

Design of a Waterjet-Propelled Barge: A First Computer Modeling Project*

MICHAEL REX MAIXNER

USAF Academy, Department of Engineering Mechanics, CO 80840, USA.

E-mail: Michael.Maixner@usafa.af.mil

A computer project for an introductory design course is presented which entails preliminary calculations associated with a rectangular, waterjet-propelled barge. It combines ideas of computer modeling, tradeoffs, iteration, and optimization into a problem that can be solved without requiring an extensive technical science background. This quasi-steady problem requires recalculation of various parameters at each time step, thereby necessitating looping. Variations on the design are suggested as possible modifications for different design groups within a class or from one term to the next. With suitable documentation and assistance to students, the project could also be used in an introductory computer course.

INTRODUCTION

MANY SCHOOLS OFFER an introductory course in computers early in their engineering curricula, during which students are exposed to spreadsheet and word processing software, and perhaps to a programming language. After this course, students develop proficiency through continued use of word processing and spreadsheet software, but usually allow their programming skills to stagnate [1]; the ability to think in terms of iteration, looping, or program modules is soon forgotten. The reinforcement of these skills is one of the key objectives of the project described here.

Numerous examples exist of design projects which involve iteration or looping through repetitious calculations or repeated passes through the 'design spiral': rockets [2], airplanes [3, 4], hydrofoil craft [5], conventional displacement ships [6], and many others. Of these, [2-4] are amenable to solution by students with limited exposure to the design process, while others require very detailed design packages [5, 6]. What was required for students in the Marine Systems Engineering (MSE) program at Maine Maritime Academy (MMA) was a relatively simple computer design project (with at least a pretence of nautical flavor) that was sufficiently detailed to require looping and which tied together much of the coursework covered to date. Without a computer, even simple changes to the analysis would take an inordinate amount of time.

BACKGROUND

The design sequence for students in this five-year design (plus Merchant Marine officer's license) curriculum is comprised of five courses:

Es180 Engineering Design I (freshman year: basic introduction to engineering design, including fabrication of a working model), Es380 Engineering Design II (junior year: more analytical and structured approach to the design process), Es430 Machine Component Design (senior year) and Es598/Es599 Capstone Design Preparation/Project (fifth year: a 2-semester capstone experience). Whereas Es180 provides students with an intuitive sense of many aspects of the design process, Es380 introduces them to a more structured approach and includes the use of computers.

Students enrolled in Es380 will normally take Es490 (Computer Methods in Engineering Analysis) and Es245 (Engineering Fluid Mechanics) concurrently. (During many semesters, an Es490 project early in the semester was to perform an altitude versus time analysis for a missile whose mass (fuel) was expended during the boost phase; many of the looping concepts required in the Es380 barge project were included in the missile project.) As freshmen, they would also have taken Cs150 (Structured Problem-Solving Using Computers) which exposes them to spreadsheets and the BASIC programming language. Technical communication is also stressed in Es380, since preparation and delivery of the final report is also a part of the design process. In many respects, Es380 is a 'mini-capstone' course, tying together much of what they have learned to date.

The design problem is typically assigned a weighting of 20% of the overall Es380 course grade. Of this percentage, 10% is assigned to the written report, 5% to the oral presentation, and 5% to the design notebook.

THE DESIGN PROBLEM

The assignment given to each design group of three students requires computer simulation of a

* Accepted 1 January 2005.



Fig. 1. Waterjet discharge on the bottom of the craft built for a freshman introductory design course.

rectangular barge carrying a water tank which provides gravity feed to a submerged waterjet propulsor; the objective is to ascertain the combination of various barge dimensions which will result in the shortest time to travel a given distance (nominally 100 yards). Essentially, the problem involves vertical force equilibrium between barge displacement and buoyant force, and horizontal force equilibrium between drag, thrust, and acceleration forces; all are changing until the tank is emptied. The barge problem was developed by Dr. Harold Alexander at MMA and was based on a rolling land cart model used at New York Maritime Academy. In several years, freshmen have been required to build and test a vehicle which will traverse the width of the college's swimming pool in minimum time. Some design teams have chosen a gravity-fed waterjet (see Figs 1 and 2), very similar in concept to the junior computer design project.

ASSUMPTIONS

As freshmen, students may have utilized 2-liter soda bottles as hull flotation devices for their projects (Figs 1 and 2); for the junior computer simulation, however, they are required to employ a



Fig. 2. Students filling the water column with 'fuel'.

