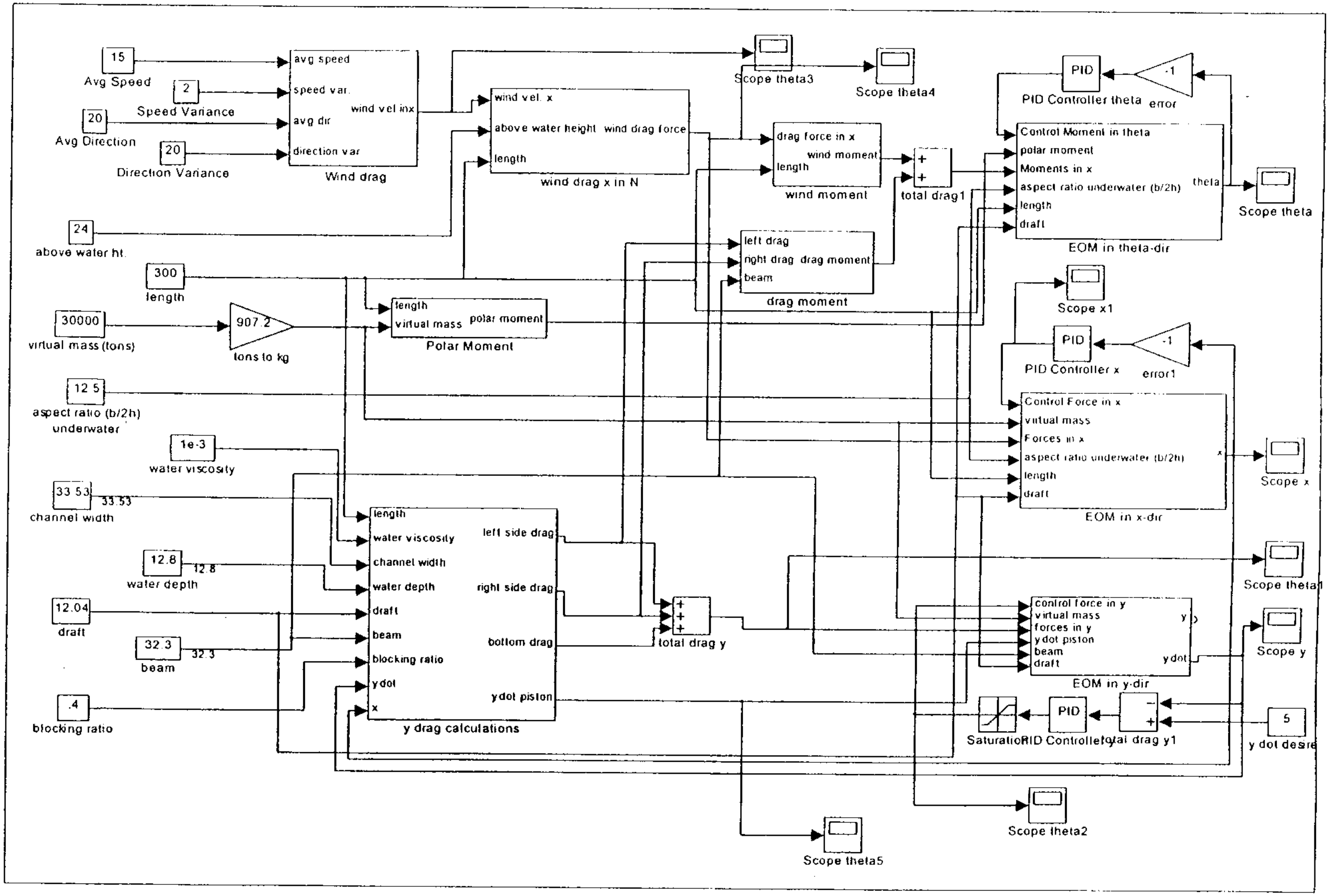


Figure 21 Simulink System Diagram

Analysis for Design

Conceptual Drawings

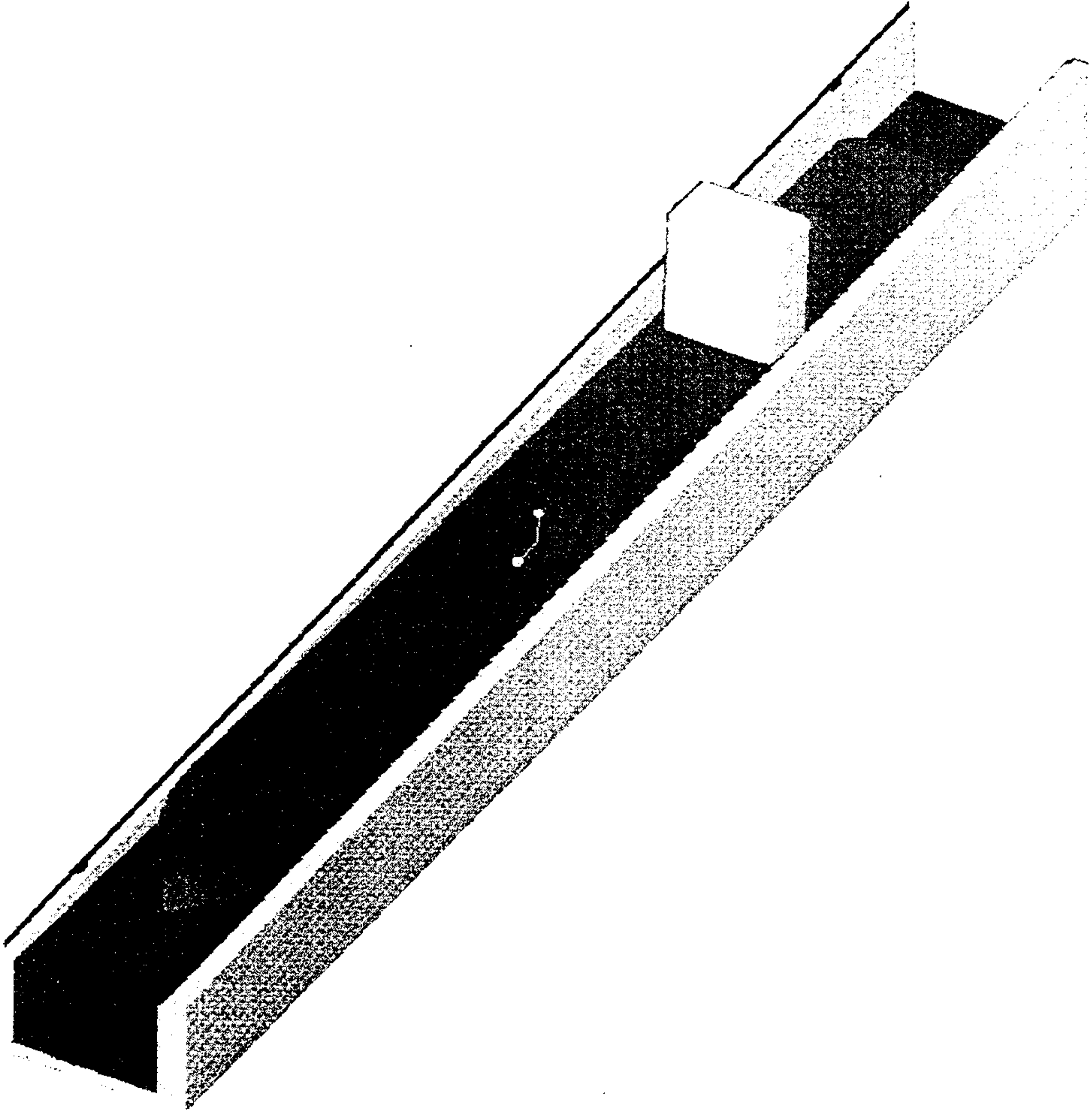


Figure A1: Isometric View of Lock Chamber with Integrated Robot Winch System

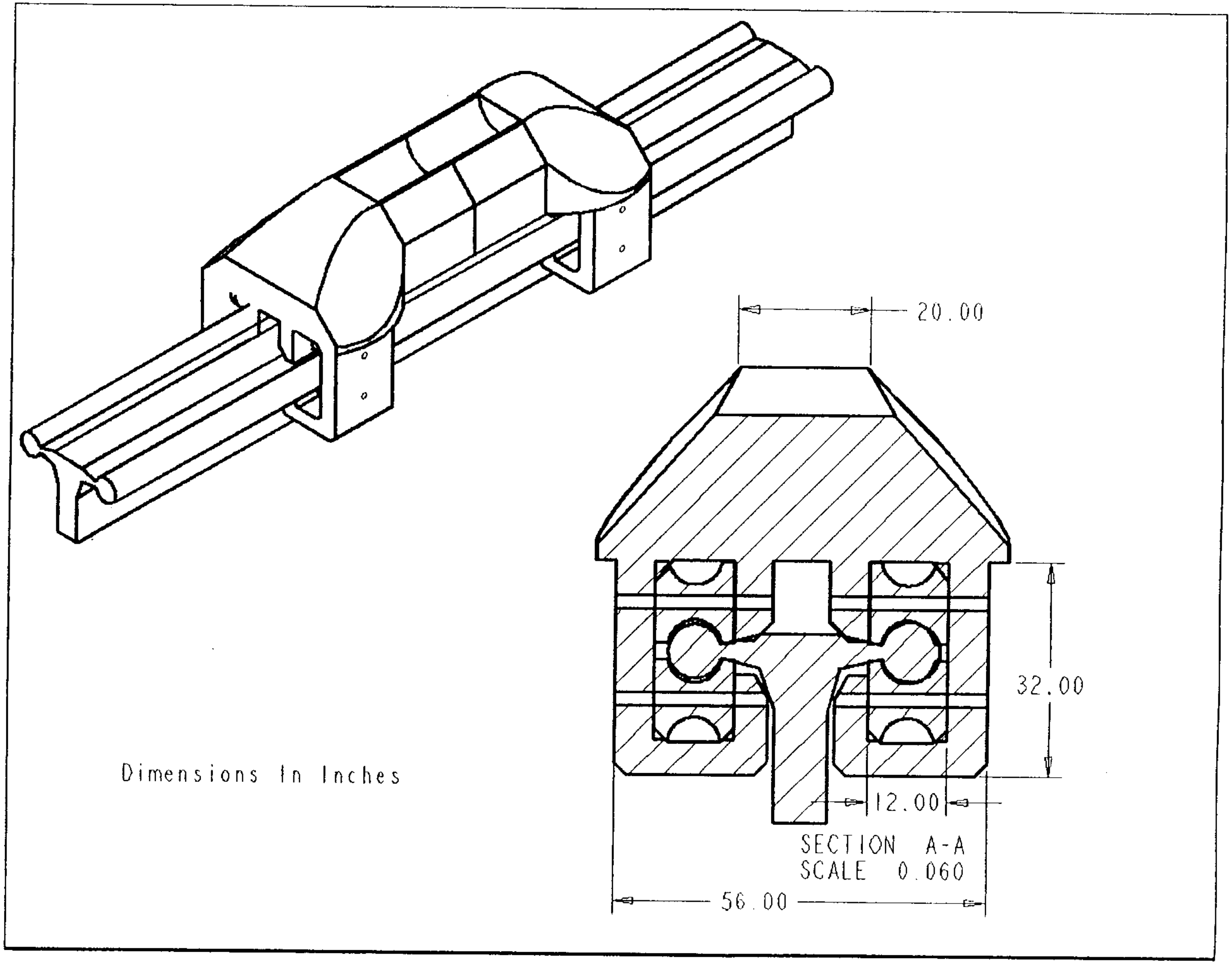


Figure A2: Rail Car – Cross Sectional View

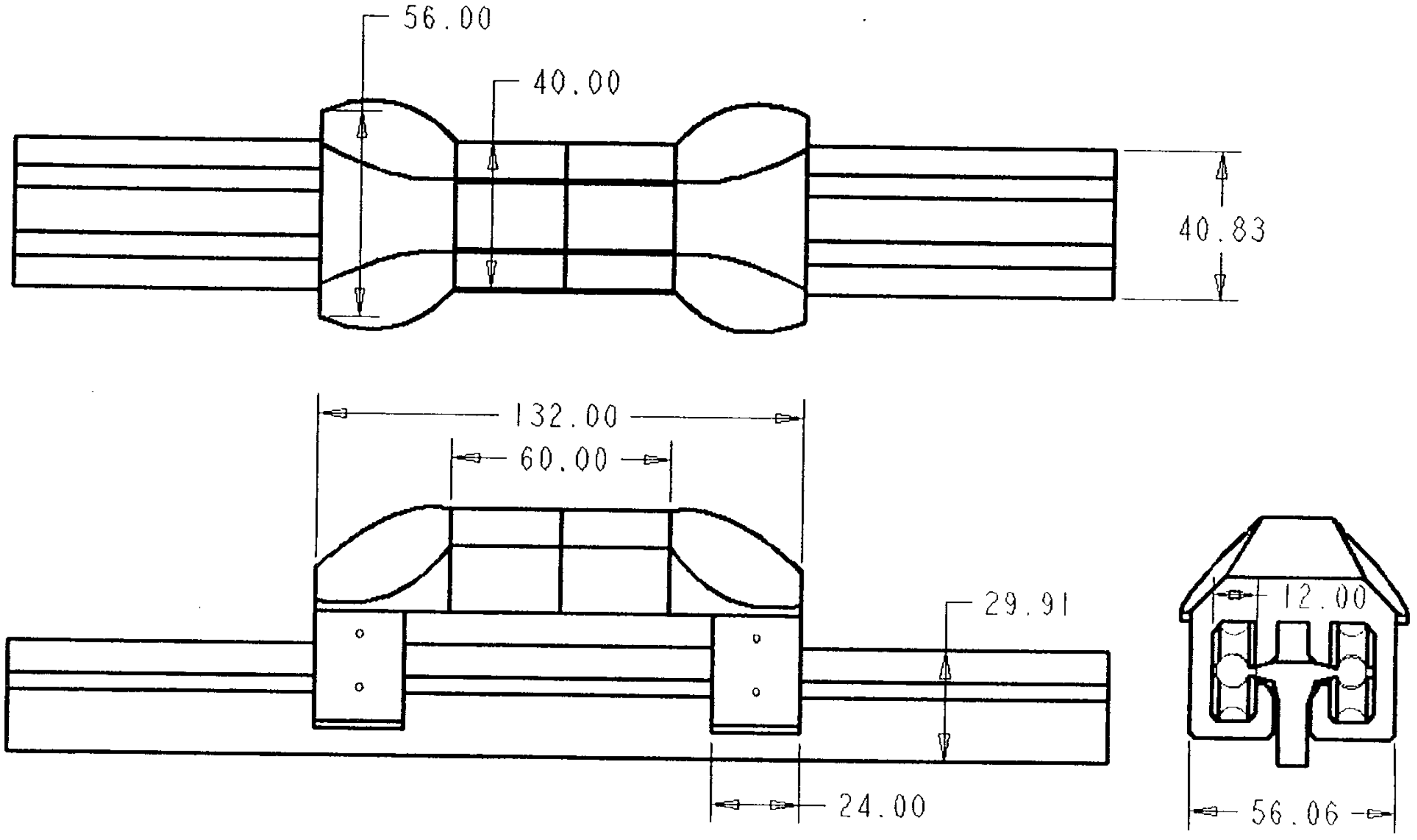


Figure A3: Rail Car – Orthogonal View

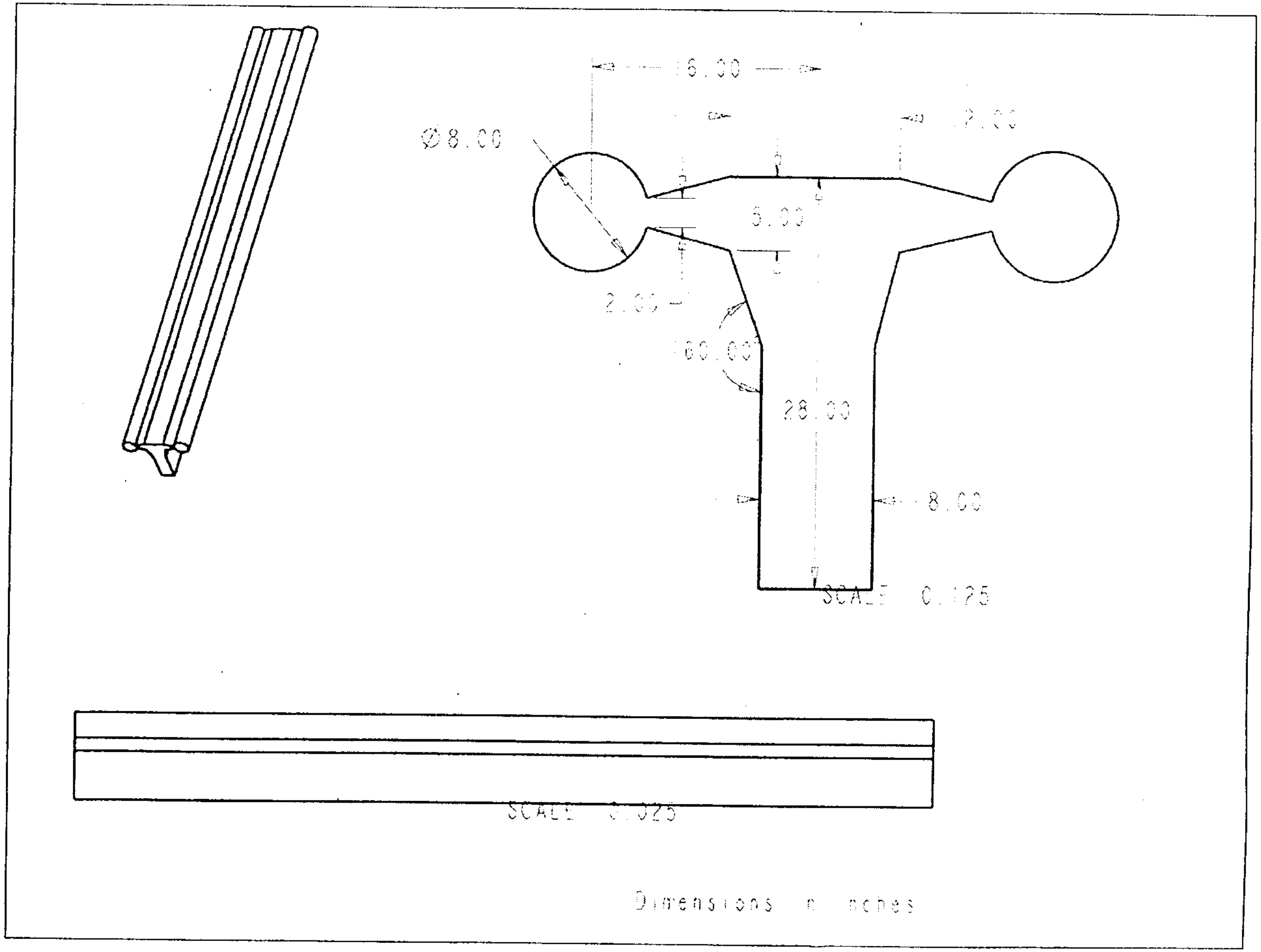


Figure A4: Cross Sectional View of the Rail

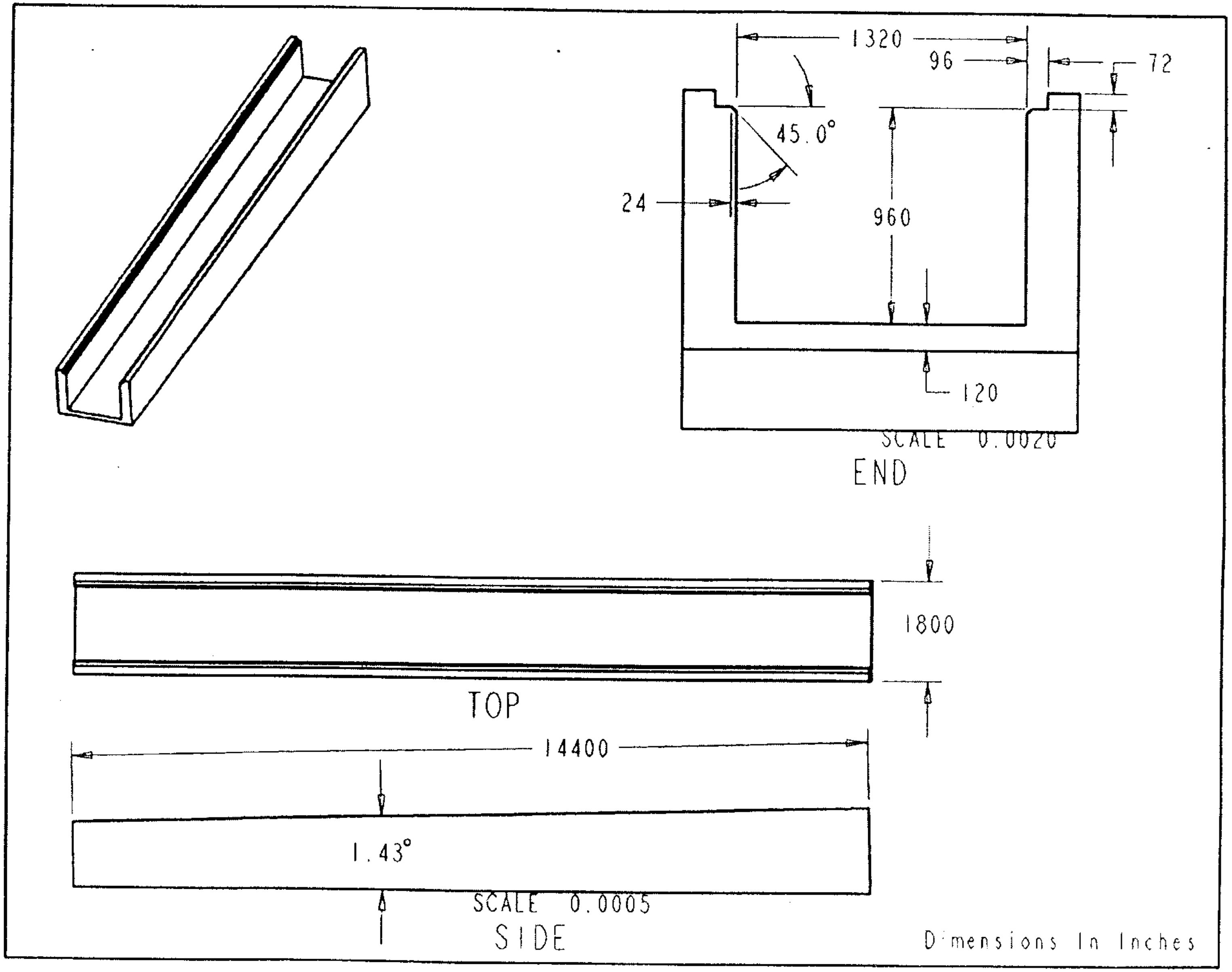


Figure A5: Cross sectional view of the Lock.

Critical Calculations for the design

Integrated Robot Winch Stress Calculation

Purpose:

This calculation is completed to verify the basic structural integrity of the integrated robot winch car under maximum cable loading.

Fundamental Equation:

Stress in a beam subject to a center point load:

$$\sigma_{\max} = \frac{M \cdot y}{I_{xx}}$$

where:

M = Maximum applied load (at center of beam);
y = Maximum distance from center of the beam

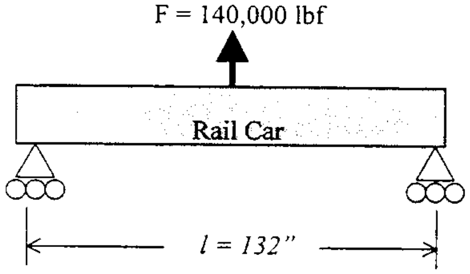
Assumptions:

- Transverse shear is neglected.
- Constant area cross-section is assumed through the entire length of the rail car.
- Loading is directly perpendicular to the top of the rail car.

Diagram:

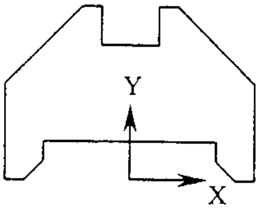
The geometry and loading of the rail car is described in the following schematic:

Loading Geometry



Minimum Cross-Section

(center of the rail-car)



Design Requirements:

The following parameters were obtained from a Pro-Engineer CAD part file of the rail car:

- Material: AISI 1020 hot-worked steel: Yield Strength = 30×10^6 psi
- Mass of entire rail car = 30,000 lb.
- Center of Gravity: X = 0, Y = 14.62 in.
- Moment of Inertia about the center of gravity, I_{xx} = 9.538 E4 in^4

Solution:

σ_{max} = 708.2 psi → obviously over-designed!

Conclusions:

The presented rail car geometry should be further optimized to minimize the geometry, weight, and cost.

Rail-Car Stress Calculation

Purpose:

This calculation is completed to quantify the effects of vertical cable position relative to the ships mooring points (free board height). Both lateral and longitudinal components of the applied cable tension are calculated as a function of the vertical angle. Initially, several design concepts arose which allowed for vertical movement of the rail car in order to accommodate the elevation changes. The intent of this calculation is to identify the level of "pay-off" or "trade-off" for adding the system capability to maintain the cables horizontal to the mooring points at all times.

Fundamental Equation:

$$FX = Cable\_Tension \cdot \cos(\theta_z) \cdot \cos(45°)$$

$$FY = Cable\_Tension \cdot \cos(\theta_z) \cdot \sin(45°)$$

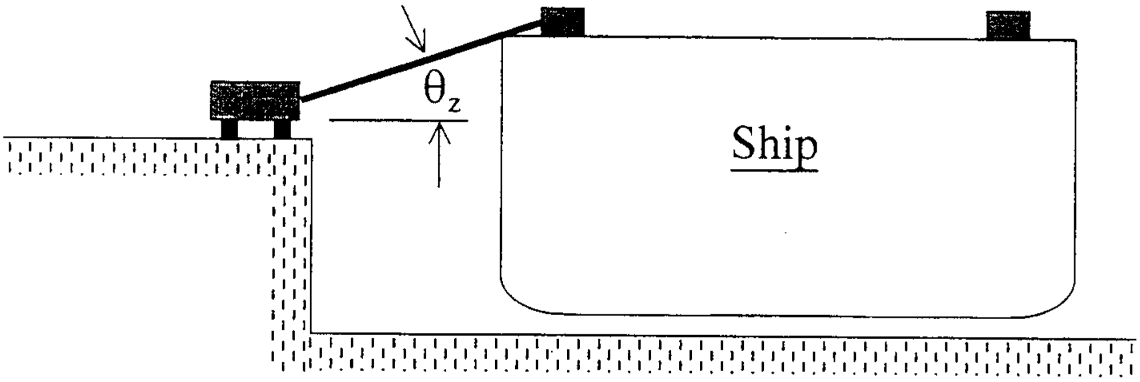
$$Trade\_Off = \frac{\cos(45°) - \cos(\theta_z) \cdot \cos(45°)}{\cos(45°)}$$

Assumptions:

- Longitudinal Angle (out of the plane of paper) ahead or behind this ship is maintained at a constant 45° at all times.
- Cable tension is maintained constant at 140,000 lb_f.

