Water-Train
The Most Energy-Efficient Inland Water Transportation

Kurian George, Kerala State Electricity Board

In a government-aided research project carried out at Cochin University, the inventor of the Water-Train demonstrated that his invention requires only 24 BTU/ton-km of energy whereas barges use 328 BTU in the same Inland water transportation situation. The use of this Water-Train can invariably curtail, to a large extent, the emission of greenhouse gasses thereby decreasing the effect on global warning. Conventional water vehicles use screw propellers which have high reacting energy loss in propulsion whereas the Water-Train relies on the earth for reaction which is an infinite mass causing no reacting energy loss at all. The propelled water takes away a large quantity of kinetic energy ($\frac{1}{2}mv^2$ where its mass is $m$ and velocity is $v$). Water-Train requires a monorail rigidly fixed to the earth through cross arms and pillars for applying the traction/propulsion force. The reacting body is the earth and so the traction efficiency tends toward 100%. It utilizes low friction of water and also the vehicles are connected serially like a locomotive and hence the wave making and skin resistances are also reduced. The NITIE study conducted earlier in India showed that diesel and electric trains use 166.3 BTU and 105.76 BTU, respectively, for the same purpose.
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Editor
Nikolaos I. Xiros, University of New Orleans

The Ocean Systems Engineering Series publishes state-of-the-art research and applications oriented short books in the related and interdependent areas of design, construction, maintenance and operation of marine vessels and structures as well as ocean and oceanic engineering. The series contains monographs and textbooks focusing on all different theoretical and applied aspects of naval architecture, marine engineering, ship building and shipping as well as sub-fields of ocean engineering and oceanographic instrumentation research.

Water-Train: The Most Energy-Efficient Inland Water Transportation
Kurian George
2020

Feedback Linearization of Dynamical Systems with Modulated States for Harnessing Water Wave Power
Nikolaos I. Xiros
2020

Marine Environmental Characterization
C. Reid Nichols and Kaustubha Raghukumar
2020
Water-Train
The Most Energy-Efficient
Inland Water Transportation

Kurian George
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SYNTHESIS LECTURES ON OCEAN SYSTEMS ENGINEERING
#3

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ABSTRACT

In a government-aided research project carried out at Cochin University, the inventor of the Water-Train demonstrated that his invention requires only 24 BTU/ton-km of energy whereas barges use 328 BTU in the same Inland water transportation situation. The use of this Water-Train can invariably curtail, to a large extent, the emission of greenhouse gasses thereby decreasing the effect on global warning. Conventional water vehicles use screw propellers which have high reacting energy loss in propulsion whereas the Water-Train relies on the earth for reaction which is an infinite mass causing no reacting energy loss at all. The propelled water takes away a large quantity of kinetic energy ($1/2mv^2$ where its mass is $m$ and velocity is $v$). Water-Train requires a monorail rigidly fixed to the earth through cross arms and pillars for applying the traction/propulsion force. The reacting body is the earth and so the traction efficiency tends toward 100%. It utilizes low friction of water and also the vehicles are connected serially like a locomotive and hence the wave making and skin resistances are also reduced. The NITIE study conducted earlier in India showed that diesel and electric trains use 166.3 BTU and 105.76 BTU, respectively, for the same purpose.

KEYWORDS

inland water transport, water train, tractor wheel propulsion, propulsion efficiency, energy efficiency, rail connected traction, BTU/ton-km
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Water-Train is a new concept intended to transport both passengers and cargo through inland waterways especially in the equatorial region where sea levels are almost steady. The vessels of the Water-Train move one behind another like a locomotive-powered train on land. In the case of Water-Train, a monorail track is used—front vessel or any middle vessel in the train can be the tractor. The front vessel and the last vessel are designed with a hydrodynamic or streamlined shape to improve efficiency and decrease power requirements. The middle vessels have a rectangular box-like shape. All the vessels are connected to each other using flexible couplings. The vessels are connected to a monorail track supported by concrete pillars. The pillars are fixed in the bed of the waterway at regular intervals and have cross arms at the top to carry the monorail of slender cross-section. The rail is fixed in the cross arm in the inverted position as the vessel’s weight is not resting on the rail. The purpose of the rail is for creating the traction and stopping through brakes and all the more for guiding the vessels in the specific route during wind and waves which tend to deviate the vessels from the fixed path parallel to the monorail. The physical basis for the Water-Train is that the rate at which water mass is pushed backward during propulsion is much less than the mass of the vehicle as well as that of the forward-moving water due to wave making and skin friction. Furthermore, since the tandem motion of several vehicles causes the system to reduce the overall wave-making and skin-resistance components faced by the system in its forward motion, the energy required is less.