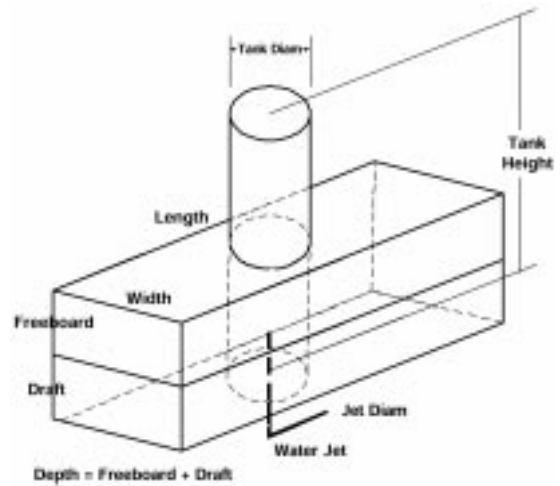


Fig. 3. Barge nomenclature.

rectangular steel hull and a right-circular cylinder as the water reservoir, as depicted in Fig. 3.

Additional specific assumptions include:

Barge

- Starts from rest in fresh water
- Length is twice the width
- Depth must be sufficient to produce adequate buoyancy to support the vessel weight

Water tank

- Circular cross-section
- Open top
- Centered on barge longitudinally and laterally
- Neglect-free surface effect of water in tank
- Height limited only by stability concerns
- Diameter must be less than or equal to the barge beam
- Bottom is situated at the bottom of the barge (it may not be elevated to provide additional potential)
- Fluid friction drag through the tank and exit may be considered negligible
- Barge and tank are constructed of 1/4-inch thick steel plate
- Aerodynamic and hydrodynamic drag must be considered, and are of the form $F_{\text{drag}} = \frac{1}{2} \rho V^2 A_{\text{projected}} C_{\text{drag}}$, where ρ is fluid density, V is velocity, $A_{\text{projected}}$ is the projected area, and C_{drag} is the appropriate drag coefficient.
- Thrust may be calculated from linear momentum theory as $T = m(V_{\text{jet}} - V_{\text{barge}})$, where m is the mass flow rate of water issuing from the jet, V_{jet} is the velocity of the water from the jet (obtained from Torricelli's theorem), and V_{barge} is the velocity of the barge
- No wind, tide, current, or waves
- Ambient air temperature 70°F
- 100-yard course
- Added mass effects are negligible
- Simple Eulerian method to move from one time-step to the next
- Design is to be optimized on tank height, tank diameter, and jet exit diameter

METHOD OF ANALYSIS

As water issues from the tank, the following occurs:

- Increase: hydrodynamic drag, aerodynamic drag
- Decrease: total weight (displacement), buoyant force, hydrostatic head in tank, height of center of gravity

To the average junior, even this short list may appear daunting. It may be worthwhile to allow

the students a short period to ponder their approach to the problem prior to suggesting they think of it in terms of a flowchart—this is a great point about which to generate discussion. It is not until they begin to think in terms of a series of loops (Fig. 4) that they realize that a logical solution is actually very simple. Students are encouraged to begin with as simple a model as possible, gradually increasing the degree of sophistication as they are convinced that their results are reasonable. The ability to make sense of their results is, of course, another key learning point. Another good discussion point is the choice of timestep size—a sensitivity analysis discussion is usually very productive.

The problem does not lend itself to mathematical optimization—it is usually easiest for students to plot the results of a parametric analysis where one parameter is held constant (say, the tank diameter) and the other two quantities (tank height and jet diameter) are varied. For each combination of parameters, stability must first be checked; if satisfactory, then the time looping must begin. For each timestep, calculate the jet exit speed, the thrust, and the vessel acceleration. Assume acceleration and thrust are constant over a suitably short time interval, and calculate the speed and distance covered at the end of the time interval. Continue repeating these calculations until the total distance covered is 100 yards. In addition to the time required to cover the 100 yards, other deliverables include plots of distance vs. time, speed vs. time, thrust vs. time, thrust vs. distance, tank depth vs. distance.

Any programming language (FORTRAN, BASIC, QBASIC®, VISUAL BASIC®, C++®, etc.), spreadsheet, or problem-solver (MathCad®, TK Solver®, etc.) may be used in the solution of this problem. If a spreadsheet approach is adopted, unless Visual Basic for Applications® is used, key parameters will have to be changed by hand and the results recorded for later comparison. If, however, a programming approach is used, then three nested loops (one for each variable dimension) may surround an inner time loop; at the completion of each time loop, the various parameters may be printed out or saved to allow easy comparison of times, along with tank diameter, tank height, and jet diameter. However obtained, the ‘optimum’ design should be checked to ensure that practical considerations are not violated—this is where students become ‘engineers.’