Diagram:

The geometry describing the vertical angle θ_Z between the rail car and the ship's mooring points is shown in the following schematic:

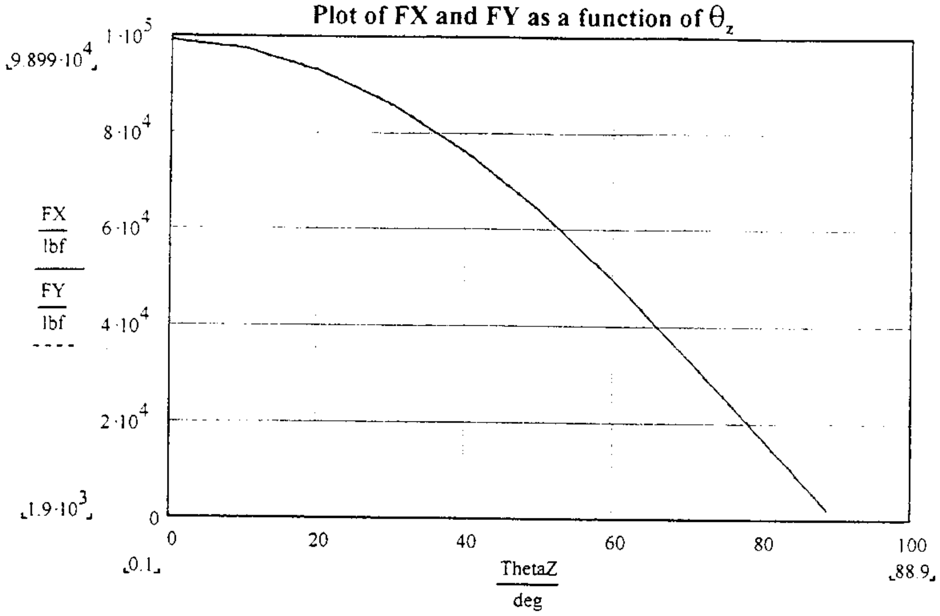


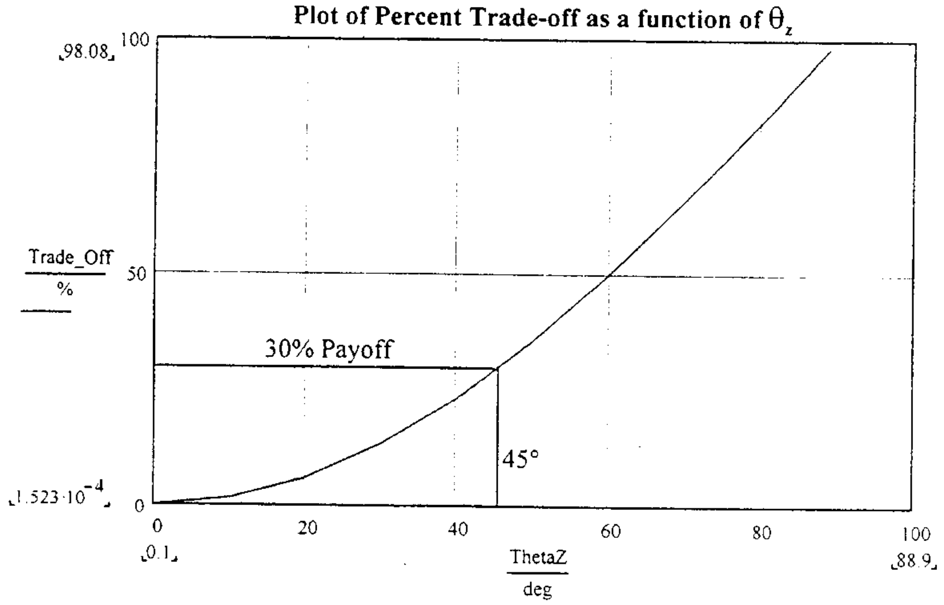
Design Requirements:

θ_Z = Angle from vertical reference axis (variable)

Cable_Tension = 140,000 lbf
FX = Component of Force in X-direction (longitudinal)
FY = Component of Force in Y-direction (lateral)
Trade_Off = Percent reduction in force comparing current system with proposed system (which maintains θz = 0 at all times).

Solution:


Plot of FX and FY as a function of θ_z


Plot of Percent Trade-off as a function of θ_z

Conclusions:

As shown in the second plot, the percent trade-off for adding the capability to maintain a zero θz as compared to +/- 45° results in only a 30% payoff in terms of force. This suggests that the pay-off for maintaining a zero θz is minimal.

Feasibility study of Linear Induction Motors

Purpose:

The purpose of this calculation is to demonstrate the feasibility of using linear induction motors in the Integrated Robot Winch to provide motive force to the cars.

Fundamental Equation:

The equations used to determine the thrust of the motors are idealized relationships and do not account for the starting and the stopping.

- Tp (m) is the distance between coils of the LIM.
- f (1/s) is the frequency of the power source.
- I_2' (Amperes) is the current passing through the motor.
- R_2' (Ohms) is the resistance of the motor.
- Vs (m/s) is the synchronous velocity.
- S is the slip.
- V (m/s) is the velocity of the motor.
- F (Newtons) is the thrust of the motor.

$$V_S = 2 \times T_P \times f$$

$$S = \frac{V_S - V}{V_S}$$

$$F = \frac{3 \times I_2'^2 \times R_2' \times S}{V_S}$$

Assumptions:

For this calculation we are assuming that the system must produce around 70,000 lbs or 311,000 Newtons at a velocity close to 3 mph or 1.3 meters/sec. For this case we will assume the following values:

- I = 500 Amperes
- R = 3 Ohms
- V = 1500 Volts
- f = 20 Hz
- Tp = .05 meters

These values were adopted from the specification of electric train locomotives.

Solution:

First we find the synchronous velocity.

$$V_S = 2 \times T_P \times f = 2 \times .05 meters \times 20 \sec^{-1} = 2 \frac{meters}{\sec}$$

Next we must determine the slip.

$$S = \frac{V_S - V}{V_S} = \frac{2 - 1.3}{2} = .35$$

Now we can determine the thrust given the previous values.

$$F = \frac{3 \times I_2'^2 \times R_2' \times S}{V_S} = \frac{3 \times 500^2 \times 3 \times .35}{2} = 394{,}000\,Newtons$$

$$F = 88{,}000\,lbs$$

Conclusions:

This calculation has served to show that a linear induction motor can be made to provide the large values of thrust needed to operate on the Panama Canal. The values assumed for the amperage, resistance and frequency are all reasonable and obtainable.

Efficiency of Linear Induction Motors

Purpose:

The purpose of this calculation is to determine the efficiency of the linear induction motor configured in the previous calculation.

Fundamental Equation:

The efficiency of any system is defined as the ratio of the energy supplied to the system to the work done by the system. Efficiency can also be defined as the power into the system divided by the power out of the system.

$$Efficiency = \frac{Power_{out}}{Power_{in}}$$

Assumptions:

For this calculation we will assume the values used in the previous calculation.

- Amperage = 500 Amps
- Resistance = 3 Ohms
- Force = 394,000 Newtons or 88,000 lbs
- Velocity = 1.3 meters/sec or 2.91 mph

$$Power_{out} = Force \times Velocity = 394{,}000\,Newtons \times 1.3\frac{meters}{\text{sec}} = 0.512\,MW$$

$$Power_{in} = Amperage^2 \times \mathrm{Re}sis\tan ce = 500^2\,Amps \times 3\,Ohms = .75\,MW$$

Solution:

The efficiency is therefore:

$$Efficiency = \frac{Power_{out}}{Power_{in}} = \frac{.512}{.75} = 68.3\%$$

Conclusions:

This value for efficiency is lower than what would be expected from a rotating electric motor, but this configuration could be optimized to provide better efficiency. This value will be used in subsequent equations.

Power and Energy Requirements

Purpose:

The purpose of these calculations is to determine the maximum power requirement of the Integrated Robot Winch system, assuming that two cars are exerting 140,000 lbs. at 3 mph. This calculation also assumes that the cars are powered by linear induction motors with an efficiency of 68.25%.

Fundamental Equation:

The fundamental equation used to calculate the power requirements is:

$$P = V \times F$$

Where P is power, V is velocity and F is the force.
Therefore for our system:

$$P = 2 * 4.4\frac{feet}{\sec} \times 140{,}000 lbs = 1{,}232{,}000\frac{ft-lbs}{\sec}$$

With an efficiency of 68.25%,

$$P_{required} = \frac{P}{efficiency} = \frac{1{,}232{,}000\frac{ft-lbs}{\sec}}{.6825} = 1{,}805{,}000\frac{ft-lbs}{\sec}$$

$$P_{required} = 3{,}282 horsepower$$

$$P_{required} = 2.45 MW$$

Assumptions:

In this calculation we are assuming an efficiency of %68.25. We are also assuming that 2 cars are exerting 140,000 lbs at 3 mph.

Solution:

This calculation is performed by first determining the power output of the system. This would be the case when a very large ship with a high blocking coefficient is traversing the lock, or when trying to stop a large vessel in a short distance.

Conclusions:

It is important to note that this power requirement is 1.62% of the total installed capacity of 151 MW. This would be the power requirement of a "minimum" system capable of applying 280,000 lbs of force to the vessel. Larger forces would require more power.

Cost Estimates

The following discussion is in concern to estimated capital investment for the integrated robot winch positioning system. As the design is purely conceptual, a qualitative perspective is maintained.

Rail / Concrete Structure:

The rail design suggested for this application will be more expensive to manufacture and install than the existing system. The rail itself can be cold-rolled in two symmetric pieces and bolted or welded together in modular sections. As the system requires the rail car to travel on its side, additional installation costs will be incurred, in addition to a more expensive concrete grounding mechanism. However, these costs should be easily offset by the tremendous benefit of removing shear loads from the rail, as in the current system (much lower maintenance costs).

Rail Car:

The structural components for the "robot" rail car should pose little technical challenge in terms of materials and engineering design. The components should be designed in a modular fashion to minimize future replacement and maintenance costs. Considering four rail cars per ship acting in three consecutive locks, up to 12 rail cars will be required to remain active at any one time. Additional rail cars may be required if a "merry-go-round" system is implemented to allow continuous one-way operation of any of the locks.

Upon several attempts, the group was not able to locate sufficient estimates in terms of cost for the linear induction motors. Capital investment costs for the rail car will be significant, but are expected to be significantly lower than the current locomotive system, considering the reduction in weight, complexity, and size.

Winch and Cables:

As these two components are directly similar to the current baseline, capital investment is expected to be similar. Additional costs will result in development of the mechanical angle sensing system and integrated control system.

Position Sensing:

Currently, position-sensing technologies sufficient for this design application are available off-the-shelf. Therefore, longitudinal position sensing of the rail cars should not impose significant capital cost.

Angle Sensing:

Initially, concerns were voiced in regards to the expense of implementing an optical angle-sensing system. However, the group found several current applications of this technology in the areas of ship guidance and docking. To date, this technology has been demonstrated and should require little development costs. In terms of equipment, the following costs indicate an attractive design embodiment is likely:

Laser Source ≈ $400 US

Retro-Reflector ≈ $500 US

Photo Sensor ≈ $500-1000 US

Additional equipment and standardization will be required to develop methods to consistently mount the retro-reflectors onto the bow and stern of the ship hull near the mooring points.

Alternatively, it should be noted that radar-sensing systems were also proposed, and are expected to be available at minimal cost.

Control System:

The control system itself will consist of standard equipment currently available from the electronics industry. Materials and equipment will be minor in comparison to the design and development cost, which is still expected to be on the order of the costs required to develop the optical angle sensing system.

Pilot Interface:

In the present design, an "high-tech" pilot interface is envisioned, with graphical user interface, active data feedback, and joystick control. The system will be required to communicate several degrees of freedom to the pilot in an easy-to-interpret format. Additionally, the pilot interface will be required to communicate by radio frequency to the control system. As this control is critical, backup systems will be necessary, adding further cost.

For this component of the design, costs associated with development and testing of the interface will be significant. Considering the reliability, agility, and flexibility required of the system, a figure exceeding $500,000 US would not be surprising. However, the technology is again currently available, and has been demonstrated in several applications (example: Boeing's 777 graphical pilot interface, customizable for each individual user).

Systems Integration:

Significant development, testing, and implementation cost are expected here. As all technologies discussed are presently available, effective systems integration will certainly be feasible, but will come at high cost. The task of implementing the entire lock control system into an integrated "auto-pilot" will present by far the largest cost challenge in this design.