At the same time, the U.S. military is exploring the viability of unmanned surface vessels, or USVs, to conduct a range of dangerous cross-ocean missions without a crew on board. But while the smaller, versatile watercraft can be useful for tasks involving surveillance, logistics, electronic and expeditionary warfare, and offensive operations, their size, shape, and other components have proven at times to limit the vessels’ ability to endure choppy waves.

According to a recent announcement unveiled in late 2019, the Pentagon’s research arm aims to improve the long-range operational capabilities of the Navy
and Marine Corps’ USVs by creating “sea trains” of four or more physically connected vessels, or vessels that are not connected but sail in coordinated formations. The ultimate goal is to develop systems of smart, crewless warships that can travel thousands of ocean miles and perform their own duties, all while exploiting wave-making resistance reductions. Specifically, the Defense Advanced Research Projects Agency (DARPA) Sea Trains program seeks to revolutionize the next generation of unmanned surface vessels, as officials support in the announcement.

Through the program, DARPA envisions the development of a four-vessel-or-more system that can persist through arduous transits of about 7,500 miles, then disaggregate and conduct their own tasks. Alternatively, the vessels may conduct independent yet collaborative operations consisting of transits, loiters, and sprints in varied sea state conditions for more than 1,100 miles. The vessel will then reassemble for transit as the connected Sea Train for another 7,500-mile journey—all without human intervention. The agency is open to any technical approaches that proposers wish to offer but highlighted three that could potentially achieve the overall concept. Officials recommend fleets of connected or connector-less Sea Trains that essentially create a mid-body for the vessel to decrease wave-making resistance while also allowing for the vessels to separate and conduct tactical missions independently. The agency also suggests “formation sea trains,” or a fleet made up of four or more vessels that travel closely and exploit wave interference between one another while in transit.

DARPA is very interested in nontraditional approaches that reduce risk early in the program. Early, aggressive, and insightful modeling, analysis, and testing is encouraged and desired.

The program is anticipated to envelop two phases. The first phase will encompass conceptual design, analysis, simulation, scaled model testing, and the second will include updates and additional testing.

Research will also have to address two technical areas over the course of the program. For the first area, researchers will need to develop a conceptual design of an integrated system comprised of the vessels’ hull form, connectors, propulsion, and gap mitigation techniques. For the second technical area, participants will be expected to create a dynamic “open-standard, autonomous” control architecture that can monitor environmental conditions the vessels endure in the middle of the ocean, their alignment and spacing, and control solutions to maximize Sea Train efficiency and seaway survivability.
Many of these issues and obstacles for the Sea Train have been successfully tackled in a proven fashion by the Water-Train concepts. Specifically, three projects were carried out to validate the Water-Train concept and have it verified in the field. The first project was carried out in the Kerala State Science and Technology Museum, Thiruvananthapuram; it was a mini working model outfitted with eight bogies. The energy efficiency of the Water-Train was investigated in the one-tractor, one-trailer system developed in the second project carried out at the Cochin University of Science and Technology. All tests and operations in the first two field-testing projects were carried out in calm water and some experts expressed doubts about how the Water-Train would respond to waves. In effect, a third project was carried out at the Indian Institute of Technology, Kharagpur. Flexible couplings, flexible driving arm, flexible guiding arms, and flexible transmission were developed for a larger-scale Water-Train outfitted three bogies. The Water-Train was run in the towing tank on waves created by the wave maker. The test results of this third project proved that the Water-Train performed really well on waves.