Standard engineering format was demanded of the students in their reports; a suggested format is provided by Moran *et al.* [7]. Of particular importance is the section where assumptions are listed—the students should be ready to defend their model and to explain how the various assumptions might alter their results.

While this project would be ideally suited for curricula in which naval architecture is taught, not all engineering curricula include coverage of the static stability of floating objects—this material

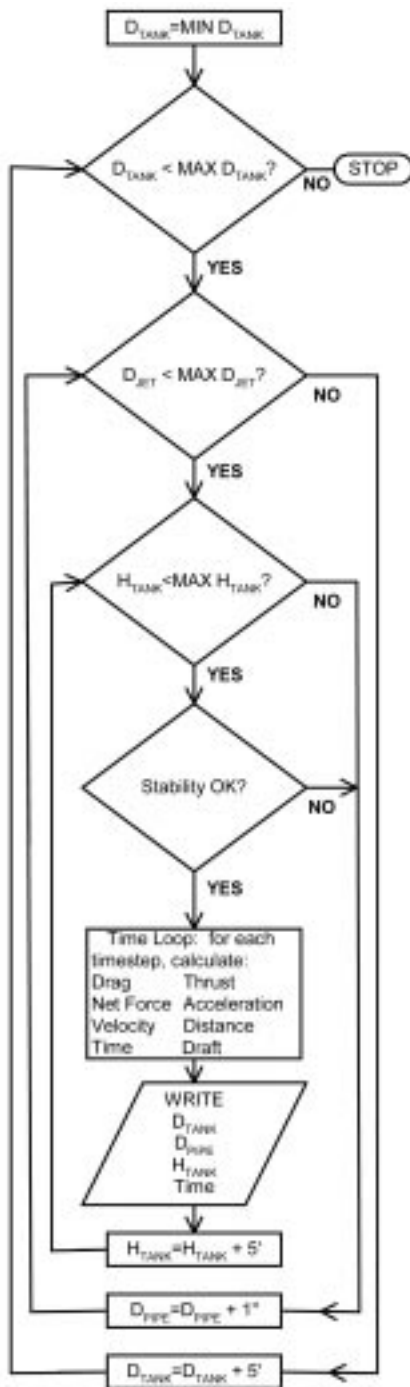


Fig. 4. Possible looping configuration to solve for optimal sizing of tank diameter, tank height, and jet diameter.

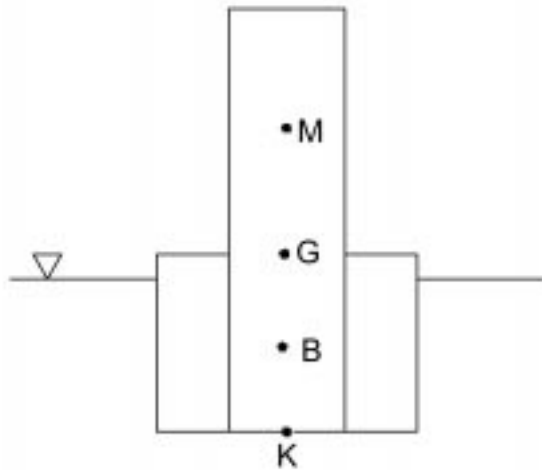


Fig. 5. Nomenclature for barge stability.

could, however, be covered in a couple of hours or it could merely be presented to the students in the form of a design constraint without further explanation. The usual measure of stability employed is that of metacentric height, which is a strong function of longitudinal area moment of inertia of the waterplane area and displaced volume: positive values of GM are desired (i.e., M above G , as depicted in Fig. 5). Several good texts are available on this topic [8–11].

POSSIBLE MODIFICATIONS

Depending on the point in the curriculum at which the project is assigned, students may be able to handle additional or different design constraints or problem statement modifications. The list of possible changes includes, but is not limited to:

Safety

- Incorporate a design margin for GM . This is tantamount to specifying a factor of safety in the design.
- Specify minimum freeboard. The distance between the waterline and the deck edge is normally a measure of reserve buoyancy, and could easily be specified.