Analysis for Design

Conceptual Drawings

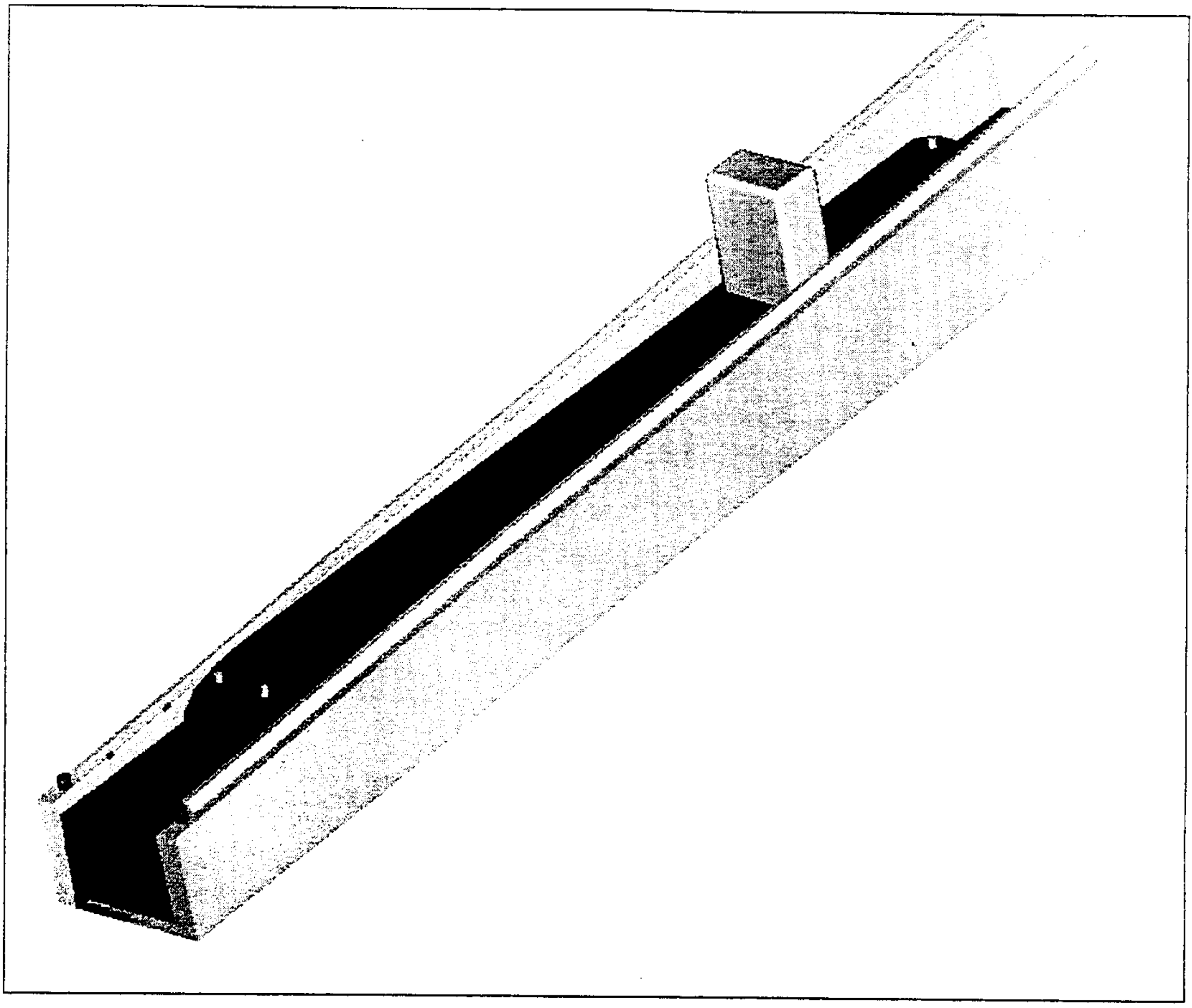


Figure B1: Isometric View of Lock Chamber with Travelling bit system

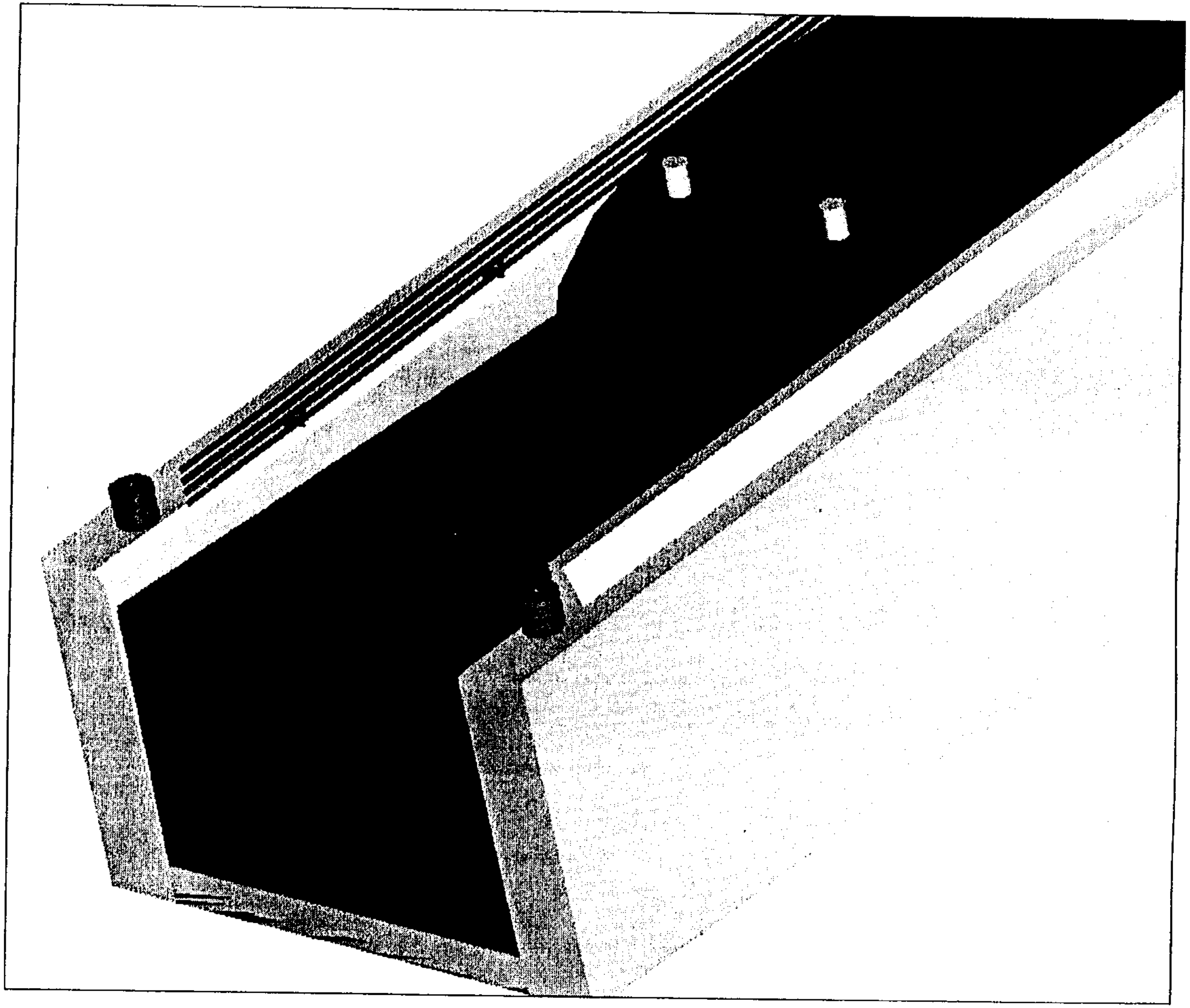


Figure B2: Close up view of the bit system

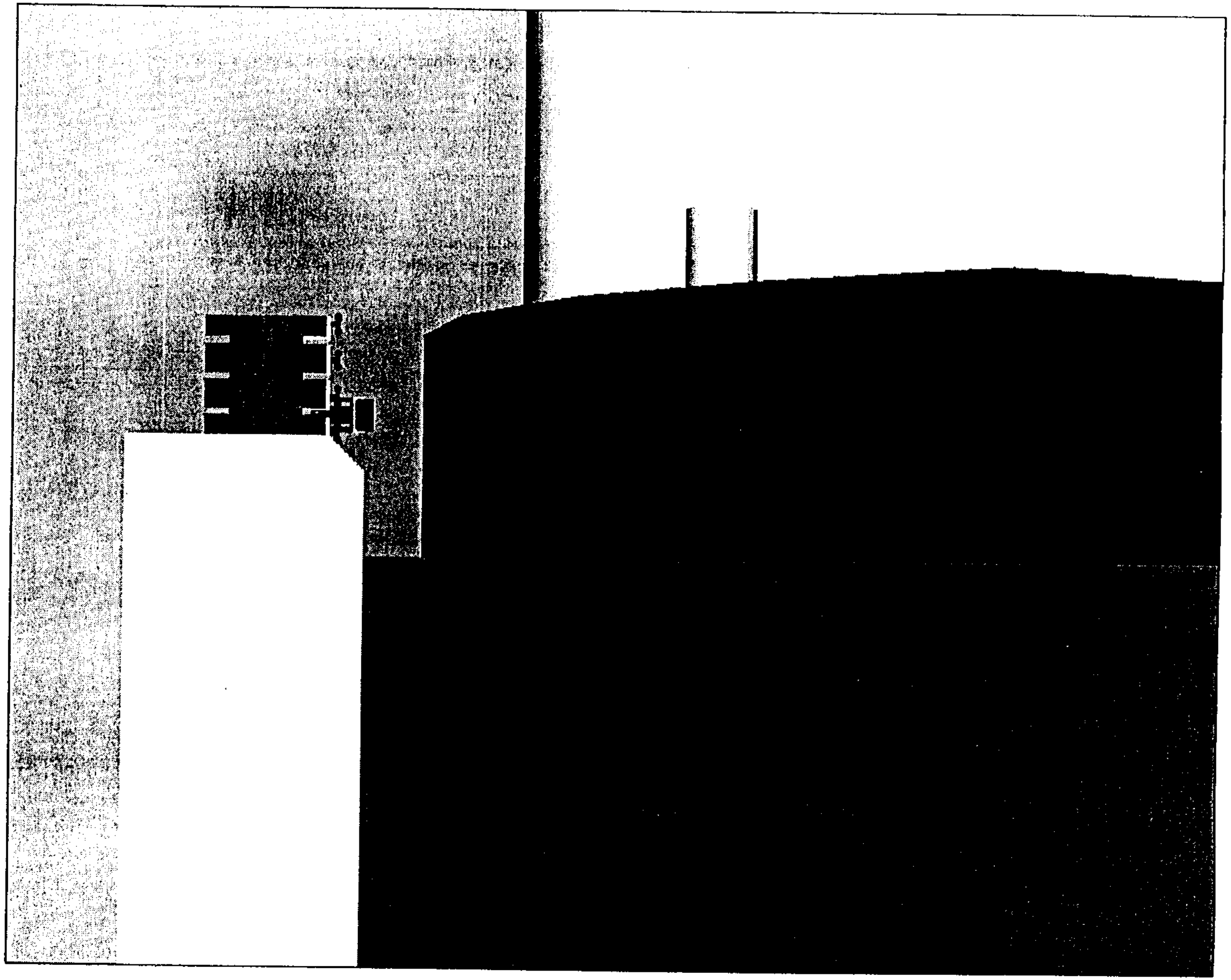


Figure B3: Blow up of the Travelling bit drive System

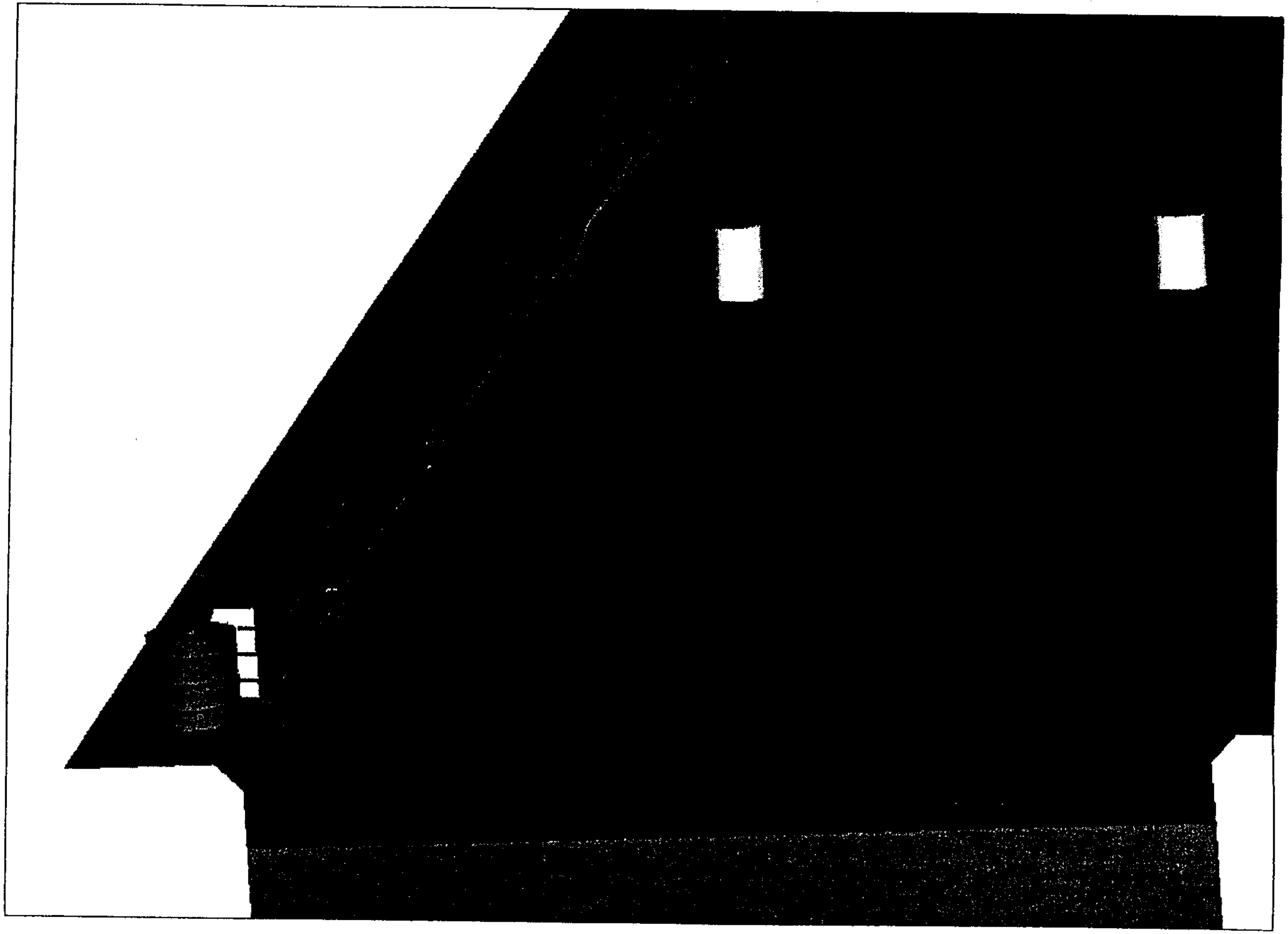


Figure B4: Close up isometric showing the Travelling bit system

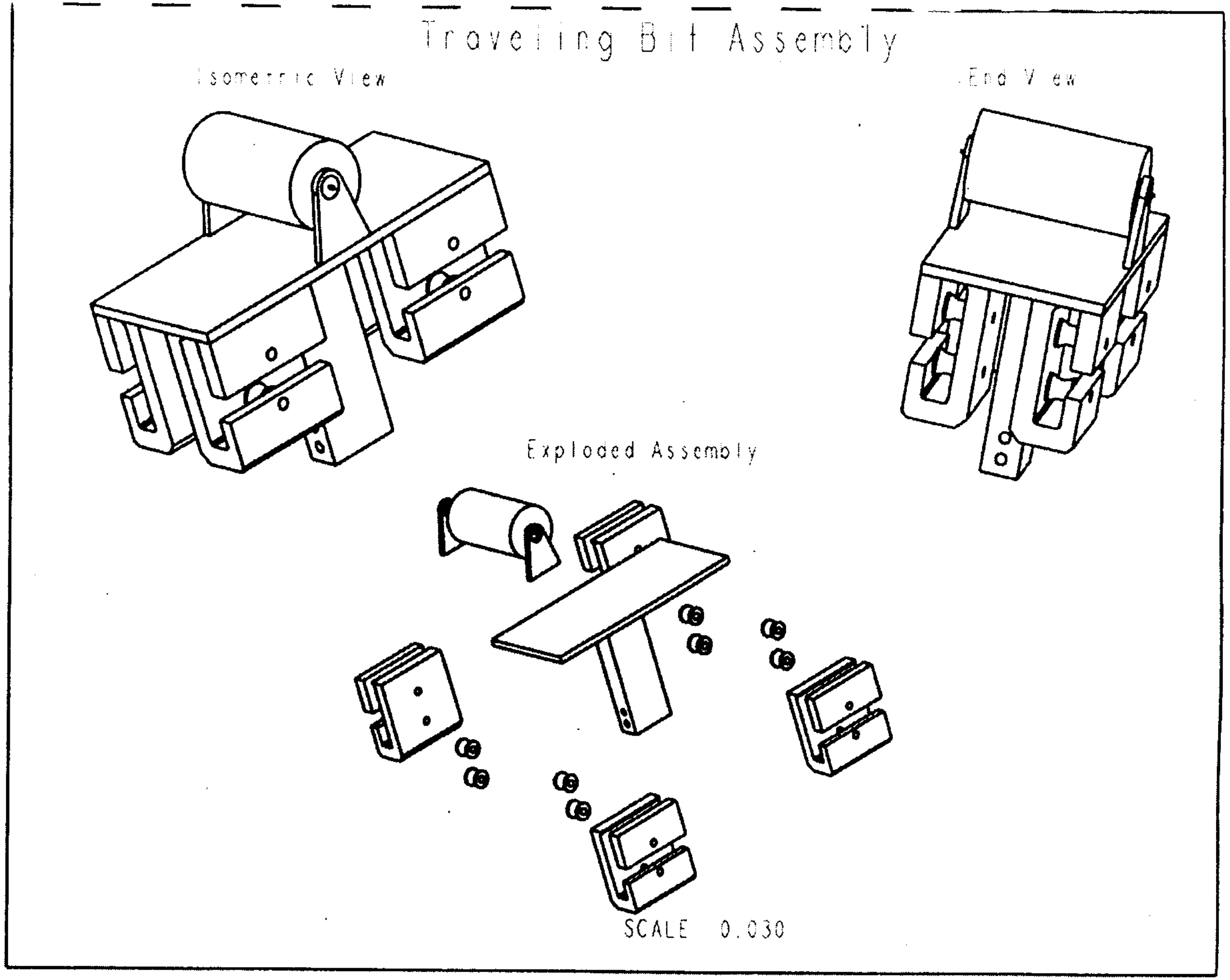


Figure B5: Traveling Bit – Cross Sectional View

Critical Calculations for the design

Bit Kinematics

Purpose:

The purpose of this calculation is to demonstrate a possible method for determining the length of the cables used in the traveling bit.

Fundamental Equation:

It is helpful in gaining the correct perspective to realize that L1, L2 and L3 are all in the same plane when in full tension. However we consider the general case where the 3 cables are in 3 different planes.

L1= length of cable 1

L2= length of cable 2

L3= length of cable 3

D is the driving bit.

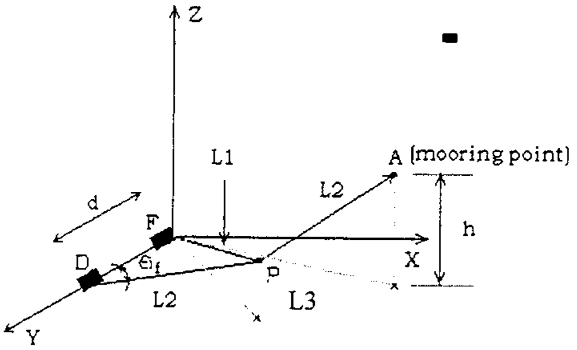
F is the following bit.

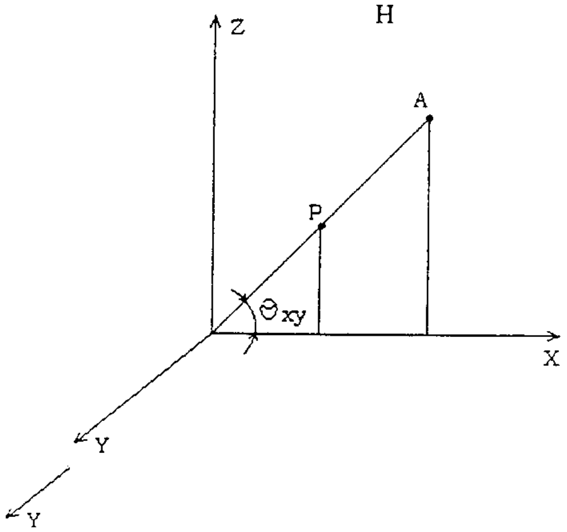
P is where the three cables meet.

A is the mooring point.

H is the freeboard height.

d is the distance between the bits.





Given the coordinate system shown above (where the reference is at the center wall), the position of the mooring point of the vessel can be defined by the following relationship:

$$A_X = [l_2 \times \sin(\theta_f) + l_3 \times \sin(45)] \times \cos(\theta_{XY})$$
$$A_Z = H$$
$$Ay = D_Y - l_2 \times \cos(\theta_f) - l_3 \times \cos(45)$$

Assumptions:

In this calculation we are assuming that a vessel with known parameters (length, free board height and distance between mooring points) is entering a lock. As this vessel travels the lock the elevation will rise. To determine the correct cable lengths and initial distance between the carts, it is necessary to eliminate certain variables, therefore we will assume the following relationships:

$$d = \sqrt{2} \times l_2$$
$$l_1 = l_2$$

Solution:

Now we use the equations shown to determine the initial settings in the traveling bit system.

$$H = [l_2 \times \sin(\theta_f) + l_3 \times \sin(45)] \times \sin(\theta_{XY})$$
$$X = \frac{H}{\tan(\theta_{XY})}$$
$$\cos(\theta_f) = \sqrt{2}$$
$$l_2 = \frac{[(\frac{H}{\sin(\theta_{XY})} - l_3 \times \sin(45)]}{\sin(\theta_f)}$$
$$\theta_{XY} = \tan^{-1}(\frac{H}{X})$$

With these formulas, the lengths of the cables are pre-determined.

Conclusions:

These calculations show the kinematic relationship of the cable lengths and the distance between cars to the position of the vessel mooring points. These fixed cable lengths are used to keep the vessel off the lock walls.

Power and Energy Requirements

Purpose:

The purpose of these calculations is to determine the maximum power requirement of the traveling bit system assuming that all four driving bits are exerting a nominal force of 70,000 lbs at 3 mph. This calculation also assumes that the cars are powered by a drive system with an efficiency of 80%.

Fundamental Equation:

The fundamental equation used to calculate the power requirements is:

$$P = V \times F$$

Where P is power, V is velocity and F is the force.

Assumptions:

In this calculation we are assuming an efficiency of 80%. We are also assuming that 4 carts are exerting 70,000 lbs at 3 mph.

Solution:

$$P = 4 * 4.4 \frac{feet}{\sec} \times 70{,}000 lbs = 1{,}232{,}000 \frac{ft - lbs}{\sec}$$

With an efficiency of 80%,

$$P_{required} = \frac{P}{efficiency} = \frac{1{,}232{,}000 \frac{ft - lbs}{\sec}}{.80} = 1{,}540{,}000 \frac{ft - lbs}{\sec}$$

$$P_{required} = 2{,}800 horsepower$$

$$P_{required} = 2.1 MW$$

This calculation is performed to determine the maximum power output of the system. This would be the case when a very large ship with a high blocking coefficient is traversing the lock, or when trying to stop a large vessel in a short distance.

Conclusions:

It is important to note that this power requirement is %1.4 of the total installed capacity of 151 MW. This would be the power requirement of a "minimum" system capable of applying 280,000 lbs of force to the vessel. Larger forces would require more power.

Cost Estimates

The following discussion is in concern to estimated capital investment for the traveling bit positioning system. As the design is purely conceptual, a qualitative perspective is maintained.

Rail / Concrete Structure:

The rail and concrete design suggested for this application potentially represents the area of highest capital investment for the traveling bit positioning system. Each rail will be more expensive to manufacture and install than the existing system. Similar to the integrated robot winch design, the rail itself can be cold-rolled in two symmetric pieces and bolted or welded together in modular sections. As the system requires three parallel rails mounted on a concrete structure above the maximum water level, additional installation costs will be accompanied by a tremendous increase in material cost, as compared to the current locomotive system. However, a significant portion of these costs should be offset by the tremendous benefit of removing shear loads from the rail, as in the current system.

Traveling Bit:

The structural components for the traveling bit should pose little technical challenge in terms of materials and engineering design. The only component in question for development and design costs is the linear induction motors The components should be designed in a modular fashion to minimize future replacement and maintenance costs. Considering four rail bits per ship acting in three consecutive locks, up to 12 rail bits will be required to remain active at any one time. Additional rail bits may be required if a "merry-go-round" system is implemented to allow continuous one-way operation of any of the locks.

Winch and Cables:

Since the winch required for this system is not "active," lower costs are expected. For the cables, additional costs will be incurred due to the three-cable pulley system.

Position Sensing:

The costs here will be directly similar to the integrated robot winch system. Currently, position-sensing technologies sufficient for this design application are available off-the-shelf. Therefore, longitudinal position sensing of the rail cars in a global coordinate system should not impose significant capital cost.

Control System:

The control system itself will consist of standard equipment currently available from the electronics industry. Materials and equipment will be minor in comparison to the design and development cost, which is still expected to be low in comparison to other system components.

Systems Integration:

Significant development, testing, and implementation cost are expected here. As all technologies discussed are presently available, effective systems integration will certainly be feasible, but will come at fairly significant cost. As the traveling bit system offers fewer pilots operated control capabilities, the system integration costs for this design will be substantially lower than that for the automated robot winch system. Either way, these costs will present the largest cost challenge in this design.