So as the Sea Train program seeks to enable extended transoceanic transit and long-range naval operations by exploiting the efficiencies of a system of connected vessels, the Water-Train concept seeks to do so in inland waters and exploiting the benefits of both propulsion over land and movement with low friction when moving through water. Indeed, land vehicles like trucks and trains are relatively more efficient because a major portion of the energy output of the engine is absorbed by the vehicle itself in the form of kinetic energy as the reacting mass is the earth which is practically infinite in value. However, watercraft have the advantage of low friction loss at low speeds as compared to friction between solids. In effect, the Water-Train is the only system of water transportation which eliminates propellers and uses the rail-connected traction taking advantage of low water friction.

The Sea Train program can take the Water-Train concept to the next logical step of development. If successful, it will demonstrate long-range deployment capabilities for a distributed fleet of tactical USVs. DARPA will develop and demonstrate approaches to overcome the range limitations inherent to medium unmanned surface vessels (MUSVs) by exploiting wave-making resistance reductions. DARPA envisions sea trains formed by physically connecting vessels with various degrees of freedom between the vessels, or vessels sailing in
collaborative formations at various distances between the vessels, just like the Water-Train concept has pioneered and envisioned as well.

Nikolaos I. Xiros, DEng
Professor, University of New Orleans
Naval Architecture & Marine Engineering
New Orleans, July, 2020
Acknowledgments

I am extremely thankful to the Director of The Kerala State Science and Technology Museum and the State Government for funding the design, fabrication, and installation of a mini working model of the Water-Train in the museum. Also, the KSEB granted me duty leave for five months to complete the above work for which I am very grateful.

I also wish to acknowledge The Kerala State Science, Technology, and Environment Committee for providing financial support for the second project. I am grateful to the Cochin University Authorities, especially the then Vice Chancellor, T.N. Jayachandran, for the various encouragements rendered for the execution of the project. The authorities of KSEB and Kerala Government granted one extra year of duty leave to me during the period in which the major portion of the work in this second project was completed and I thankfully cherish this support. I also wish to acknowledge the authorities of the workshop in the physics department, USIC, and the ship technology department of Cochin University for providing all the facilities available during the fabrication of the model. The various technical advices received from Dr. K. Sathianandan (guide of the project), Dr. Dileep K. Krishnan (Reader) and Manu Korulla (Student) of the Cochin University are thankfully acknowledged. I wish to thank Ralli Wolf Ltd., Bombay for designing, fabricating, and donating the traction motor for the project. The various assistances received from the authorities of the KERI, Peechi is thankfully acknowledged and the roles of Prabhakaran, Ambujakshan, and Sivaraman are worth mentioning.

This useful invention had remained ignored in India. My repeated attempts could not open the eyes of the government officials who could not realize the fact that India is the ideal place for implementing such a highly energy-efficient water transport as the country is near to the equator with many steady waterways. Dr. Nikolas Xiros (Professor of Naval Architecture and Marine Engineering, University of New Orleans, USA) found out the significance of the
invention and came forward, making use of his earnest effort for its implementation and so his open mind and wisdom are very gratefully acknowledged.