Fluid mechanics

- Use multiple waterjets. Students could be tasked to determine the benefits and drawbacks of two waterjets compared to a single waterjet.
- Impose the free surface effect. The sloshing effect in the tank manifests itself as a virtual rise in the barge's center of gravity. While this effect was neglected in the basic problem, it should be included for students of naval architecture.
- Include the effects of added mass. This topic is not normally covered in undergraduate fluid mechanics courses.

Structural

- Vary hull shape. By specifying a v-shaped hull, the rectangular waterplane area will shrink as the hull rises out of the water, changing the longitudinal area moment of inertia of the waterplane and the stability of the vessel.
- Vary length/beam ratio.
- Vary planform of the hull. Instead of a perfectly rectangular hull, consider adding a triangular bow section, and/or a semi-circular transom.
- Specify other tower locations. The current configuration criteria put the tower amidships; placing it forward or aft of midships would introduce a trim. Alternatively, the use of multiple tanks might be investigated.
- Investigate stresses in the hull and tank (if students have had sufficient exposure to strength of materials).

Environmental

- Impose depth restrictions. As posed above, there was no limitation on water depth; consequently, draft was never an issue.
- Include wind, tide/current.

Computer-related

- Utilize more sophisticated integration techniques. Modified Euler, Runge-Kutta, etc., may be used in lieu of the simple Eulerian timestep method, assuming students have been exposed to these techniques in a numerical analysis course.
- Specify a maximum code length, output file storage size, etc.

SUMMARY

While simple enough to be accomplished midway in the MSE curriculum, the barge design project is sufficiently detailed to require the use of a computer in the simulation of the barge's performance. After completing the project, students understood how to implement loops in programming, the utility of computers in making small design changes, and how to interpret results to see whether or not they were realistic. With this as an introduction, they were much better prepared for the possibility of constructing a mathematical model in conjunction with their capstone design projects.

Acknowledgements—Thanks are due to Dr. Harold Alexander for allowing the author to audit his course and to assist students with their projects. Thanks also to Dr. Groves Herrick and Dr. Dan Jensen for critiquing a preliminary version of the manuscript and for suggesting several modifications.

Disclaimer: The views expressed are those of the author and do not reflect the official policy or position of the U.S. Air Force, Department of Defense or the U.S. Government.

REFERENCES

1. S. A. Lowe, Using visual basic to interact with Excel, *Computers in Education Journal*, **XI**(3) (July–September 2001), pp. 6–8.
2. C. N. Eastlake, *AE101—Introduction to Aerospace Engineering Space Vehicle Design Project*, Course Handout (1 April 1994; revised 24 January 1995).
3. C. N. Eastlake, An aircraft design project for the high school level, *International Journal of Engineering Education*, **14**(1) (1998), pp. 54–58.
4. C. N. Eastlake, *AE101—Introduction to Aerospace Engineering Aircraft Design Project*, Course handout (14 September 1996).
5. J. H. King and M. Devine, HANDE-A computer-aided design approach for hydrofoil ships, *Naval Engineer's Journal*, **93**(1) (April 1981). Presented at ASNE Day, 30 April–1 May 1981. Session Title: Ship Design III, Paper No. 3.
6. Advanced Surface Ship Evaluation Tool (ASSET) (<http://www.dt.navy.mil/asset/overview.htm>; current July 2003).
7. M. J. Moran, H. N. Shapiro, B. R. Munson and D. P. DeWitt, *Introduction to Thermal Systems Engineering: Thermodynamics, Fluid Mechanics and Heat Transfer*, Wiley, New York (2003), p. 26.
8. R. Zubaly, *Applied Naval Architecture*, Cornell Maritime Press, Centreville, MD (1996).
9. J. P. Comstock (ed.), *Principles of Naval Architecture*, Society of Naval Architects and Marine Engineers, New York (1967).
10. T. C. Gillmer and B. Johnson, *Introduction to Naval Architecture*, Naval Institute Press, Annapolis (1982).
11. V. L. Streeter and E. B. Wylie, *Fluid Mechanics* (seventh edition), McGraw-Hill, New York (1979), pp. 55–58.

Michael Rex Maixner graduated with distinction from the U.S. Naval Academy and served as a commissioned officer in the U.S.N. for 25 years; his first 12 years were spent as a shipboard officer, while his remaining service was spent strictly in engineering assignments. He received his Ocean Engineer and S.M.M.E. degrees from MIT and his Ph.D. in mechanical engineering from the Naval Postgraduate School. He served as an instructor at the Naval Postgraduate School and as a Professor of Engineering at Maine Maritime Academy. He is currently a member of the Department of Engineering Mechanics at the U.S. Air Force Academy.