COUNTERWEIGHTS

Analysis for counterweights design

Drawings for Counterweights Design

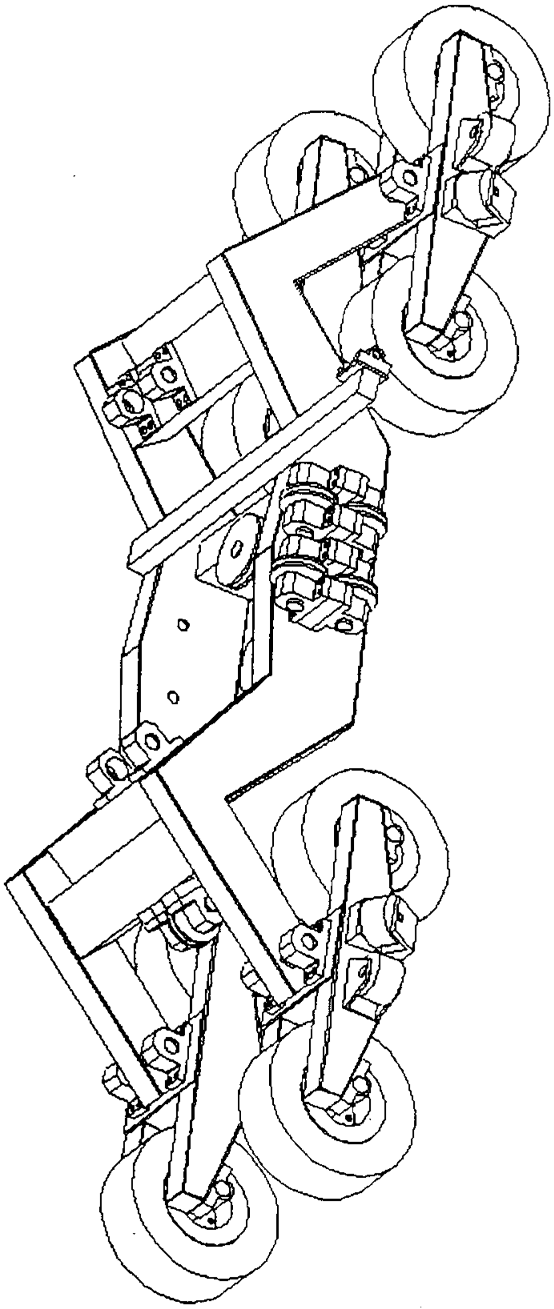


Figure A1: Isometric View of Counterweight Chassis

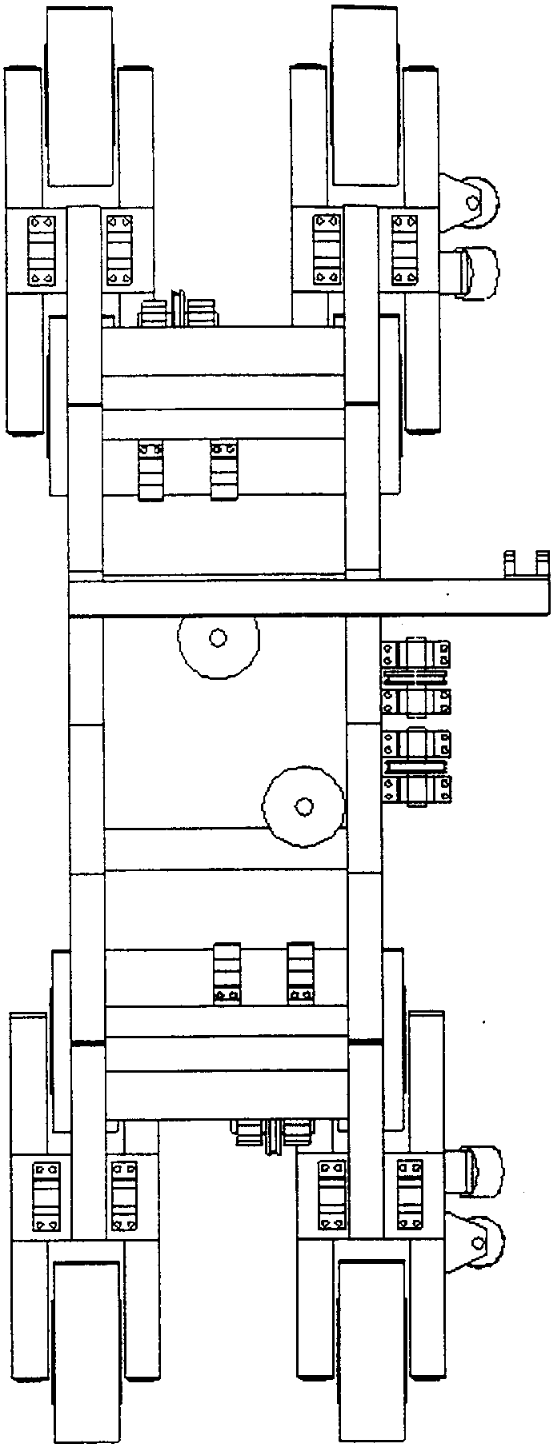


Figure A2: Top View of Counterweight Chassis

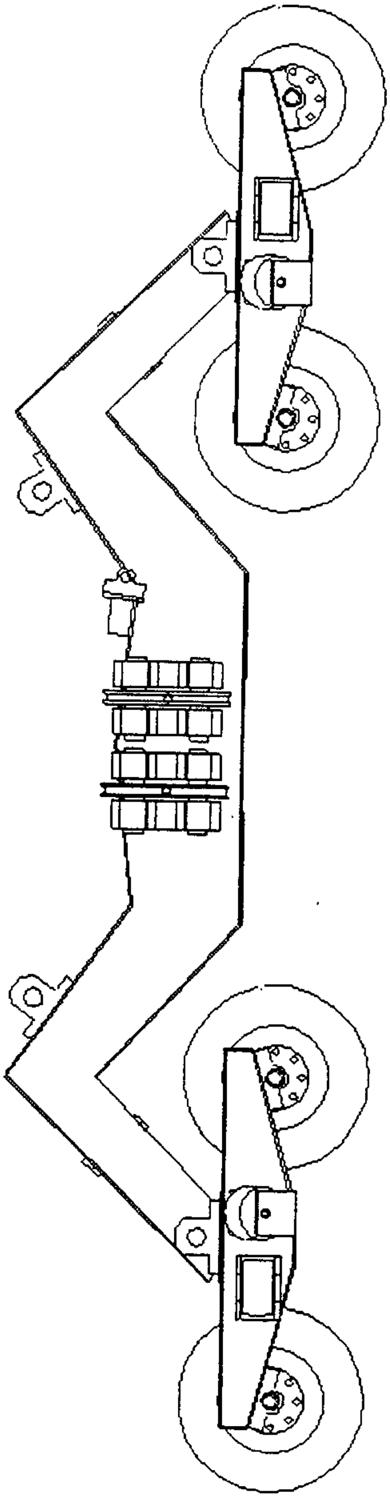


Figure A3: Side View of Counterweight Chassis

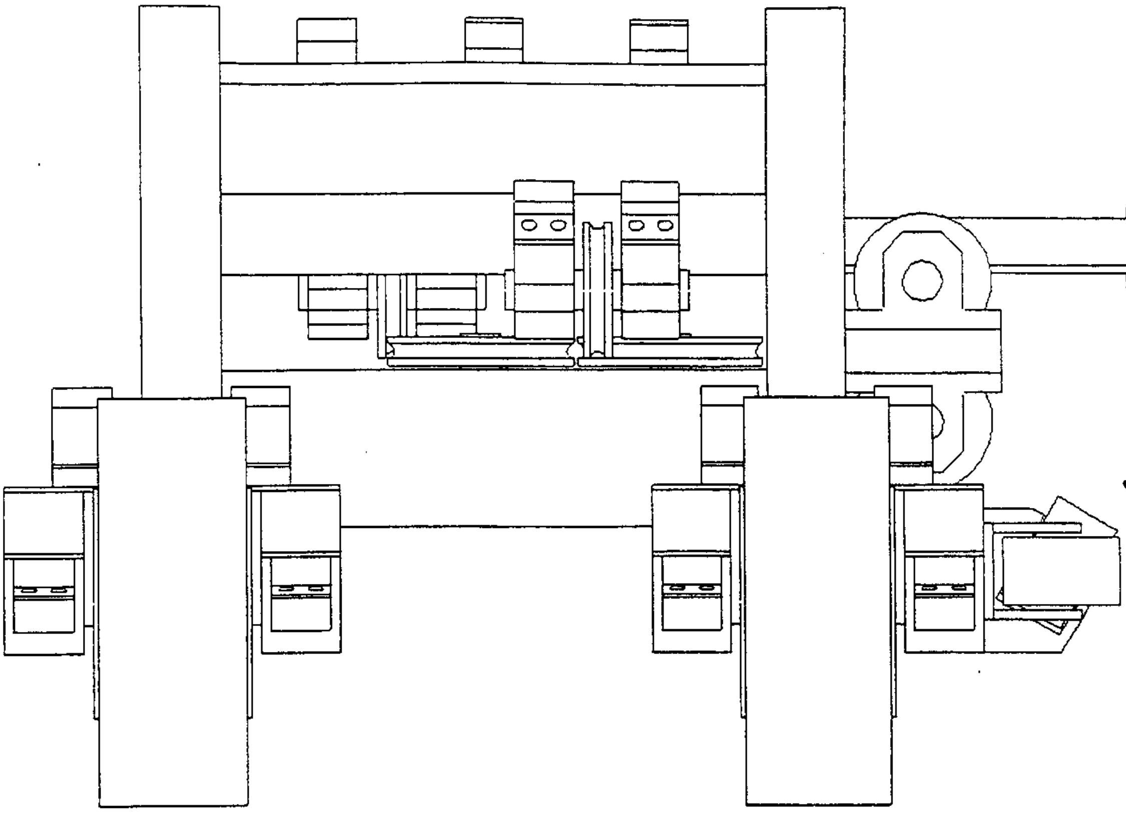


Figure A4: Front View of Counterweight Chassis

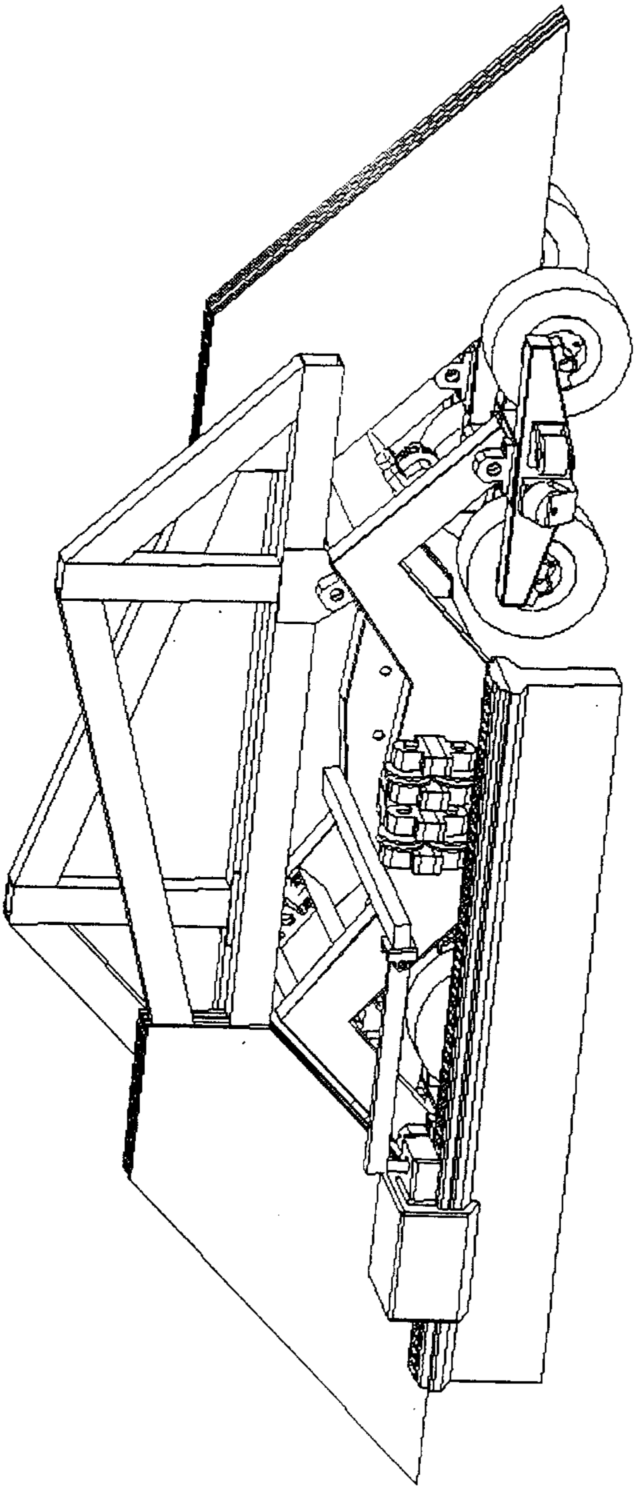


Figure A5: Isometric View of Counterweight System

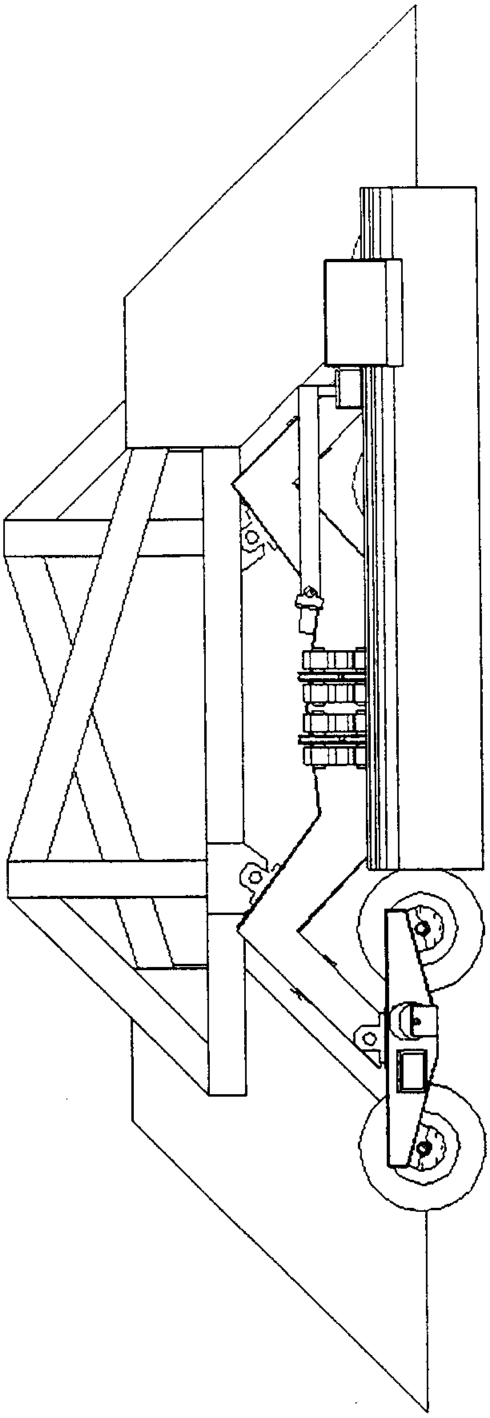


Figure A6: Side View of Counterweight System

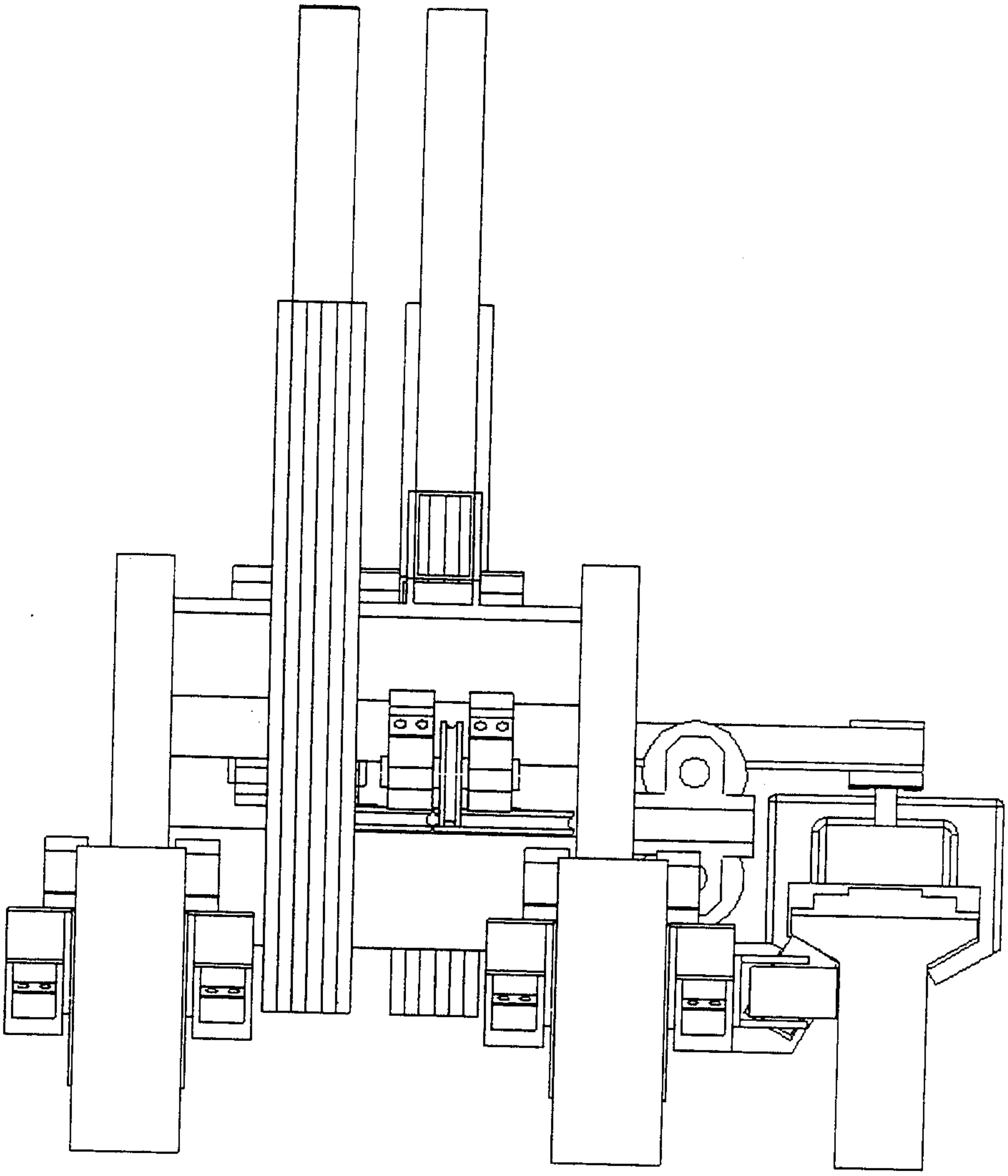


Figure A7: Front View of Counterweight System

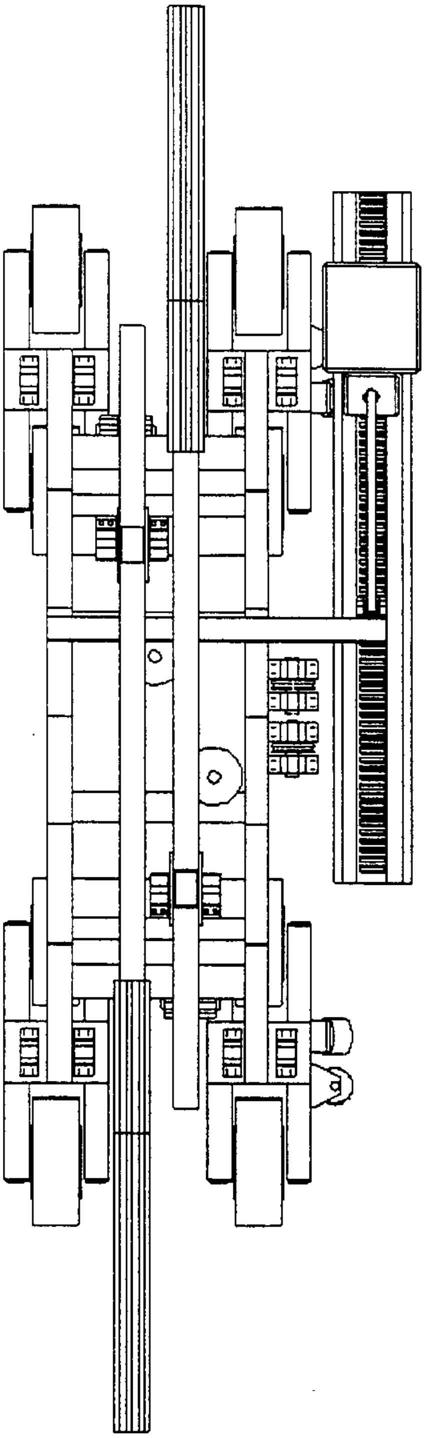


Figure A8: Top View of Counterweight System

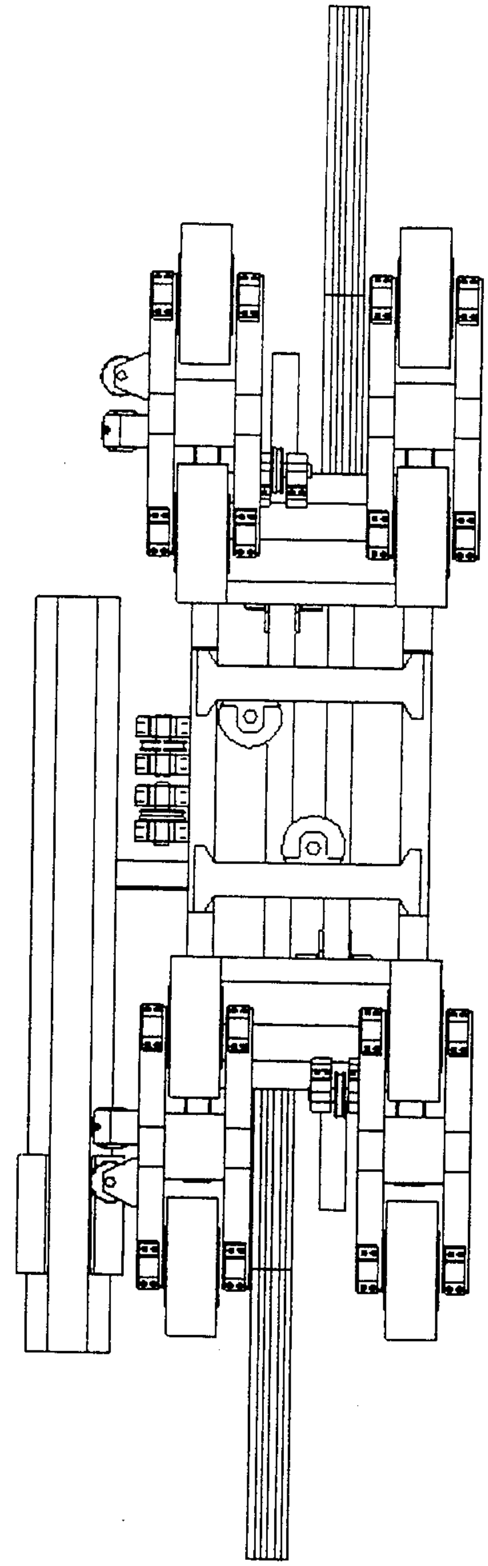


Figure A9: Bottom View of Counterweight System

Steel Roller on Steel Track Calculations

Purpose:

Steel rollers are used in numerous locations in this design to transmit loads through a moving structure to a fixed reference such as the track. The diameter and axial length of such wheels determine the stress levels in the wheel material for a given loading condition.

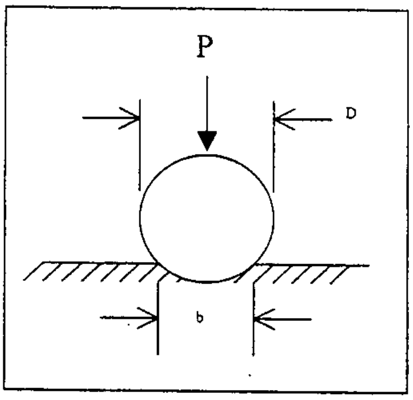
Fundamental Equation:

For a wheel and base of the same material:

$$\sigma_C = 0.591\sqrt{\frac{pE}{D}}$$

where $p = P/L$ and σ_C is the maximum contact stress.

Here P is the applied radial load and L is the axial length of the cylinder.



Assumptions:

The equations above are valid for loading resulting in elastic deformations in the cylinder and substrate material.

Design Requirements:

Steel wheels on steel tracks were primarily employed for the purposes described above. The American Railway Association employs contact stresses 2.5 times yield in railcar wheels. For applications where the rolling velocity is lower and there is less shock load due to track imperfections, contact stresses of 3 times yield can be employed. The modulus of the wheel material was assumed to be 50,000,000 psi and the yield stress to be 30,000 psi.

Solution:

As a sample solution process common to all such calculations performed for this design, the wheel mounted on the side of the counterweight chassis which thrusts against the vertical wall will be considered. This wheel must withstand radial loads of 70,000 lbs. For an axial length of 7 in., we can solve for the required diameter to maintain contact stresses at yield level. Solving the contact stress equation for the diameter

$$D = \frac{0.591^2 PE}{\sigma_C^2 L}$$

where σ_C is the maximum contact stress of 3 times yield. Inserting the given values and solving for the diameter, D, yields a value of 12.9 inches.

Conclusions:

This particular wheel was given a diameter of 14 inches in the design, and should provide long service.

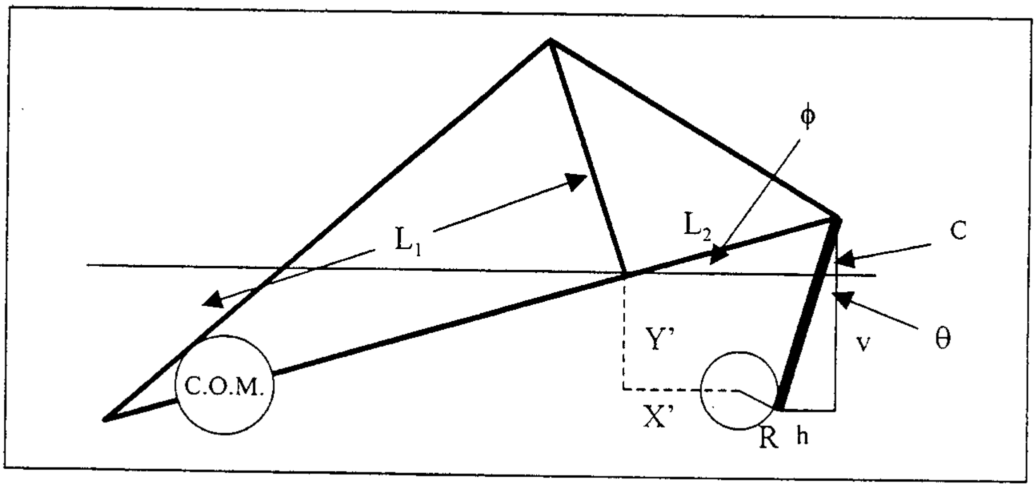
Force/Lateral Displacement Calculation

Purpose:

The passive lateral restoring force provided by the counterweight system is quantified here as a function of the counterweight truss geometry and its angle from horizontal.

Fundamental Equation:

The governing equations are developed below from the diagram provided.



L_1 is the distance from the truss pivot to the composite mass center

L_2 is the distance from the truss pivot to the cable connection point

Y' is the vertical distance from the pivot to the pulley axis

X' is the horizontal distance from the pivot to the pulley axis

R is the radius of the pulley

ϕ is the angle the moment arm makes with horizontal

θ is the angle the cable makes with vertical

v and h are lengths to be computed to determine the relationship between ϕ and θ

The lengths v and h can be written as:

$$v = L_2 \sin\phi + y' + R\sin\theta$$
$$h = L_2 \cos\phi - x' - R\cos\theta$$

Noting that

$$\tan\theta = \frac{h}{v}$$

we can obtain the following relationship between θ and ϕ:

$$\tan\theta = \frac{L_2 \cos\phi - x'}{L_2 \sin\phi + y'} - \frac{R}{\cos\theta}$$

This is not an explicit solution, but can be solved numerically. Once this relationship has been determined, the associated lateral vessel travel and tension in the cable can be determined. The associated vesel travel can be related to the angle ϕ through computation of the length of the section of cable C. C is given by:

$$C = \sqrt{v^2 + h^2}$$

If we let δ be the lateral displacement of the vessel from the center of the lock, we can write

$$\delta(\phi) = C_0 - C(\phi)$$

The summation of moments about the pivot can be written as

$$(weight)L_1 \cos\phi = TL_2 \cos\phi \cos\theta$$

which reduces to

$$T = \frac{(weight)L_1}{L_2 \cos\theta}$$

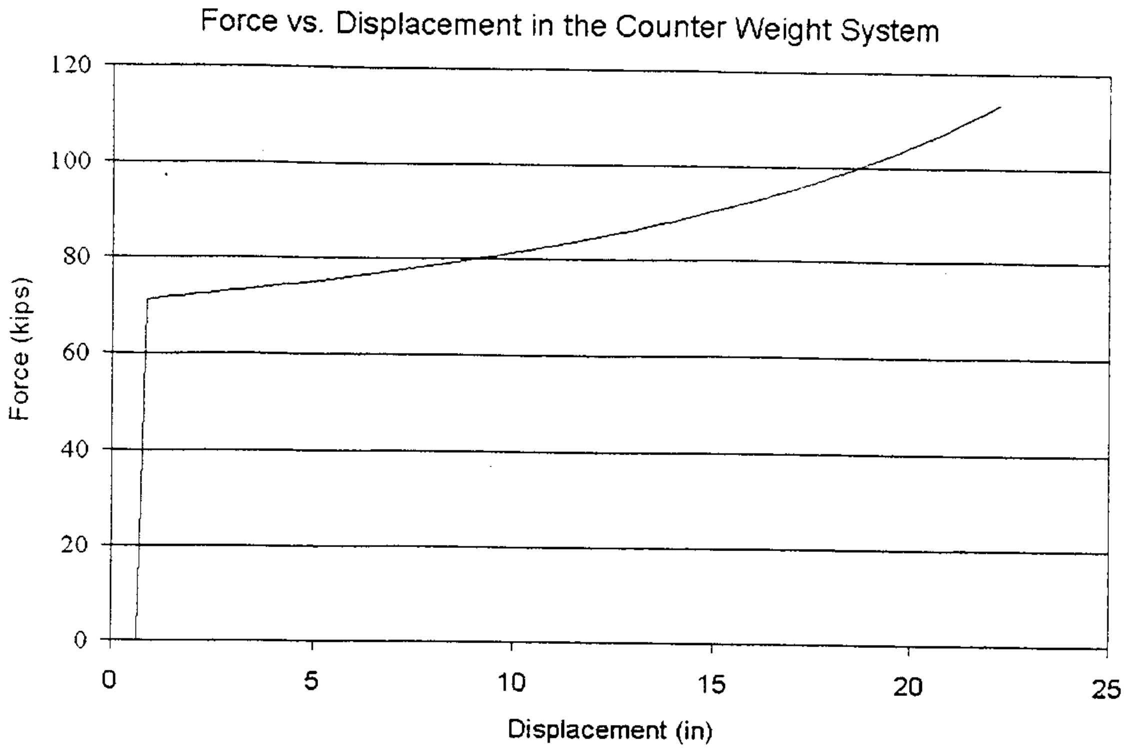
From these equations, we can determine a force-lateral displacement curve for the counterweight system.

Assumptions:

The equations above are valid for a cart which is on a horizontal plane with respect to the gravity field.

Design Requirements:

The geometry of each of the two redundant trusses in the counterweight concept was designed to provide a 70,000-lb force on the vessel exactly when it deviates from its center position. This force level increases nonlinearly with increased lateral deviation to a level of 115,000 lbs. at 2 feet of lateral deviation.



Conclusions:

The assumptions for these calculations are valid for most of the operation, but do not apply during the transition from one lock level to another while the cart is negotiating the incline. The system still operates in this mode, however, the force-lateral displacement curve will change as a function of the inclination of the cart.

Power and Energy Requirements for Longitudinal Actuation

Purpose:

This calculation will be used to determine the amount of horsepower needed to provide 200,000 lbs. of force while traveling at 3 mph. This should be the maximum consumption experienced by the drive mechanisms providing longitudinal starting and stopping force.

Fundamental Equation:

Power = Force * Velocity

Assumptions:

It will be assumed that the any energy supplied to the motor will be transferred without loss to the application of the desired force and velocity.

Design Requirements:

Force = 200,000 lbs.

Velocity = 3 mph.

Solution:

The power in horsepower is desired. Therefore the speed will be converted to feet per second.

3 mph = 4.4 ft/sec

Given that 1 hp = 550 ft lbs/sec

P (ft lbs/sec) = 200,000 lbs * 4.4 ft/sec = 880,000 ft lbs/sec

P (hp) = 1600 hp

Conclusions:

This large power requirement shows that it is impractical to expect the system to provide these forces at these speeds. It is also useful to note that this equation is linear in both force and velocity, i.e. 10% of the speed means 10% of the hp required.

Cost Estimates for Counterweights Design

Purpose:

The purpose of the table given is to estimate the cost of all parts, components and sub-assemblies in the main system assembly to provide a cost estimate for the whole system. One counterweight cart with two redundant counterweight levers will be analyzed in the detailed estimate. The final number will be multiplied by four since four carts are required to control a Panamax vessel.

Equation:

The cost per item will be calculated based on an estimation technique that includes material weight, cost per unit weight, a fabrication complexity factor and the amount used. The following equation is used for this calculation:

$$ItemCost = weight \times \frac{cost}{weight} \times factor(complexity) \times quantity$$

For OEM items, the quantity and cost are the only parameters used. The

Assumptions:

The only assumption was that the cost of steel is $0.25/lb, and the following fabrication complexity factors apply:

Operation	**Factor by which to multiply material cost**
Simple material cut	3
Light machining – drilling, low tolerance lathe operations, simple facing	6
Heavy and high tolerance machining	9

Solution:

The following table provides the itemized cost analysis by assembly. Some of the lower assemblies on the list include totals for one or more sub-assemblies above it. For the total cost, however, only the last group of items followed by the total should be used.

Sub-Name	**Part-Name**	**Count**	**Mass [lb]**	**Cost/ (Unit/Mass)**	**Fab. Factor**	**Item Total**
Tandembeam	tandemplate	2	138.7	$0.25	3	$208.05
	tandemtopplate	1	94.7	$0.25	3	$71.03
	Bottomtandemplate	2	42.1	$0.25	3	$63.15
	tandemcaps	2	7.3	$0.25	3	$10.95
	tandembase	1	13.5	$0.25	3	$10.13
					subtotal	**$363.30**

Sub-Name	**Part-Name**	**Count**	**Mass [lb]**	**Cost/ (Unit/Mass)**	**Fab. Factor**	**Item Total**
Doublepulley	Doublepulleybracket	2	118.4	$0.25	6	$355.20
	chassisbearing	4	na	$1,200.00	na	$4,800.00
	pulleyshaft	2	182.3	$0.25	9	$820.35
					subtotal	**$5,975.55**

Sub-Name	**Part-Name**	**Count**	**Mass [lb]**	**Cost/ (Unit/Mass)**	**Fab. Factor**	**Item Total**

Framerails	frameplate	2	730.5	$0.25	3	$1,095.75
	topcenterplates	2	40.9	$0.25	3	$61.35
	top2plate	2	53.9	$0.25	3	$80.85
	top3plate	2	73.3	$0.25	3	$109.95
	bottom2plate	2	53.1	$0.25	3	$79.65
	bottomplate	1	90.2	$0.25	3	$67.65
					subtotal	**$1,495.20**

Sub-Name	**Part-Name**	**Count**	**Mass [lb]**	**Cost/ (Unit/Mass)**	**Fab. Factor**	**Item Total**
Tandembox	tandembeam	2	na	$363.30	na	$726.60
	thrustblock	2	na	$1,200.00	na	$2,400.00
	radialblock	2	na	$1,200.00	na	$2,400.00
	bigwheel	2	na	$12,000.00	na	$24,000.00
	tandembridge	1	126.6	$0.25	3	$94.95
	bridgeplate	1	95.9	$0.25	3	$71.93
	chassisbearing	2	na	$1,200.00	na	$2,400.00
					subtotal	**$32,093.48**

Sub-Name	**Part-Name**	**Count**	**mass [lb]**	**Cost/ (Unit/Mass)**	**Fab. Factor**	**Item Total**
Chassis	framerails	2	na	$1,495.20	na	$2,990.40
	doublepulley	2	na	$5,975.55	na	$11,951.10
	crossmember	2	321.3	$0.25	3	$481.95
	Uppercrossmember	4	322.8	$0.25	3	$968.40
	chassisbearing	12	na	$1,200.00	na	$14,400.00
	bearingblock	4	81.2	$0.25	6	$487.20
	pulleyshaft	2	182.3	$0.25	9	$820.35
	horpulley	2	288.9	$0.25	9	$1,300.05
	rabbitbar	1	1252.1	$0.25	3	$939.08
	pullplate	1	25.4	$0.25	3	$19.05
	rabbitbearing	2	na	$1,000.00	na	$2,000.00
					subtotal	**$36,357.58**

Sub-Name	**Part-Name**	**Count**	**mass [lb]**	**Cost/ (Unit/Mass)**	**Fab. Factor**	**Item Total**
Lowerunit	chassis	1	na	$36,357.58	na	$36,357.58
	tandembox	4	na	$32,093.48	na	$128,373.90
	Wallwheelbracket	2	86.3	$0.25	6	$258.90
	wallwheel	4	na	$500.00	na	$2,000.00
	upwheelbracket	2	221.1	$0.25	6	$663.30
					subtotal	**$167,653.68**

Sub-Name	**Part-Name**	**Count**	**mass [lb]**	**Cost/ (Unit/Mass)**	**Fab. Factor**	**Item Total**
Ctruss	base	1	500	$0.25	3	$375.00
	upright	1	268.7	$0.25	3	$201.53
	shorthyp	1	223.7	$0.25	3	$167.78
	longhyp	1	500	$0.25	3	$375.00
	innermass	4	121.1	$0.25	3	$363.30
	outermass	4	3809.1	$0.25	3	$11,427.30
	trussshaftbrace	2	111	$0.25	3	$166.50

	trusspipe	1	31.7	$0.25	3	$23.78
	massplate	2	4425	$0.25	3	$6,637.50
					subtotal	**$19,737.68**

Sub-Name	**Part-Name**	**Count**	**mass [lb]**	**Cost/ (Unit/Mass)**	**Fab. Factor**	**Item Total**
Wholeunit	lowerunit	1	na	$167,653.68	na	$167,653.68
	ctruss	2	na	$19,737.68	na	$39,475.35
	towbar	1	389.1	$0.25	6	$583.65
	rabbit	1	na	$30,000.00	na	$30,000.00
	wenches	2	na	$35,000.00	na	$70,000.00
					TOTAL	**$307,712.68**

The total system cost for single vessel capability is equal to $1,230,850. This estimate excludes the fabrication and installation of the track.