Kurian George
July 2020
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>B</td>
<td>Breadth of vessel</td>
<td></td>
</tr>
<tr>
<td>BTU</td>
<td>British thermal unit</td>
<td></td>
</tr>
<tr>
<td>C_{TL}</td>
<td>Thrust loading coefficient</td>
<td></td>
</tr>
<tr>
<td>CUSAT</td>
<td>Cochin University of Science &amp; Technology</td>
<td></td>
</tr>
<tr>
<td>Fn</td>
<td>Froude Number</td>
<td></td>
</tr>
<tr>
<td>IIT</td>
<td>Indian Institute of Technology</td>
<td></td>
</tr>
<tr>
<td>KERI</td>
<td>Kerala Engineering Research Institute</td>
<td></td>
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<tr>
<td>KSEB</td>
<td>Kerala State Electricity Board</td>
<td></td>
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<tr>
<td>L_{OA}</td>
<td>Length Overall of vessel</td>
<td></td>
</tr>
<tr>
<td>n</td>
<td>Revolutions per second of the propeller</td>
<td></td>
</tr>
<tr>
<td>NITIE</td>
<td>National Institute of Industrial Engineering</td>
<td></td>
</tr>
<tr>
<td>OPC</td>
<td>Overall Propulsive Coefficient</td>
<td></td>
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<tr>
<td>P_{B}</td>
<td>Brake Power</td>
<td></td>
</tr>
<tr>
<td>P_{D}</td>
<td>Delivered Power</td>
<td></td>
</tr>
<tr>
<td>P_{E}</td>
<td>Effective Power</td>
<td></td>
</tr>
<tr>
<td>P_{s}</td>
<td>Density of Water</td>
<td></td>
</tr>
<tr>
<td>P_{T}</td>
<td>Thrust Power</td>
<td></td>
</tr>
<tr>
<td>Q</td>
<td>Propeller torque</td>
<td></td>
</tr>
<tr>
<td>QPC</td>
<td>Quasi-Propulsive Coefficient</td>
<td></td>
</tr>
<tr>
<td>R_{TOTAL}</td>
<td>Total Resistance</td>
<td></td>
</tr>
<tr>
<td>t</td>
<td>Thrust deduction fraction</td>
<td></td>
</tr>
<tr>
<td>T</td>
<td>Propeller thrust</td>
<td></td>
</tr>
<tr>
<td>T</td>
<td>Draft of vessel</td>
<td></td>
</tr>
<tr>
<td>USIC</td>
<td>University Science Instrumentation Centre</td>
<td></td>
</tr>
<tr>
<td>V</td>
<td>Speed of model or prototype</td>
<td></td>
</tr>
<tr>
<td>V</td>
<td>Voltage</td>
<td></td>
</tr>
<tr>
<td>V_{A}</td>
<td>Velocity of advance of the propeller</td>
<td></td>
</tr>
<tr>
<td>w</td>
<td>Wake fraction</td>
<td></td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
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<tr>
<td>--------</td>
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<td></td>
</tr>
<tr>
<td>ηb</td>
<td>Propeller Efficiency</td>
<td></td>
</tr>
<tr>
<td>ηh</td>
<td>Hull Efficiency</td>
<td></td>
</tr>
<tr>
<td>ηi</td>
<td>Ideal Efficiency of Propeller</td>
<td></td>
</tr>
<tr>
<td>ηo</td>
<td>Open Water Efficiency</td>
<td></td>
</tr>
<tr>
<td>ηr</td>
<td>Relative Rotative Efficiency</td>
<td></td>
</tr>
<tr>
<td>ηp</td>
<td>Propulsion Efficiency</td>
<td></td>
</tr>
<tr>
<td>ηt</td>
<td>Transmission Efficiency</td>
<td></td>
</tr>
<tr>
<td>s</td>
<td>Scale factor</td>
<td></td>
</tr>
<tr>
<td>ss</td>
<td>Wetted surface area of full-scale Water-Train</td>
<td></td>
</tr>
<tr>
<td>vs</td>
<td>Speed of the full-scale Water-Train</td>
<td></td>
</tr>
<tr>
<td>m</td>
<td>Mass</td>
<td></td>
</tr>
<tr>
<td>v</td>
<td>Velocity</td>
<td></td>
</tr>
<tr>
<td>KE</td>
<td>Kinetic Energy</td>
<td></td>
</tr>
<tr>
<td>Δm</td>
<td>Displacement of Model (Tons)</td>
<td></td>
</tr>
<tr>
<td>Δn</td>
<td>Displacement of full-scale prototype (Tons)</td>
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CHAPTER 1