Analysis for Tellescoping Truss design

Drawings for Design Telescoping Truss

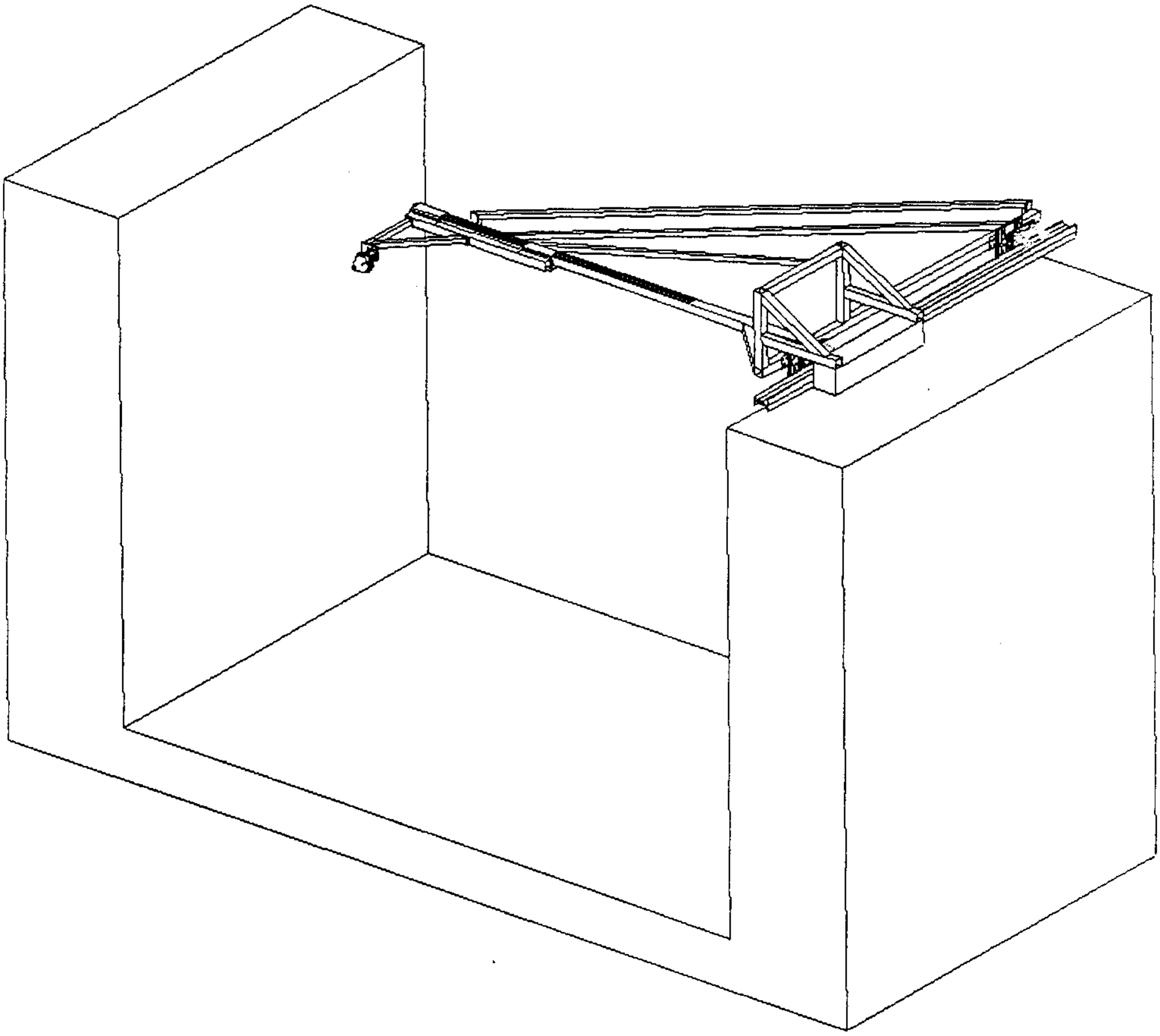


Figure B1: Scaled Isometric of One Truss in Relation to the Lock Cross Section

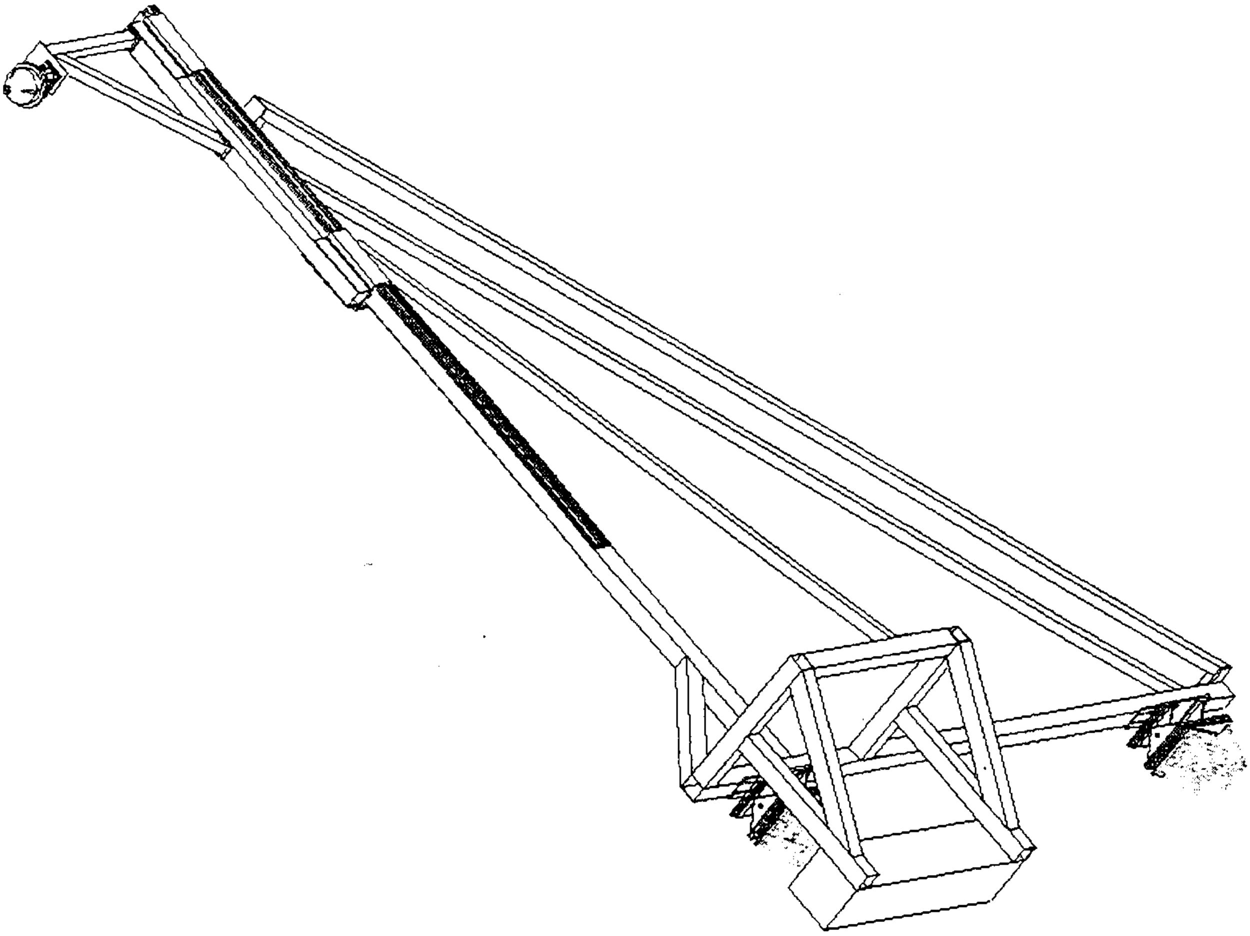


Figure B2: Isometric of Truss System

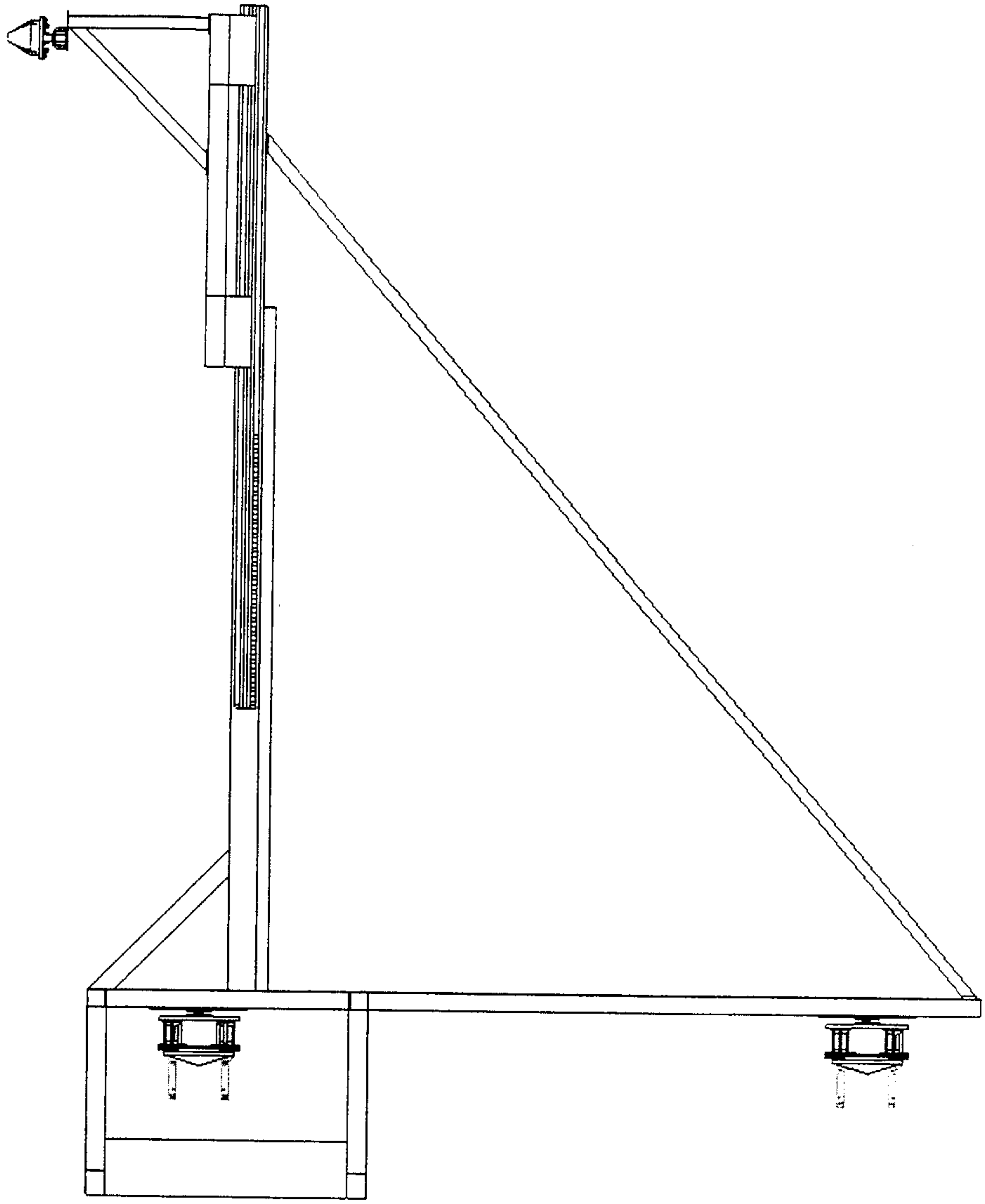


Figure B3: Top View of Truss System

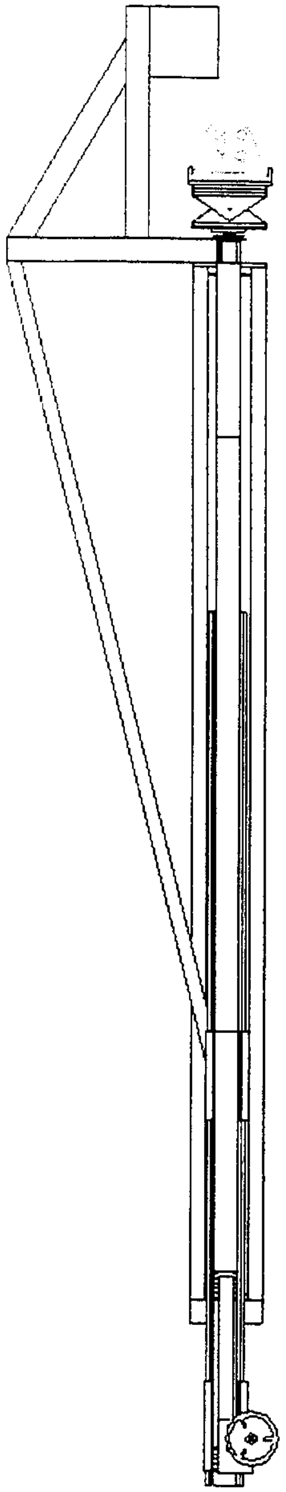


Figure B4: Side View of Truss System

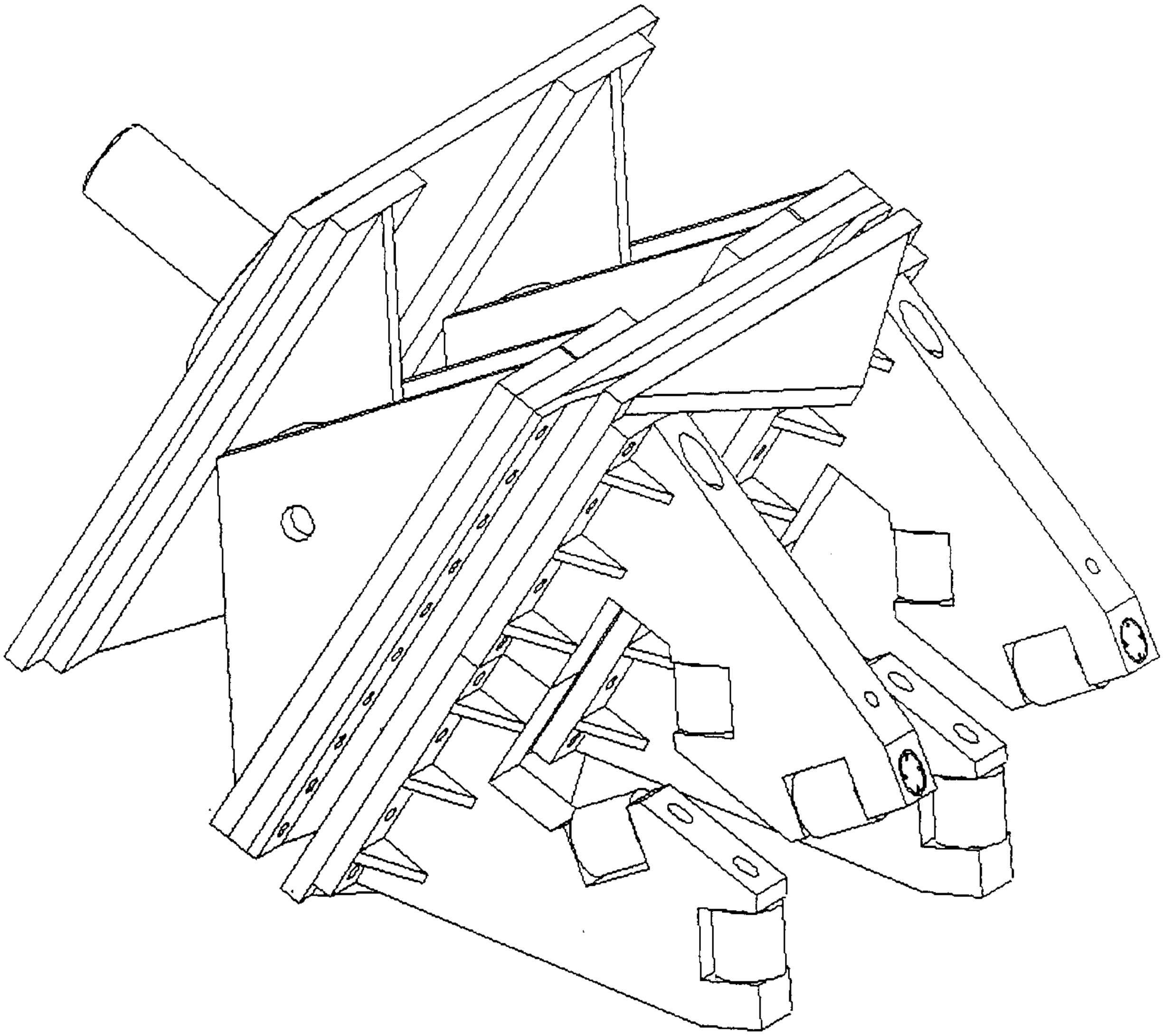


Figure B5: Isometric View of Truck

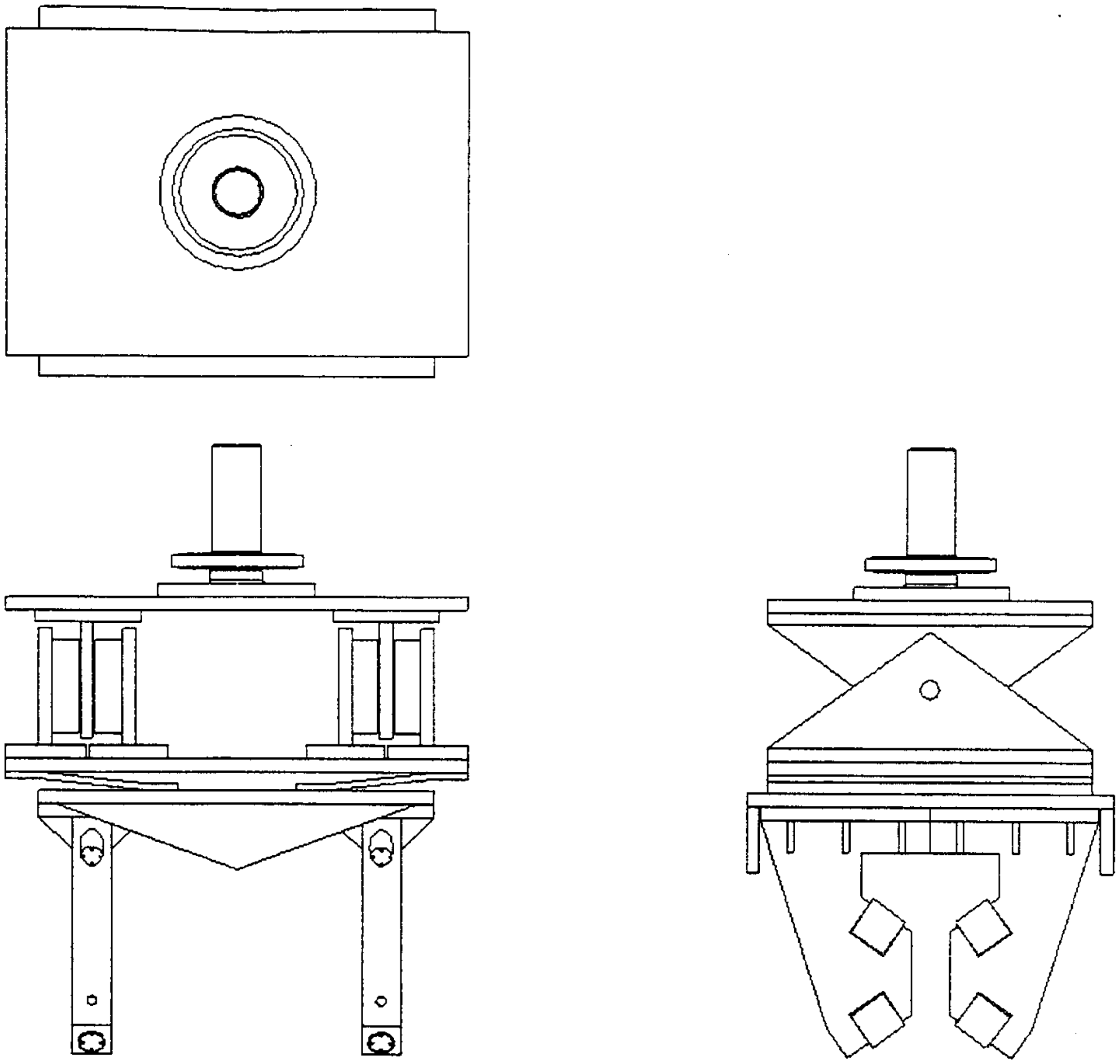


Figure B6: Rear, Top and Side Views of Truck

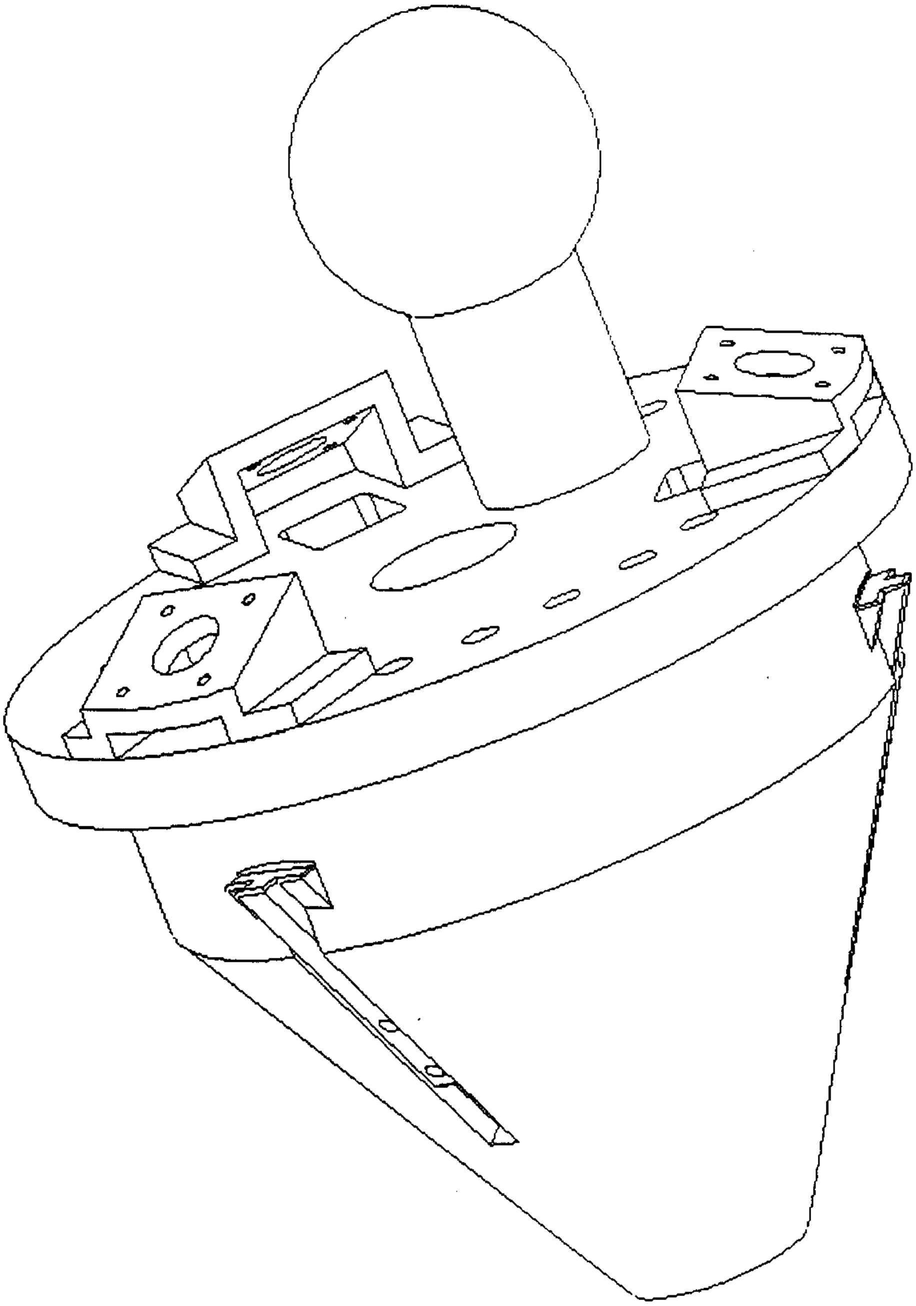


Figure B7: Isometric View of Boot

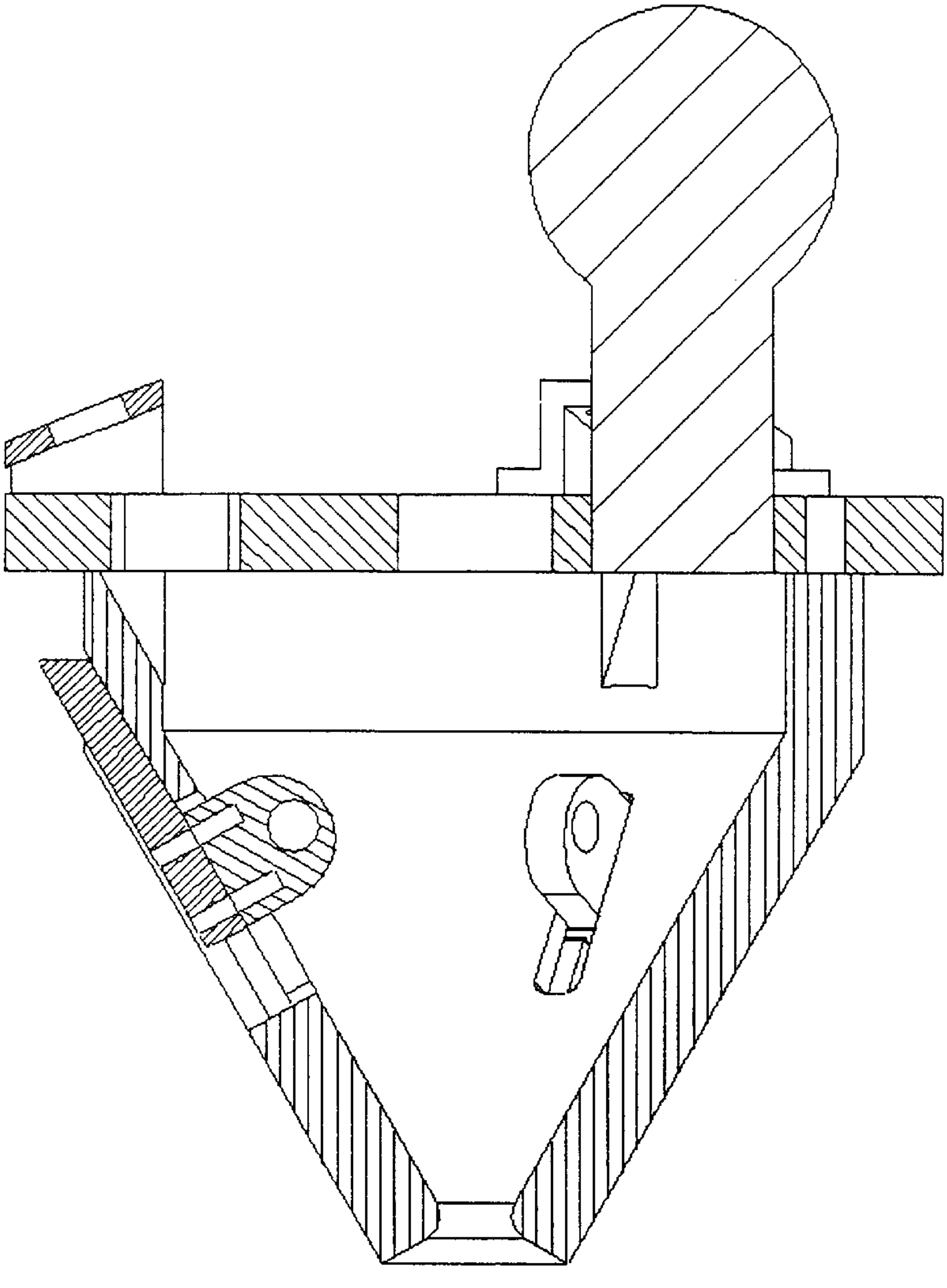


Figure B8: Cut View of Boot Showing Clamping Devices Actuated

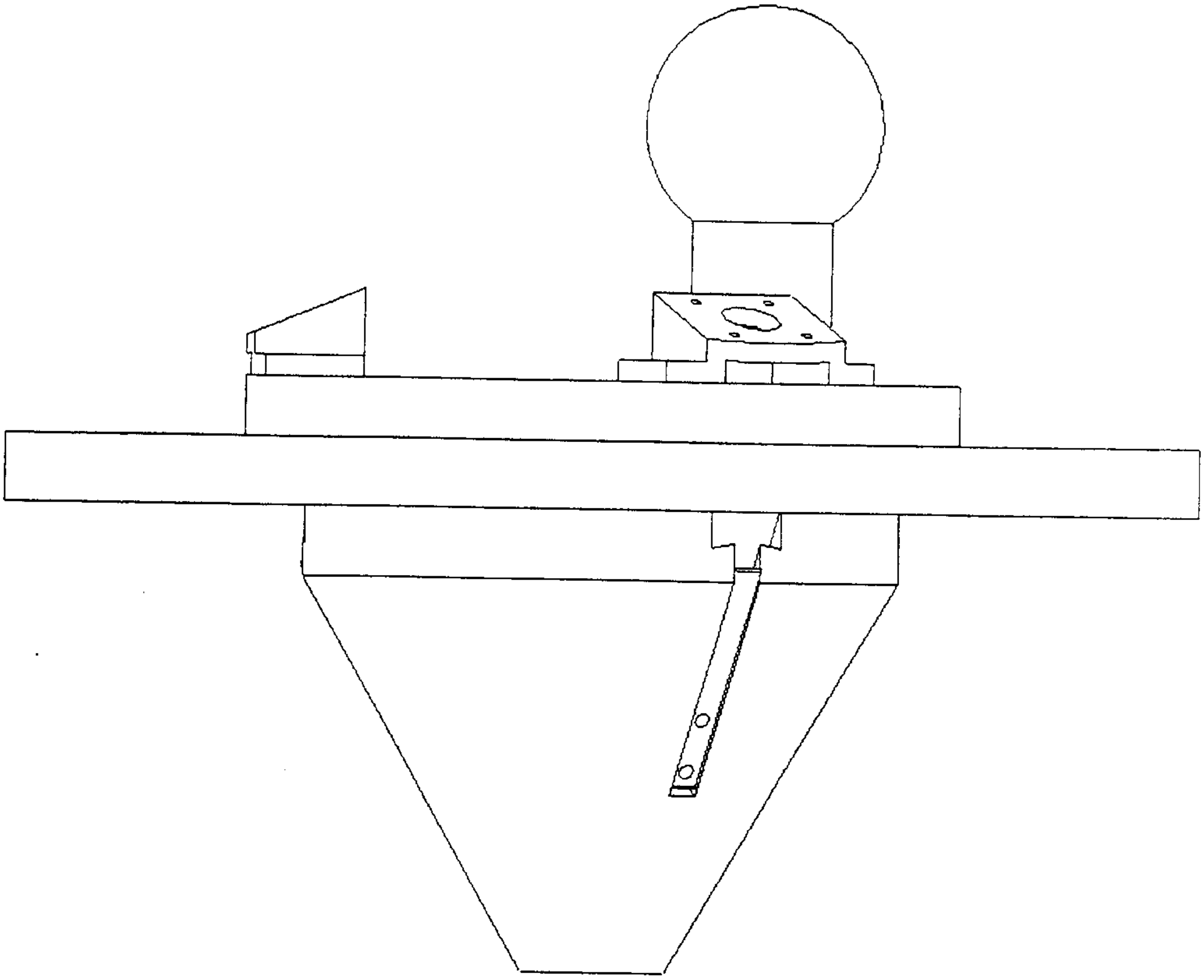


Figure B9: Side View of Boot In Chock Showing Clamping Devices Released

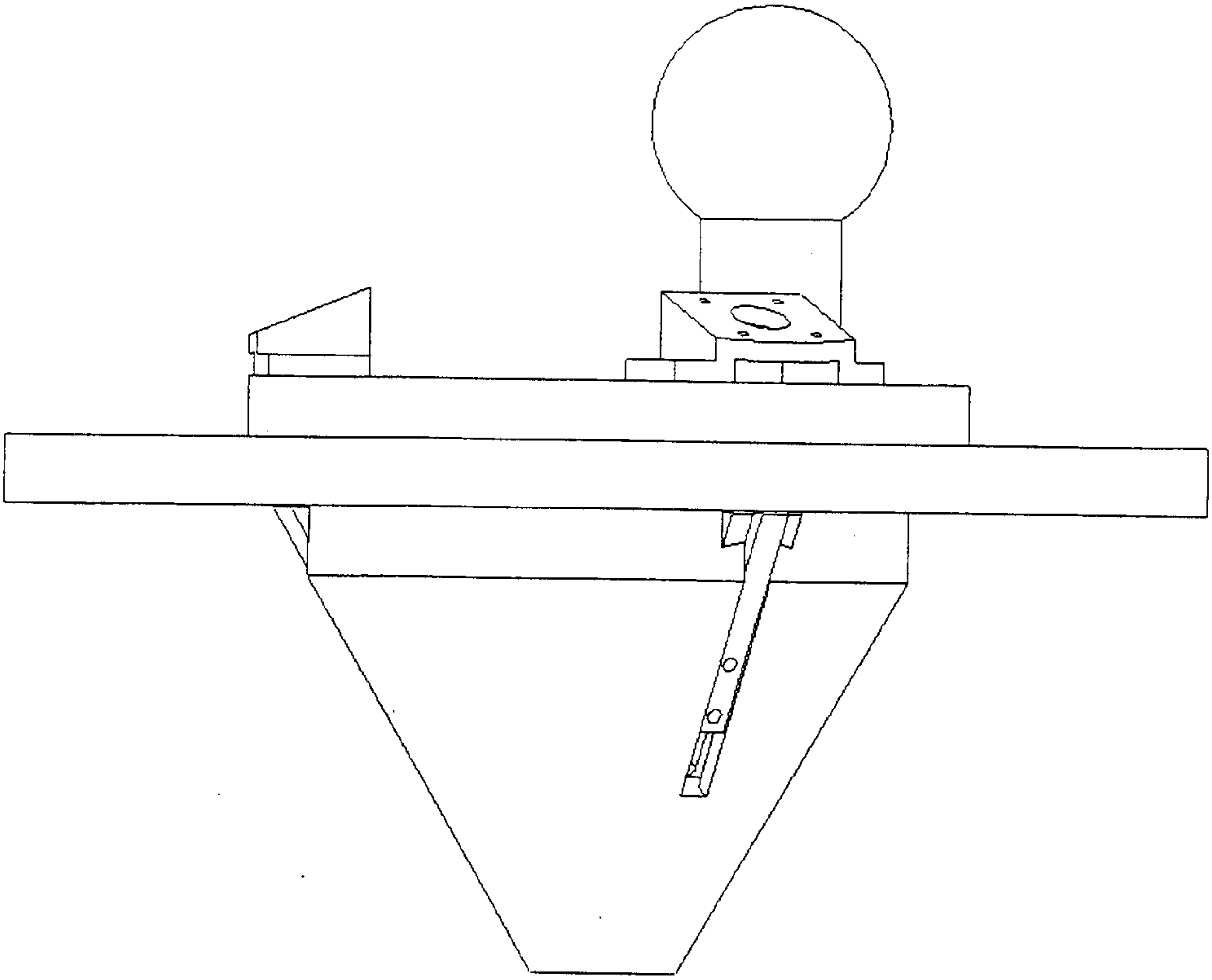


Figure B10: Side View of Boot in Chock Showing Clamping Devices Actuated

Buckling Considerations for the Telescoping Truss

Purpose:

The members which comprise the truss system are susceptible to buckling when they are experiencing a compressive load. This calculation will determine the loads that the members are experiencing and the minimum cross section for members experiencing compressive loads.

Fundamental Equation:

From Euler Beam Theory:

$$P_{critical} = \frac{\pi^2 EI}{L^2} \qquad (1)$$

where:

Pcritical = compressive load that initiates first mode buckling

E = modulus of elasticity

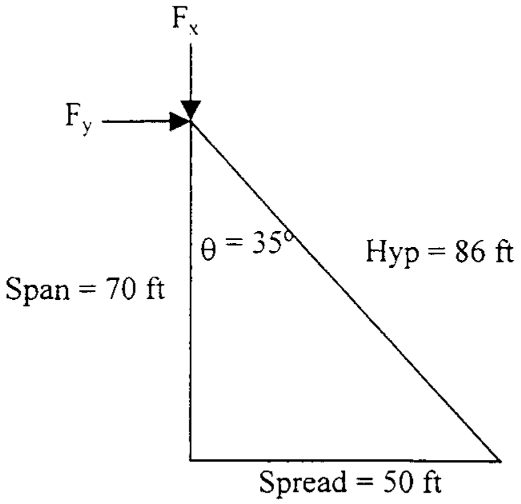
I = area moment of inertia

L = length of the member

Assumptions:

Equation (1) assumes a free-free beam however, the beam in question has clamped ends therefore the result will be conservative. Assume that the truss members are made of steel (E = 30,000,000 psi)

Diagram:



Design Requirements:

$F_y = 200{,}000$ lbs.

$F_x = 140{,}000$ lbs.

It was determined in a previous calculation (Calculation A.18) that these forces represent the following loads in the two members:

$P_{hyp} \approx 350{,}000$ lbs. Compression

$P_{span} \approx 146{,}000$ lbs. Tension

The critical member for buckling is the hyp member. Therefore, the following equations apply only to this member.

Solution:

To solve for the necessary moment of inertia, equation (1) can be solved for I:

I = 1,260 in4

Conclusions:

Assuming a circular cross-section:

$$I = \frac{\pi}{4}\left(r_o{}^4 - r_i{}^4\right)$$

The resulting cross-section has an outer radius is equal to 10 inches with a wall thickness of 0.25 in. In the actual design the beam will have clamped ends therefore these dimensions are conservative.

Angular Compliance of the Truck

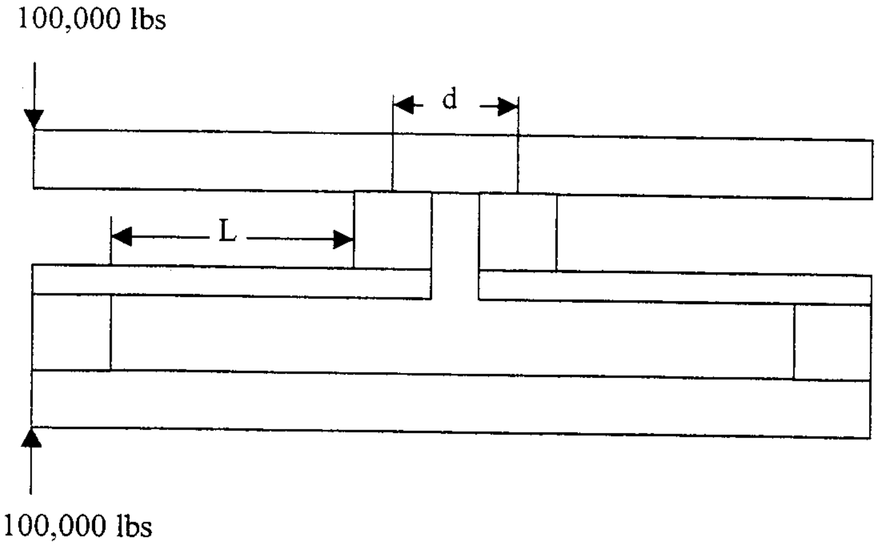
Purpose:

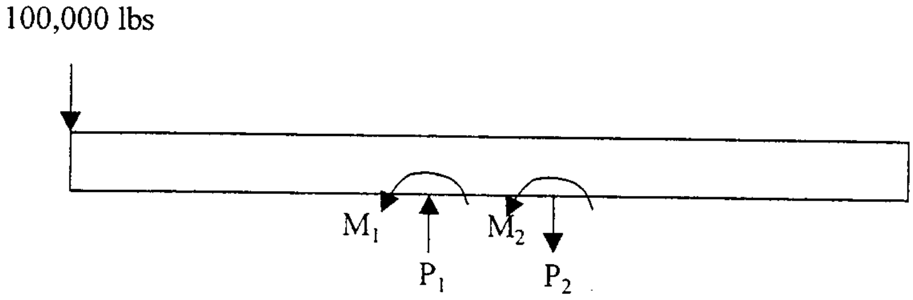
The purpose of this calculation is to determine the geometry of the connection between the truck and the truss. The connection needs to complaint in order to ensure that all of the wheels on the truck contact the rail. This compliance will help alleviate poor loading due to manufacturing variations.

Assumptions:

Assume that the compliant members can be approximated as cantilever beams.

Diagram:





Solution:

Force/Geometry:

$$2.5P_2 - M_1 - M_2 = 125{,}000$$

$$P_1 - P_2 = 100{,}000$$

This results in two equations and four unknowns. However the angle of the end of the beam due to P_1 must equal the angle due to M_1. This implies:

$$\theta_{P1} = \frac{P_1L^2}{2EI}$$

$$\theta_{M1} = \frac{M_1L}{EI}$$

$$\Rightarrow M_1 = \frac{P_1L}{2}$$

$$M_2 = \frac{P_2L}{2}$$

This results in the following resultant forces and moments:

P_1 = 250,000 lbs.

P_2 = 150,000 lbs.

M_1 = 156,000 ft-lbs.

M_2 = 94,000 ft-lbs.

Assume d = 30 in. θ_{max} = 2o

This implies that the total relative deflection of the beams must be 1.02 inches. The total deflection can be determined by adding the displacements due to the shear and moment forces. This results in:

$$deflection = -\frac{P_1L^3}{3EI} + \frac{M_1L^2}{2EI} - \frac{P_2L^3}{3EI} + \frac{M_2L^2}{2EI}$$

When L = 25 inches the width into the page = 50 inches and E = 30,000,000 psi, the moment of inertia = 14.7 in4. The thickness must be 0.25 inches.

Conclusions:

The resulting members will fit into the designated space and will be of an appropriate size to handle the loads that they will transmit.

Power and Energy Requirements for Longitudinal Actuation

Purpose:

This calculation will be used to determine the amount of horsepower needed to provide 200,000 lbs of force while traveling at 3 mph. This should be the maximum consumption experienced by the drive mechanisms providing longitudinal starting and stopping force.

Fundamental Equation:

Power = Force * Velocity

Assumptions:

It will be assumed that the any energy supplied to the motor will be transferred without loss to the application of the desired force and velocity.

Design Requirements:

Force = 200,000 lbs

Velocity = 3 mph

Solution:

The power in horsepower is desired. Therefore the speed will be converted to feet per second.

3 mph = 4.4 ft/sec

Given that 1 hp = 550 ft lbs/sec

P (ft lbs/sec) = 200,000 lbs * 4.4 ft/sec = 880,000 ft lbs/sec

P (hp) = 1600 hp

Conclusions:

This large power requirement shows that it is impractical to expect the system to provide these forces at these speeds. It is also useful to note that this equation is linear in both force and velocity, i.e. 10% of the speed means 10% of the hp required.

Cost Estimates for Telescoping Truss Design

Purpose:

The purpose of the table given is to estimate the cost of all parts, components and sub-assemblies in the main system assembly to provide a cost estimate for the whole system. One truss system will be analyzed in the detailed estimate. The final number will be multiplied by two since two trusses are required to control a Panamax vessel.

Equation:

The cost per item will be calculated based on an estimation technique that includes material weight, cost per unit weight, a fabrication complexity factor and the amount used. The following equation is used for this calculation:

$$ItemCost = weight \times \frac{\cos t}{weight} \times factor(complexity) \times quantity$$

For OEM items, the quantity and cost are the only parameters used. The

Assumptions:

The only assumption was that the cost of steel is $0.25/lb, and the following fabrication complexity factors apply:

Operation	**Factor by which to multiply material cost**
Simple material cut	3
Light machining – drilling, low tolerance lathe operations, simple facing	6
Heavy and high tolerance machining	9

Solution:

The following table provides the itemized cost analysis by assembly. Some of the lower assemblies on the list include totals for one or more sub-assemblies above it. For the total cost, however, only the last group of items followed by the total should be used.

Sub-Name	Part-Name	Count	mass [lb]	Cost/ (Unit/Mass)	Fab. Factor	Item Total
dog	tbar	1	18.7	$0.25	6	$28.05
	tbarclip	1	8.96	$0.25	6	$13.44
					subtotal	**$41.49**

Sub-Name	Part-Name	Count	mass [lb]	Cost/ (Unit/Mass)	Fab. Factor	Item Total
lower	dog	3	na	$41.49	na	$124.47
	cone	1	1321.1	$0.25	9	$2,972.48
					subtotal	**$3,096.95**

Sub-Name	Part-Name	Count	mass [lb]	Cost/ (Unit/Mass)	Fab. Factor	Item Total
upper	cap	1	732	0.25	9	$1,647.00
	ball	1	369.6	0.25	9	$831.60
	cmount	3	24.4	0.25	9	$164.70
					subtotal	**$2,643.30**

Sub-Name	Part-Name	Count	mass [lb]	Cost/ (Unit/Mass)	Fab. Factor	Item Total
chassis	Chassisflange	1	226.7	0.25	3	$170.03
	Chassisarm	1	756.3	0.25	9	$1,701.68
	Chassisflangebrace	6	3.5	0.25	3	$15.75
	Shortpin	1	11.5	0.25	6	$17.25
	Longpin	1	20.8	0.25	6	$31.20
	Wheel	2	na	700	na	$1,400.00
					subtotal	**$3,335.90**

Sub-Name	Part-Name	Count	mass [lb]	Cost/ (Unit/Mass)	Fab. Factor	Item Total
Hclevis	Hclevisback	1	338.4	0.25	3	$253.80
	Clevistaperfemale	1	249.8	0.25	3	$187.35
	Femaleclevisring	1	88.6	0.25	9	$199.35
					subtotal	**$640.50**

Sub-Name	Part-Name	Count	mass [lb]	Cost/ (Unit/Mass)	Fab. Factor	Item Total
Tclevis	Clevistapermale	1	249.8	0.25	3	$187.35
	maleclevisring	2	70.9	0.25	9	$319.05
	tclevisback	1	451.2	0.25	3	$338.40
					subtotal	**$844.80**

Sub-Name	Part-Name	Count	mass [lb]	Cost/ (Unit/Mass)	Fab. Factor	Item Total
splitsocket	splitsocket	1	133	0.25	9	$299.25
	.socketback	1	41.7	0.25	3	$31.28
					subtotal	**$330.53**

Sub-Name	Part-Name	Count	mass [lb]	Cost/ (Unit/Mass)	Fab. Factor	Item Total
socket	splitsocket	2	na	$330.53	na	$661.05
					subtotal	**$661.05**

Sub-Name	Part-Name	Count	mass [lb]	Cost/ (Unit/Mass)	Fab. Factor	Item Total
boot	lower	1	na	$3,096.95	na	$3,096.95
	upper	1	na	$2,643.30	na	$2,643.30
					subtotal	**$5,740.25**

Sub-Name	Part-Name	Count	mass [lb]	Cost/ (Unit/Mass)	Fab. Factor	Item Total
truck	chassis	4	na	$3,335.90	na	$13,343.60
	chassisplate	1	1912.1	0.25	3	$1,434.08
	taperweb	2	155.1	0.25	3	$232.65
	platespring	2	358.4	0.25	6	$1,075.20
					subtotal	**$16,085.53**

Sub-Name	Part-Name	Count	mass [lb]	Cost/ (Unit/Mass)	Fab. Factor	Item Total
Femaleclevis	hclevis	4	na	$640.50	na	$2,562.00
	femaleclevisplate	1	1974	0.25	3	$1,480.50

					subtotal	**$4,042.50**

Sub-Name	**Part-Name**	**Count**	**mass [lb]**	**Cost/ (Unit/Mass)**	**Fab. Factor**	**Item Total**
pivotclevis	tclevis	2	na	$844.80	na	$1,689.60
	maleclevisplate	1	1974	0.25	3	$1,480.50
	shaft	1	668.6	0.25	9	$1,504.35
	innerdisk	1	14.4	0.25	6	$21.60
	outerdisk	1	14	0.25	6	$21.00
					subtotal	**$4,717.05**

Sub-Name	**Part-Name**	**Count**	**mass [lb]**	**Cost/ (Unit/Mass)**	**Fab. Factor**	**Item Total**
slider	slidetube	1	1332.5	0.25	3	$999.38
	slidetubebrace	4	270.7	0.25	3	$812.10
	slidetubeplate	2	338.4	0.25	3	$507.60
	sliderail	4	1499.8	0.25	9	$13,498.20
					subtotal	**$15,817.28**

Sub-Name	**Part-Name**	**Count**	**mass [lb]**	**Cost/ (Unit/Mass)**	**Fab. Factor**	**Item Total**
subtruss	socket	1	na	$661.05	na	$661.05
	boot	1	na	$5,740.25	na	$5,740.25
	subspan	1	488.6	0.25	3	$366.45
	subhyp	1	647.4	0.25	3	$485.55
	subspanflange	1	67.2	0.25	6	$100.80
	subhypflange	1	84.3	0.25	6	$126.45
	bootskid	1	243.6	0.25	3	$182.70
					subtotal	**$7,663.25**

Sub-Name	**Part-Name**	**Count**	**mass [lb]**	**Cost/ (Unit/Mass)**	**Fab. Factor**	**Item Total**
truckjoint	truck	1	na	$16,085.53	na	$16,085.53
	femaleclevis	1	na	$4,042.50	na	$4,042.50
	pivotclevis	1	na	$4,717.05	na	$4,717.05
					subtotal	**$24,845.08**

Sub-Name	**Part-Name**	**Count**	**mass [lb]**	**Cost/ (Unit/Mass)**	**Fab. Factor**	**Item Total**
truss	slider	1	na	$15,817.28	na	$15,817.28
	subtruss	1	na	$7,663.25	na	$7,663.25
	truckjoint	2	na	$24,845.08	na	$49,690.15

spread	1	5000.5	0.25	3	$3,750.38
span	1	6973.2	0.25	3	$5,229.90
hyp	1	8932.5	0.25	3	$6,699.38
slideguide	2	8738.6	0.25	9	$39,323.70
spreadsleeves	2	123.6	0.25	6	$370.80
spreadbushings	2	na	300	na	$600.00
spreadback	2	406.9	0.25	6	$1,220.70
upright	2	951.8	0.25	3	$1,427.70
counterspan	2	1057.5	0.25	3	$1,586.25
counterhyp	2	935.4	0.25	3	$1,403.10
leadhyp	1	1011.2	0.25	3	$758.40
joiner	1	1374.8	0.25	3	$1,031.10
weight	1	155935	0.25	3	$116,951.25
tophyp	1	1646.3	0.25	3	$1,234.73
wench	1	na	35000	na	$35,000.00
slidedriver	1	na	30000	na	$30,000.00
				TOTAL	**$319,758.05**

The total system cost for single vessel capability is equal to $639,516. This estimate excludes the fabrication and installation of the track.

FLOATING LOCK

Analysis for Design

Critical Calculations for the Design (Strength Calculations)

Purpose:

The purpose of this design is to ensure that the structure withstand all possible loadings. The worst loadings in each of the case is taken and the scantlings (section parameters) are found from the required section modulus. Longitudinal bending, pressure load and loads due to the thruster are to be taken care of in the design. The design of the hull connections like the connection of the bottom cross-structure to the wall is very important.

Fundamental Equation:

The section modulus required for a section for a particular bending moment is:

$Z = M/\sigma$

Where Z is the section modulus = I/y

Where I is the moment of inertia of the section and y is the maximum distance of the section from the neutral axis.

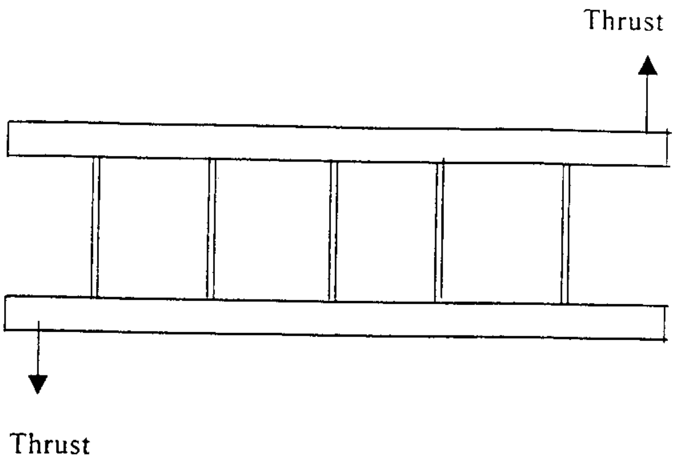
M is the bending moment

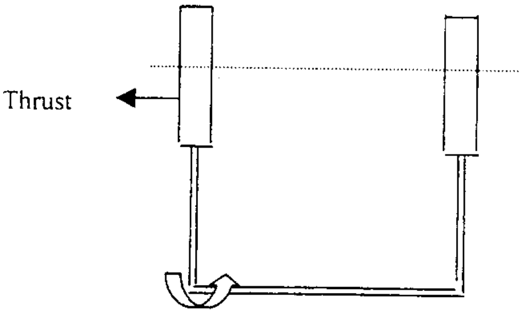
σ is the yield strength of steel.

Assumption:

It is assumed that the failure of any structure will be due to failure by bending. The structures are not analyzed for fatigue or tensile loads.

Analysis of strength of bottom frame caused by moment from the thruster.





Bending Moment

For the design of the bottom cross structure the worst case of bending for the frames is assumed. When the floating lock yaws at full power the thrust of the propeller creates a bending moment in the vertical bottom cross-structure frame. Assuming that a maximum of 40 KN of transverse thrust is required for yaw keeping, the structure should withstand this much of moment. The 40 KN of thrust of the thruster creates a moment of $4.26\text{x}10^5$ Nm. The required section modulus of the frame is given by

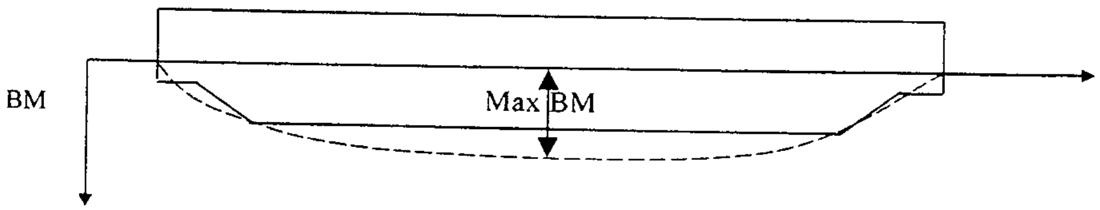
σ is the yield strength of steel, taken as $2.30\text{x}10^8$ N/m^2

So Z is calculated as 1800 cm^3.

As the Bending moment is shared by 6 vertical frames, the required section modulus is around 300 cm^3. A T frame of size T=300x12, F=300x12 is an appropriate section. Where T is the web characteristics of the section and F the flange characteristics (millimeters).

The weight per meter of this section is 56 kg/m. so the total weight of the bottom framing is around 20.0 t.

Analysis of Longitudinal Bending



Longitudinal bending of the wall of the floating wall is to be found. The section modulus of the wall is approximately 0.22 m^3.

The permissible BM = Z x σ = 48000 KNm.

If we calculate the required weight to get this moment from L/4 form the center of gravity, we get

W= 48000/(9.81*75*0.3048), where L = 300ft.

W= 50.0 t

The maximum bending moment caused by a worse case of loss of buoyancy for one compartment is around 45000 KNm. So the structure is safe from bending stresses.

Pressure load

Pressure load on the wall is considered for finding the scantling and frame spacing of the transverse frames. A triangular pressure load is assumed and the required scantling is found as shown below.

$Z = P \cdot S \cdot H \cdot R$

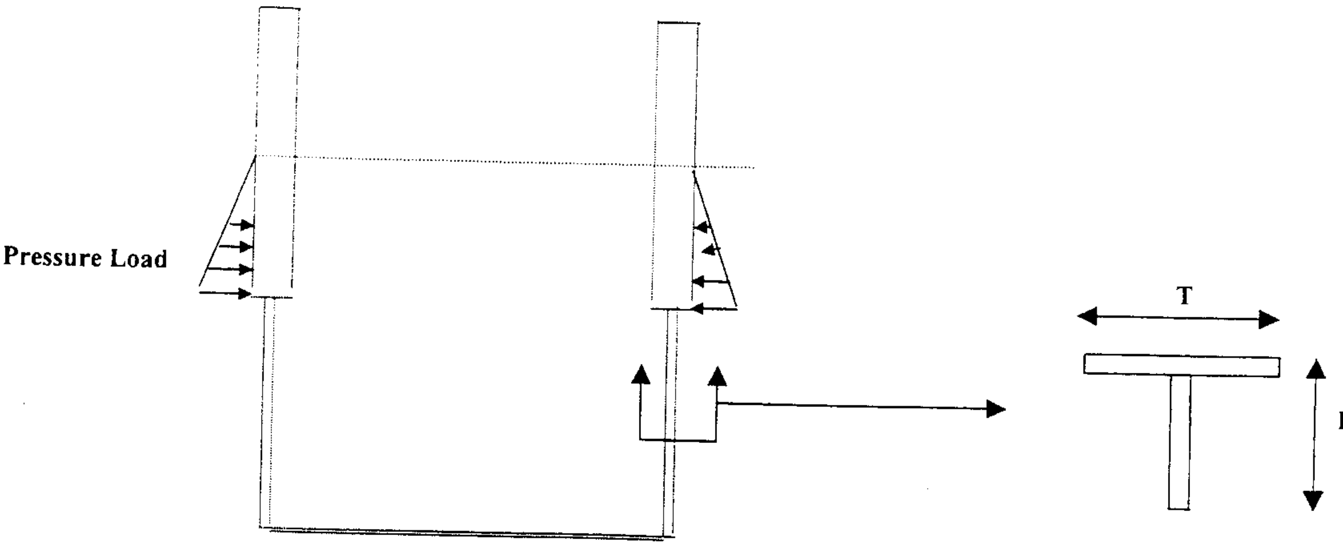
Where P is the pressure at the bottom of the wall.

S is the frame spacing (The frame spacing of the pressure hull). Assumed as 500 mm.

H is the draft of the wall

R is 2H/3.

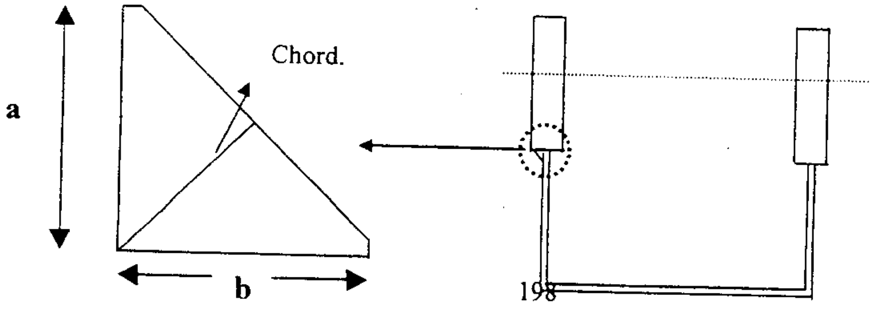
So Z = 180 cm^3



A section of L 150x150 mm is selected. L signifies an angle frame. The scantling is the width of the two angles of the angle frame in millimeters. While calculating the frame section modulus the attached plating was also taken into account.

Bracket Connections.

Brackets are designed for the connections of the frames and walls. In calculating the bracket size the minimum of the section modulus of the connecting members is used. For example the arm length (a or b as shown in the following figure) for the bracket connecting the bottom vertical frame and the wall is found to be around 400 mm. This is designed by taking into account that the section modulus of the frame is around 300 cm3 and the bracket has to have 300 cm3 of section modulus. An arm length of 400 mm will provide a section modulus of 300 cm3 at the bracket chord. The square bracket is shown below.



Critical Calculations for the Design (Weight Calculation)

Purpose:

The purpose of this calculation is to find the approximate weight of the structure. The draft of the floating lock has to be cross-checked based on this result. We are using a design draft of 12 ft. The center of gravity position is also important for the design.

Item	Scantling	Weight	Center of Gravity above Bottom (ft)	Moment from bottom. (ton-ft)
Hull	8 mm	119.23 t	51	6080
Bulkheads + framing	8 mm	11 t	51	561
Machinery	Thrusters 125 HP	10 t	41	410
Bottom Structure.	L 150 x 150 mm	10 t	13.5	135
Ballast	Fore & aft	128 t	34	4352
Diesel		10 t	31	310
		288.2 t		11848

Center of Gravity Position of the lock = 41.11 ft from the bottom line.

This center of gravity position is important for the lock dynamics. As the center of gravity is around 5 ft from the thruster center the hell during the thruster operation has to be calculated.

Critical Calculations for the Design (Buoyancy Calculations)

Purpose:

The design draft of the lock is taken as 2 ft. This is the draft at which the floating lock will be floating when it is fully loaded, i.e. when the fuel tanks are full. At this draft the buoyancy of the floating lock is to be calculated. The purpose of this calculation is to find the buoyancy of the floating lock at draft of 12 ft. But the preliminary weight estimation shows that the weight of the floating lock is approximately 288 t (refer table on the previous page), so ballast of 280 t is required to meet the design draft. The ballast amount and the position of the ballast tanks are important, as they will induce a longitudinal sagging bending moment. The ballast is in the bottom center tanks as shown in the General Arrangement plan.

Fundamental Equation:

Wt =Buoyancy

Buoyancy = $\nabla * \rho * g$

Where, ∇ is the volume of water displaced.

ρ is the density of water.

Assumption:

It is assumed that the water is fresh and there is no permanent heel or trim for the floating lock.

Critical Calculations for the Design (Transverse Stability and Heel during operation)

Purpose:

The Heel or the angle of inclination of the floating lock during operation has to be considered, as it will affect the operation of the floating lock. To find this, the transverse metacentric height of the floating lock is to be found. A positive metacentric height ensures floating stability. Assuming that the metacentric height is close to the height of metacentre from the center of buoyancy we do the following calculations. It is the purpose of this calculation to find the transverse stability of the floating lock.

Fundamental Equation:

BM, The metacentric height = I/∇, Where ∇ is the displacement of the lock.

I = Transverse Moment of Inertia of the floating lock.

θ, The Heel in Degrees = $T*LG*g*B*57.2/(\nabla*BM)$

Where T is the Thrust of the thruster = 40 KN.

LG = 5ft. (Distance of the center of gravity from the center of the thruster)

B= Breadth of the lock = 106 ft.

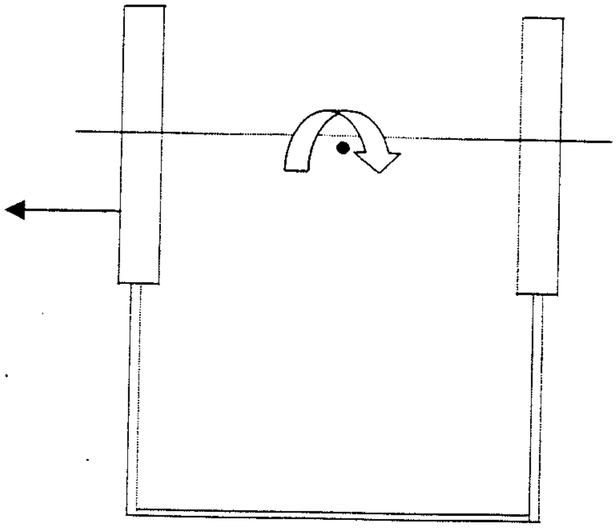
g = The acceleration due to gravity.

∇ = Displacement.

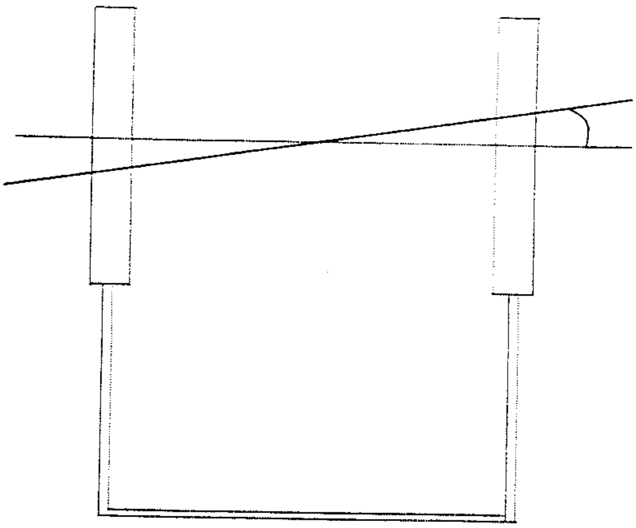
∇ = 576 m3.

Assumptions:

It is assumed that there is no trim to the lock. As the BM is very high it is assumed to be very close to the GM.



Before Thruster is started



After the thruster is operated

Calculations:

$I = 2 * (300*3^3 + 300*3*50^2)\ ft^4 = 127200\ ft^4$

So the BM = 127200/576 = 220.8 m.

As the BM is very high compared to the breadth of the lock we can conclude that the transverse stability is not a problem. The Moment causing heel is due to the moment caused by the thruster about the center of gravity. This can be critical if the heel is excessive and there is a serious problem of propeller emergence. In the case of moment we are assuming the worst case that both the thrusters on one side are damaged and the lock operates on the other two. In this case there will be a moment. The lever for this moment is about 5.5 ft. The angle of steady heel can be calculated by the following formula.

θ, The Heel in Degrees = $T*LG*g*B*57.2/(\nabla*BM)$

Heel = 0.256 degrees.

This is equal to a draft change of 4 inches, which is insignificant. This case is analogic to the transverse stability of a catamaran where the transverse stability is huge owing to the large metacentric height.

Critical Calculations for the Design (Thruster Thrust Prediction)

Purpose:

The thruster is designed to rectify the yaw of the ship caused by any disturbances on the system and to provide towing and stopping of the floating lock with the ship tethered. The thruster must provide adequate thrust to correct the yaw of the ship. The key parameter in calculating the yaw is the mass moment of inertia of the system. Also the hydrodynamic added mass moment of Inertia is very important.

Fundamental Equation:

The basic equation of motion can be written as following.

$M = (I + I_A)\,\alpha$, where M is the moment required for yaw.

I, is the mass moment of inertia of the vessel and the lock.

$I_{A,}$ is the hydrodynamic added mass moment of Inertia of yaw.

For a Panamax ship I is about $0.5*10^{12}$ kg.m^2 (I is appx. Equal to ML2/12 , M mass of the ship and L the length of the ship, all in meters).

I_A is about the same order of I. So the net mass moment of Inertia is about 10^{12} kg.m^2.

α, is the angular acceleration of the system.

Assumptions:

When the thruster is operated the ship starts accelerating and after some time it reaches a steady state. We are assuming that at the peak thrust the lock is capable of producing a yaw rate of 0.2 ft/sec. Assuming that a steady state is reached in 1.0 minute the angular acceleration is set as $7.4\text{x}10^{-6}$ rad/sec (A safe yaw rate for the ship, giving the pilot enough time to respond). So the thrust T =M/L. Where L is the spacing between the thrusters. The diametrically opposite thrusters are used to rectify or control yaw of the ship. In this case we are assuming that there is no coupling of sway and yaw. But usually for floating bodies there will be coupling between surge, sway and yaw. Assuming that diametrically opposite thrusters provide the required moment, a thrust of 40 KN is required. This value will be checked with the performance curve.

Critical Calculations for the Design (Stopping Calculations)

Purpose:

The system should be able to stop the ship. This is achieved by turning the four thrusters 180 degrees. This is one of the important features of the azimuth thruster.

Fundamental Equation:

The total force F acting on the ship while stopping is given by the equation

$F = 4T+R+P$

The distance moved by the ship before stopping is given by the equation

$S = U^2/2a$, where U is the initial velocity and 'a' is the deceleration.

T is the thrust of each thruster = 40 KN (This is not the full power of the thruster, this is the power of the thruster used for yaw control. For towing a full power of 125HP has to be used)

R is the resistance of the ship = 32 KN

P is the added force due to piston effect estimated as around 20% of the total resistance. The deceleration is given by the equation F/M. Where M is the total mass of the ship. This mass is taken as 70000t.

Assumptions:

The ship and the lock is assumed to be around 3 mph.

Results:

Max deceleration = 0.0078 m/s^2

So time taken to stop = $(3/0.0078)*(5/18)$ = 3 min appx.

Therefore $S=0.833^2/(2*0.0078)$ = 145 ft approximately.

So the pilot has to reverse the thruster around 180 ft before reaching the gate to stop the ship safely with a clearance of 35 ft from the lock gate.

Critical Calculations for the Design (Diesel Storage Calculations)

Purpose:

The diesel tank has to be designed by calculating the amount of diesel required for the thrusters. Proper storage is to be provided on the floating lock.

Fundamental equation:

The diesel required in tons is given by the formula

W_D = SFC x P x h x 10-6 t

Where W_D is the diesel amount in tons

SFC is the specific fuel consumption, taken as 180 g/kW/hr.

P is the Power in kW

h is the total hours of operation, = 24x7 hrs per week.

So the total required amount is around 3 tons in a week.

Resistance and the Thruster Power calculations

Purpose:

The resistance and thruster power calculations are to be undertaken for the proper prediction of the thruster capacity and the speed of transit. There will be a remarkable increase in resistance of the ship when the ship enters the lock from the outer canal. This can be found using the following formula. The piston effect and other drag effects should be included.

Fundamental Equation:

V_L/V_C = Sqrt (A_X/R_H)

Where V_L is the speed of the ship in the lock.

V_C is the speed of the ship outside the lock.

A_X is the Lock cross-section area.

R_H is the ratio of A_X to the wetted perimeter of the Panamax ship.

In the Resistance calculation of the floating lock we have used the famous ITTC formula. In this formula the friction coefficient is found from the Reynolds number. As there are no effects of waves the major part of the resistance would be from frictional resistance. Resistance is found as a function of the speed. The effects of the lock and currents are included later.

$C_F = 0.445/(\log_{10} Re)^{2.58}$ where Re is the Reynolds number.

Reynolds number is very high of the order of 1×10^8, which shows that the flow is considered as turbulent.

$$\text{Resistance} = C_F \times 0.5 \times \rho \times S \times V^2$$

Here Re is the Reynolds number. V is the speed of system. ρ is the density of water which is taken as 1000 kg/m3. S is the total wetted surface area of the ship and the floating lock. The value of S is taken as 16000 m2.

Assumptions:

The special case is studied for a tanker. For a tanker the wetted perimeter is approximately 45 meters. The area of cross-section of the canal is around 576 m2. So from the calculation we can see that there is an increase of resistance of about 2 times when the ship enters the lock from the canal. With the inclusion of bottom effects and piston effect the net resistance is assumed to be increased 3 times in the canal. The plot of the power of the thruster versus the speed shows that the power required is highly increased inside the lock.

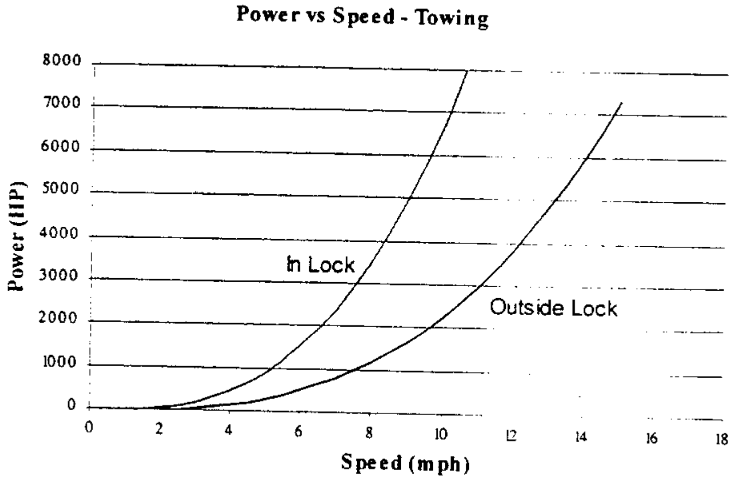


Fig 1. The plot of Thruster power versus towing speed.

Discussion on Thruster Performance:

From the figure we can see that with 4 thrusters of power 125 HP each, i.e. 500 HP total, we can get a speed of towing of 4 mph in the lock, whereas we can get around 6 miles outside the lock. The gain for the lock alone is not remarkable compared to the whole system basically for two reasons. The main reason is owing to the high area of cross section of the ship to the lock cross-section area. The second reason is owing to the high piston effect created by the ship. The floating lock itself has a very low C_B, Block Coefficient, and so it has a reduced added resistance inside the lock.

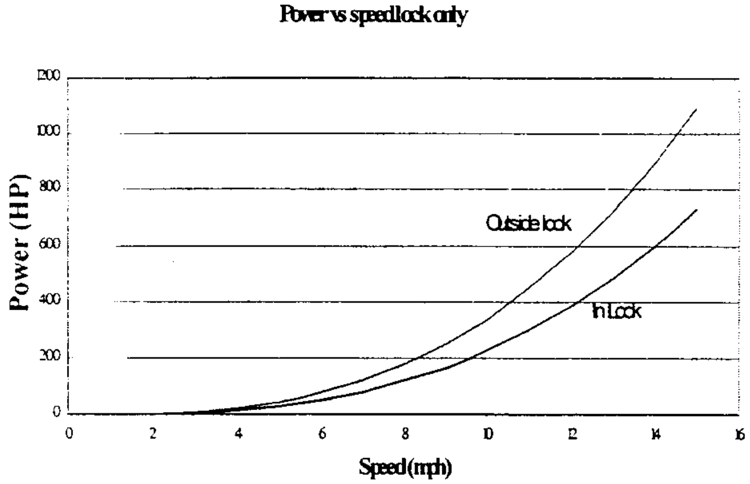


Fig 2. The plot of Thruster power versus speed of the lock.

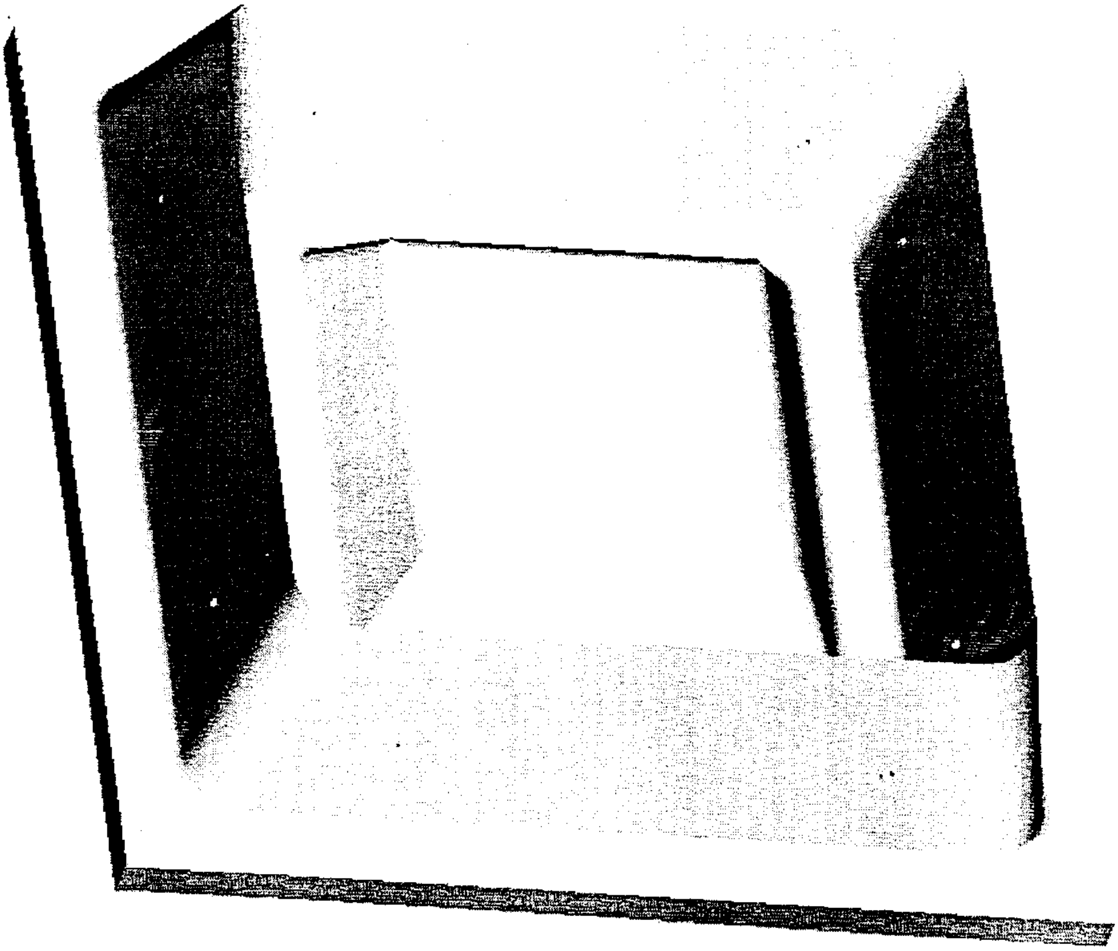
From the above graph we can see that the operation of the floating lock individually can be done around 11 mph inside the lock and around 13 mph outside the lock. The performance of the floating lock is good outside the lock compared to a tug as the maneuvering capabilities is much higher for the floating lock.

Cost Estimates

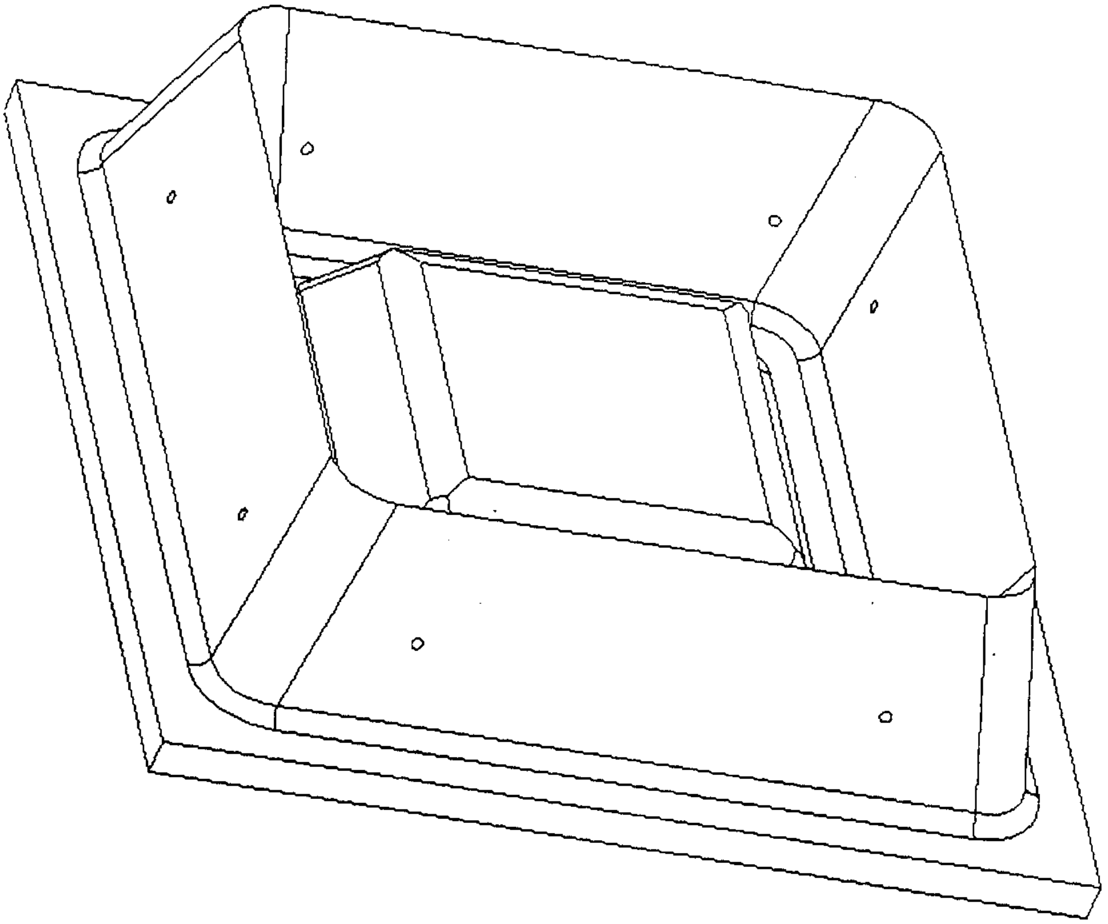
Purpose:

The purpose of this estimate is to get the rough estimate of the cost of the floating lock including the construction cost and the cost of the machinery. This estimate does not include the cost of maintenance.

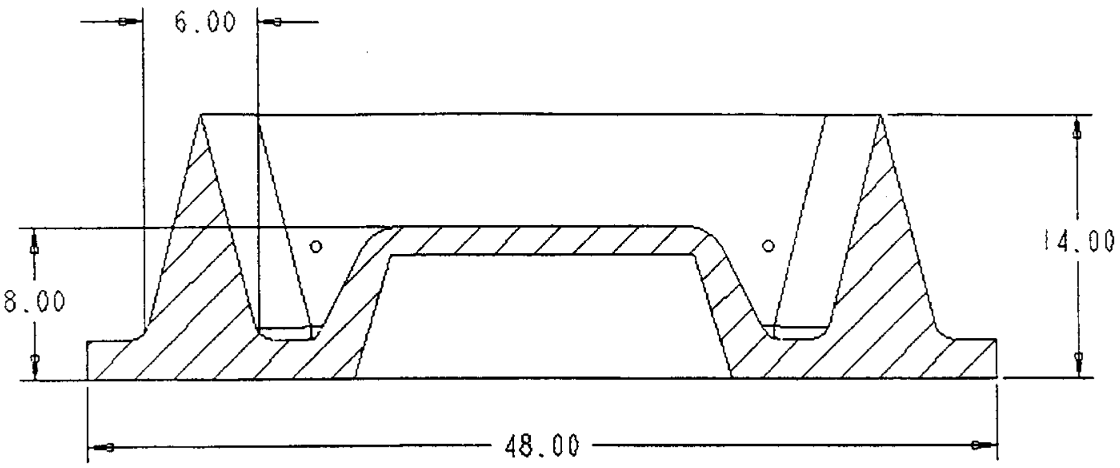
Item	Quantity	Unit Price	Total Price
Steel	300 t	$500 per ton.	$150,000
Construction cost	300 t	$2500 per ton.	$750,000
Thrusters	4 Nos.	$400,000	$1600,000
Machinery	2 Ballast pumps	$50,000	$50,000
Control Mech.	4 Thruster controls	$15,000	$60,000
Total			**$2.6 million**



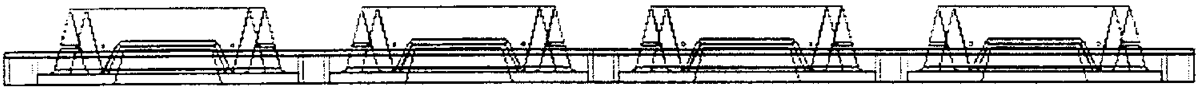
A1 Single Viscous Cell



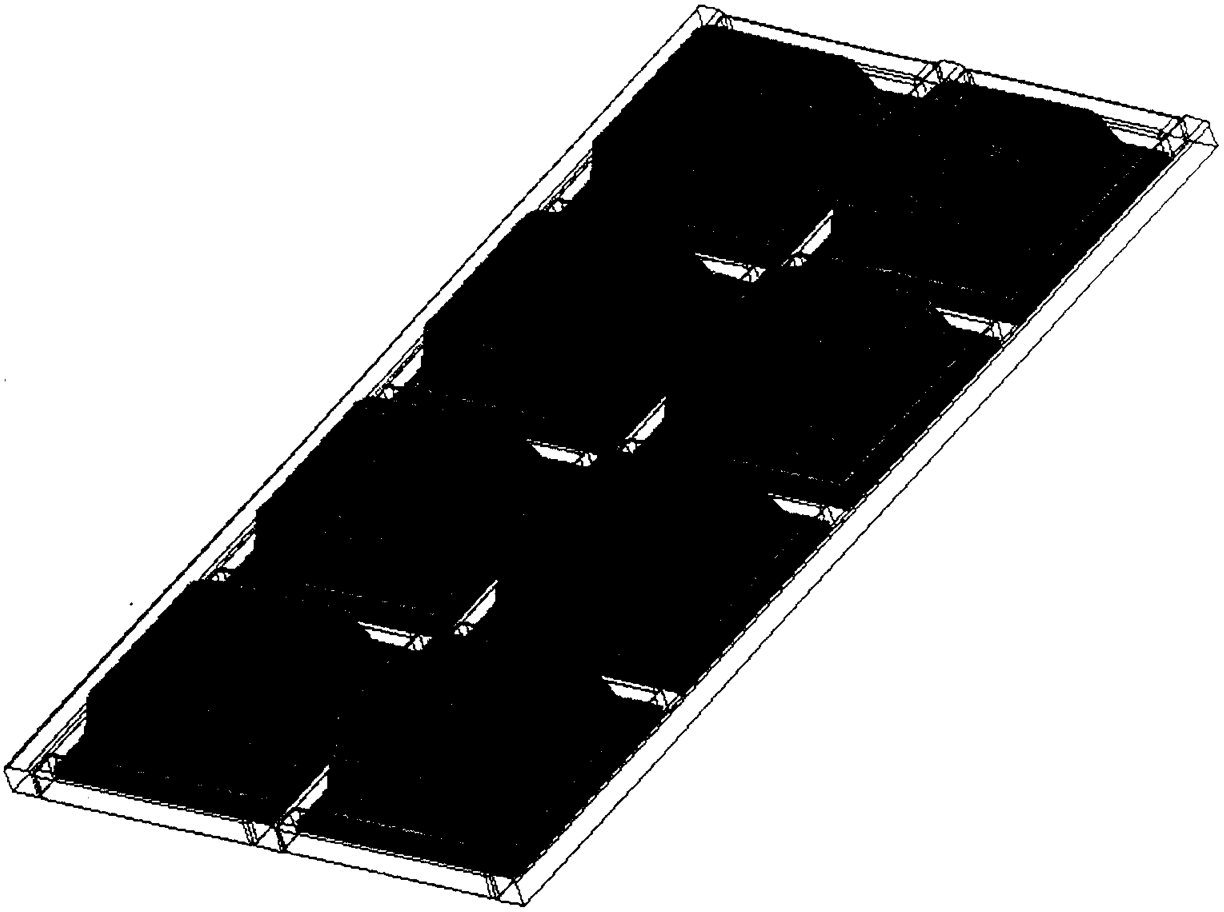
A2:Line-Drawing of a Single Viscous Cell



A3:cross-section of Viscous Cell



A4:Side View of Viscous Cells Assembled in a Grid



A5:Isometric View of Cells Assembled into the Grid

Cost Analysis

This analysis is based on developing the cost for one lock.

Component	**# Needed**	**Unit Cost**	**Total**
Viscous Cell	6250	$60	$375,000
Grid Members	25000 Feet	$1.25	$31,250
Winches	4	$250,000	$1,000,000
Total			$1,406,250

SILL MODIFICATION

Summary

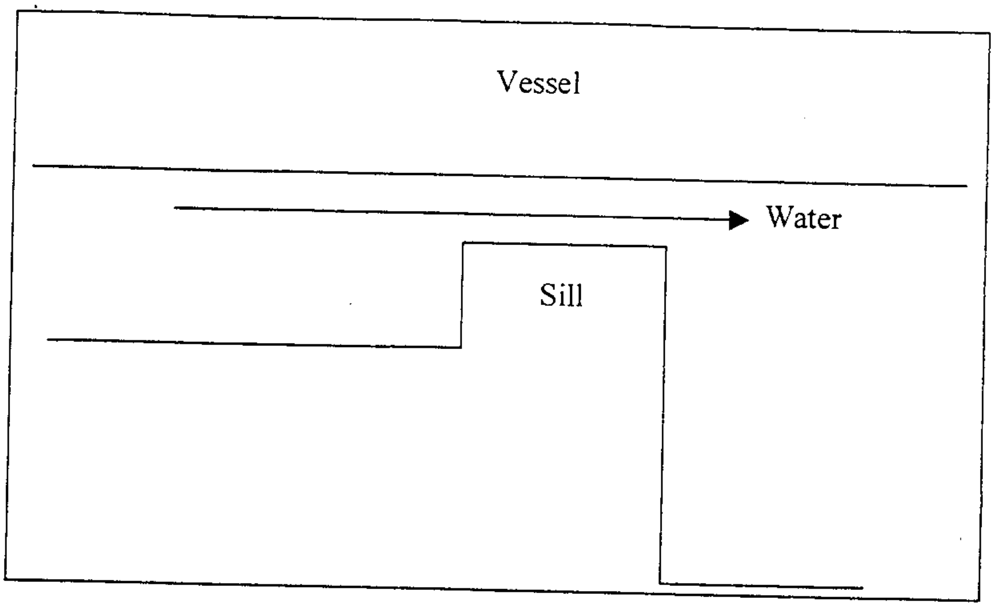


Figure 22 Vessel entering the lock from the low water side.

The "piston-effect" is a problem when large vessels with high blocking coefficients enter and exit the locks especially at low water levels. The piston-effect increases the time and power that is required to enter and exit the locks. Also, squat is a problem that is directly related to the problem of the piston-effect. The geometry of sill can greatly influence the magnitude of the piston-effect. The modification of the sill geometry to reduce the turbulence of the flow of water around the vessel as it moves into and out of the lock, can greatly reduce the problems associated with the piston-effect in a very cost effective manner.

Description

The sill acts as flow restriction as water flows past the vessel as it enters and exits the lock. The magnitude of this flow restriction is a result of the actual flow area that is available for the water to flow through. The flow is further impeded by the current sill geometry, which has sharp corners i.e. it does not have "smooth lines." This leads to high-pressure differentials necessary to move the water past the ship resulting in high forces needed to move the ship. The modification of the sill geometry or smoothing its lines can greatly reduce the pressure needed to induce flow past the ship.

It is often useful to look at a simplified case to determine the effects of modifications on complex systems. For this case let us consider the case of water entering a one inch diameter pipe from a large reservoir. If the pipe has sharp corners at the entrance, it has an entrance flow loss of twice that of a pipe with the entrance rounded with a 1/32" round. This shows how even rounding the corners of the sill could greatly reduce the flow losses associated with it. Another modification that can help is flow "ramps" can be installed to make the flow area slowly constrict and slowly expand to reduce turbulence. These modifications are shown in Figure .

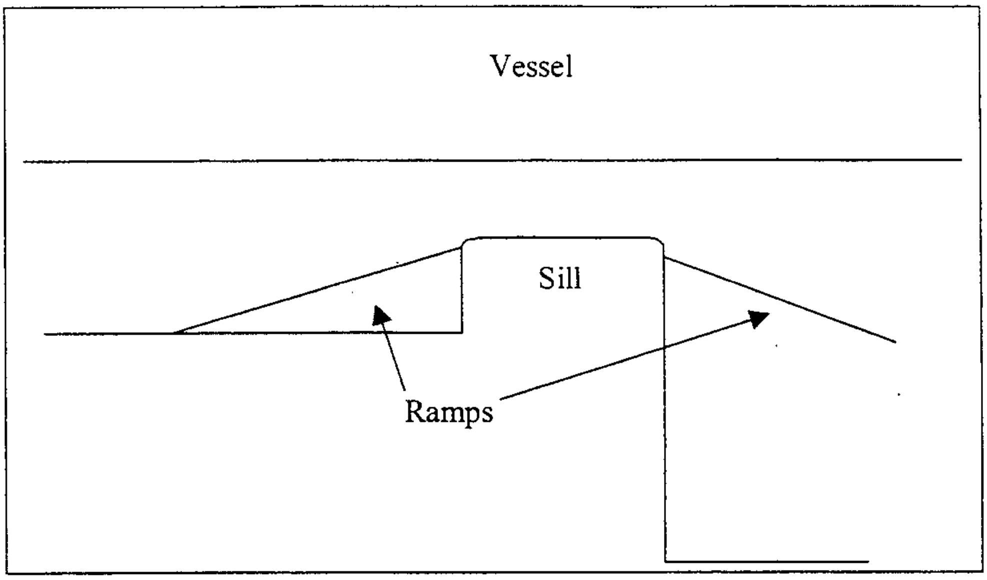


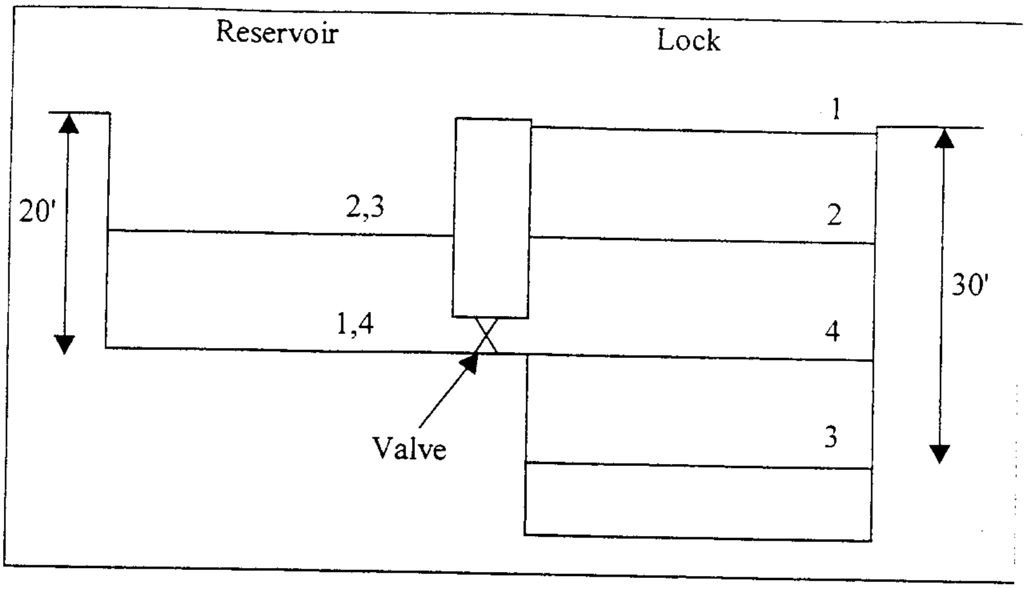
Figure 23 Modified Sill

Conclusions

The modification of the sill can greatly reduce the problems associated with the piston-effect, surge, and suction. This can be achieved with simple and inexpensive modifications to the sill such as rounding the corners with a diamond saw, or the installation of flow ramps made of painted mild steel that are bolted into place. The actual design of these rounds and flow ramps can be optimized using readily available finite element software packages. The benefits of these modifications can also be accurately approximated using these software packages.

WATER CONSERVATION CONCEPT: WATER RESERVOIR

Summary



A significant concern for future canal operations will be the efficient utilization of water resources. With projections for near-term growth in ship traffic, implementation of water conservation methods must be considered. The following concept illustrates a potential solution addressing these concerns.

Description

This concept uses a water reservoir that is placed next to each lock. The reservoir has the same length and width as the lock and the depth is 20 feet below the high water level. The reservoir is connected to the lock by a culvert, which is valved. The movement of water is entirely motivated by gravity. The reservoir need not be located immediately adjacent to the lock the only requirement is that its depth is 20 feet below the high water level and the top the reservoir is at a maximum of 10' below the high water level.

This concept can save up to 1/3 of the water used in lock operations if a reservoir is placed beside each lock. The operation is as follows:

1. The lock and reservoir are at level 1. This corresponds to the lock being full and the reservoir being empty. The valve is then opened and the levels equalize at level 2.
2. The valve is then closed and the lock is drained in the present manner. The lock is then at the low water level and the reservoir is full at level 3.

3. The valve is then opened draining the contents of the reservoir into the lock the levels are then at 4.
4. The lock can then finished being filled in the present manner such that the levels are then at 1, completing the process.

The theoretical maximum amount of water that can be saved using one reservoir is 50%. This is achieved by using a reservoir that is very wide. However, multiple reservoirs can be used to approach 100% water savings.

It is important to note that if this system is built it need not operate until water saving measures are necessary. Also, due to continuity considerations if this system is used on one lock it will need to be used on the remaining two locks on that side, i.e. if it used at one side Pedro Miguel Locks it will need to be used on one side of the Miraflores Locks.

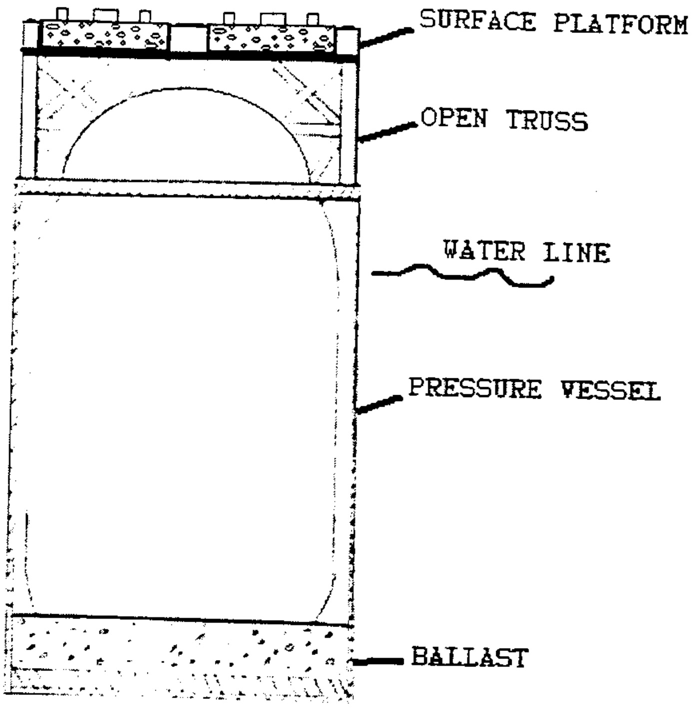
Conclusions

Water saving procedures can be implemented with moderate capital costs and low maintenance and operation costs.

- Easily adaptable to the current lock system
- Low power requirements
- Flexibility with number, size, and location of water reservoirs
- Independent operation (the system can be operated only when needed, and independent from the current lock system)

This concept is viable means of saving water in Panama Canal.

FLOATING APPROACH WALL



Summary

The floating approach wall system allows any position control system to initiate control before the ship enters into the close proximity of the non-compliant concrete lock structure. At each lock entrance, two floating structures extend out 1000 feet. These structures allowing the position control system to travel beyond the confines of the lock chamber area. The approach walls pivot about one end and have thrusters that allow them to position themselves and avoid collisions with the ship. This discussion assumes that the current locomotive system will be retained to control ship position. However, the floating wall concept can supplement any position control system. In general, they provide a safer initiation of control while facilitating full control at an earlier time than the current system.

System capabilities

The floating approach wall system is designed such that all ships that the lock currently handles (or all ships that future locks will handle) can safely pass through. The wall is designed to accommodate up to 200 tons of equipment that is used by the lock position control system. The floating approach wall offers a compliant datum for pilots to target with the additional capability initiating position control "simultaneously" from both sides of the ship.

Operational Description

Pilot Interface

The pilot will have radio contact with the operator of each approach wall. The pilot can issue instructions to the wall operators. However, normal operating procedures will be straightforward and should not require detailed instructions from the pilot. The pilot will have radio contact with, but no direct control of the approach wall. The pilot is still responsible for giving instructions to the locomotives in the current system.

Human elements in the system

A human operator is needed for each approach wall. He will initially engage the thrusters upon the pilot's command and will then disengage them when the wall is half way to its final position. He will then proceed with the standing orders to engage the thrusters only if the ship-to-wall clearance drops below some pre specified minimum.

Entrance (Gaining control of the vessel)

As a pilot approaches a lock that has the floating approach walls, it will look very similar to the existing system with a center approach wall except there will be an additional approach wall on the other side of the ship. Initially, the additional approach wall will be pivoted such that the distance between the two walls at the point of entrance will be significantly greater than the beam of the ship. It will look a little like half a funnel. The wall on the pilot's left is parallel to the lock walls, while the wall on his right is "flared" out. The pilot will steer the ship to the floating approach wall on his left, just like he approaches the current lock system. When it is evident that the ship is on course (port cables are being initiated), the outer approach wall begins to close in on the ship using its thrusters. Soon afterwards, cables are initiated from the approach wall on the starboard side of the ship. As soon as the fore locomotives have control the wall thrusters are turned off and the locomotives from both sides winch in from a "hold" position. This reeling in will bring both approach walls into final position (parallel to the lock walls). Additional locomotives are added as the ship continues "straight ahead". All the locomotives maintain a "hold" position. When the fore cables begin their control action, the role of the approach walls' thrusters changes. From this time on the wall thrusters are only engaged to avoid immediate collision with the ship. Both fore and aft mooring cables will be fully operating by the time the approach walls are in parallel position...before the ship is within 250 ft of the lock chamber. The ship continues moving forward under complete control. Each locomotive has the simple instructions to reel in from a "hold" position until the approach wall is parallel to the ship. There is no reliance on tugs at any time during normal operation.

Modifications to Existing Infrastructure

The approach wall concept can be partially implemented by leaving the present center wall in place and adding a single approach wall to the side-wall of each lock channel. The pivot post can be poured in place and joined to the end of the existing side-wall. The locomotive track could then be extended over the pivot post and joined to locomotive track already on the floating wall. So, modification would entail only an addition to the existing infrastructure and can be performed on one channel at a time.

System Robustness

The following modes of failure have been considered: thruster failure, pivot post failure, hull breech, and operational error. Thruster power can be distributed over any number of thrusters to increase the overall reliability and account for off-line units. The fully loaded structure is buoyantly stable so that the wall would float, and could be towed out of the way, in the even of complete failure of the pivot posts. The pressure vessel is compartmentalized and its buoyant factor of safety can be increased 10% for each additional foot of draft.

In the event of complete failure of any subsystem. The side approach wall can be moved out of the way and the "center" approach wall rigidly anchored. Then operation can continue just as in the existing system.

Conclusions

The floating approach wall is a supplemental system that can be added to any other position control system. It allows much safer initiation of control at an earlier time than the current system. Capital costs include the cost of the wall structures as well as the cost of a maintenance facility.

Summary

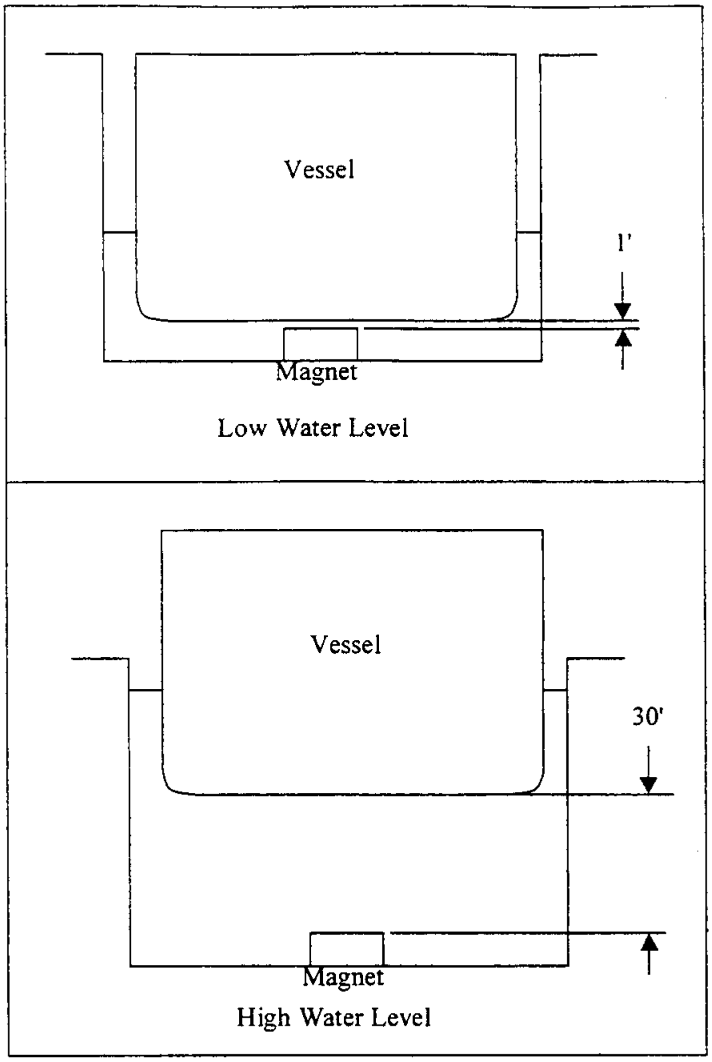


Figure 24 Magnet "Air Gap" at Different Water Levels

The use of electromagnets placed on the lock floor for vessel positioning is an innovative idea. The use of the buoyant force to counteract the electromagnetic attraction yields a stable system without the use of feedback control. However, the nature of electromagnetic phenomena presents many design challenges that need to be addressed in order to make it an attractive alternative for use in the Panama Canal.

Description

Electromagnets are placed in the middle of the canal mounted on the canal floor (Figure 1). The electromagnets attract the hull of the vessel: causing the vessel to remain in the center of the lock. The longitudinal position of the vessel can be controlled by turning off the magnets behind the vessel and turning on the magnets in front of the vessel to tow the vessel or vice versa for braking the ship.

The main problem with this type of system is that it places large tensile loads on the hull of the vessels which are usually designed to handle only compressive loads. The system will also work only with vessels with hulls made of ferromagnetic materials.

The gap between the magnet and the vessel plays a very important role. The magnetic field strength varies inversely with the square of the distance. This means that to apply the same force at 30 feet as at 1 foot the magnet must be 900 (302) times stronger than the magnet at 1 foot. The magnetic field strength varies with the current squared. This yields a current 30 times larger than that necessary for the 1 foot case. The power required for the gap of 30 feet is then 900 times more than the power required for the 1 foot gap.

The vector decomposition is also an important aspect of the design to consider. Assume the vessel has a one foot deviation to one side of the lock at high water level. Due to the angle constraints the magnet has to attract the ship with 4.2 million pounds of force to provide the 140,000 pound correcting force. This means that the tensile force on the hull is 4.2 million pounds down and this will also increase the draft of the vessel dramatically. If the vessel is at the low water level the force vector is at a 45 degree angle with the vertical so the attraction force needs to be only 200,000 pounds. This means that the current necessary to provide the proper correcting force at high water level is approximately 140 times ((4,200,000/200,000 * 302)0.5) that required at one foot when the force/geometry considerations are added. This means the power requirement is about 20,000 times higher than the power required at one foot.

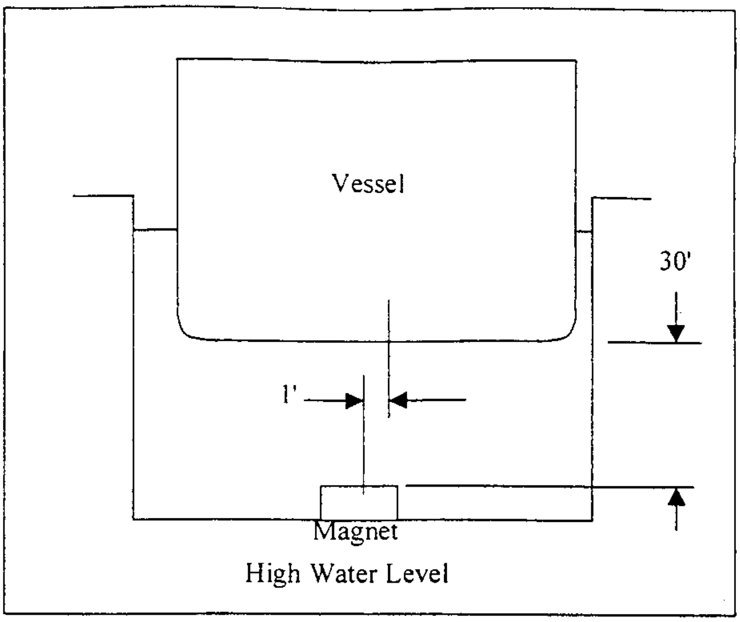


Figure 25 Vessel At High Water Level and With a 1' Lateral Deviation

Conclusions

The main advantage of using magnets to position the vessels is the Panama Canal is the lack of a need for connections to the ship. This could increase the throughput of the canal and reduce the manpower necessary for a vessel transit, however, the design challenges presented in this summary point to areas that need to be addressed. The issues associated with lateral control can be extended to longitudinal control due to the similarity of the loading conditions.