Introduction

1.1 THE GREAT NEED FOR ENERGY-SAVING DEVICES

Emission of greenhouse gases and the consequent effects on global warming is currently a great problem that humanity is facing. One way to reduce the emission of greenhouse gases is to increase the efficiency of propulsion/traction systems of marine transport. Screw propellers are the most common device used for propulsion of marine vehicles. The best efficiency of a screw propeller in ideal conditions is just about 70%. In shallow water and inland waterways, due to the limited draft of the vessels, the efficiency can be as low as 50%. But it is the propeller efficiency and not the propulsion efficiency. Any efficiency term is a fraction with the useful part in the numerator as output and in the denominator is the output plus losses which is the input. Here in the term propeller efficiency, the axial (parallel to the axis of the propeller) flow of propelled water in the backward direction is the useful part. When its mass decreases the velocity has to increase which is found out by equating the momentums. But the axial flow of propelled water can be treated only as a loss since it doesn't contribute to energy increase of the vessel or overcoming the resistance during the movement of the vessel in the forward direction. So the calculations show that the propulsion efficiency is less than 15% especially in shallow water as 85% of the input energy to the propeller is wasted in the propelled water in the form of kinetic energy. For reducing the kinetic energy gained by the propelled water, the reactive energy loss has to be minimized there by propulsion efficiency can be increased to more than 90%. If earth is used as the reacting body instead of water, then the mass of the reacting body is tending to infinity and so its backward velocity is tending to zero. So the energy loss in the reacting body is zero and the traction/propulsion efficiency is tending to 100% theoretically.
1. INTRODUCTION

1.2 THE CONCEPT

If one examines the energy transfer mechanism of the water vessels propelled by conventional propellers, it can be seen that there is considerable energy loss in the propeller itself. In the case of water vehicles like boats, barges, and ships the mass of water that is propelled backward per second is much less than the mass of the vehicle and mass of water energized due to wave making and skin resistance resulting in high reactive energy loss. The land vehicles like trucks and trains are relatively more efficient because a major portion of the energy output of the engine is absorbed by the vehicle itself in the form of kinetic energy as the reacting mass is the earth which can be treated as an infinite mass. However, water vehicles have the advantage of low friction loss at low speeds as compared to friction between solids. The energy efficiency data of the Indian Transport Policy Committee would demonstrate this (Table 4.11). Energy requirement per ton kilometer of a diesel train is 166.3 BTU whereas the same for a slow-speed diesel barge is 328 BTU. It may also be noted that the water resistance that opposes the forward motion of the vessel contains two major parts, viz. wave-making resistance and skin friction. Barge trains already in use in Europe and other parts of the world have demonstrated that if the vessels are connected in series like a train and closely packed, the overall wave making and skin resistance will be reduced. One of the methods to improve the efficiency of a water transport system is to replace the conventional propeller system by rail-connected traction, the propulsion/traction is accomplished by using the reactive force from the static monorail rigidly fixed on the ground or to the earth.

In the following sections, the design, development, manufacture, and testing of an entirely new propulsion system is described where the thrust is obtained using tractor wheels running along a monorail which is in the entire length of the route. In this system, the propulsion/traction efficiency can be as high as 90% or even higher compared to a maximum of about 15% of conventional propulsion systems. It is not the propeller efficiency of 70% or 50%, as mentioned earlier, which is wrongly conceived as propulsion efficiency. Propulsion system is not used to drive a Water-Train. It is similar to a barge train with specific advantages like low value of resistance/ton-km and flexibility of size of train.
1.3. WATER-TRAIN PROJECTS SUCCESSFULLY CARRIED OUT

Water-Train is a new technical concept intended to transport both passengers and cargo through inland waterways especially in the equatorial region where sea level is almost steady. The vessels of the Water-Train move one behind another like a locomotive-driven land train along a monorail track. The front vessel or any middle vessel can be the tractor. The front vessel and the last vessel have hydrodynamic or streamlined shape. The middle vessels have a rectangular box-like shape. All the vessels are connected to each other using flexible couplings. The vessels are connected to a monorail track which is about 3 meters above water level and is supported on concrete pillars fixed in the bed of the waterways at a regular interval of about 5 meters. The pillars have cross arms at the top to carry the monorail (single rail) of slender cross section. The rail is fixed in the cross arm in the inverted position as the vessel’s weight is not resting on the rail. The purpose of the rail is for creating the traction and stopping through brakes and all the more for guiding the vessels in the specific route during wind and waves which tend to deviate the vessels from the fixed path parallel to the monorail.

1.3 WATER-TRAIN PROJECTS SUCCESSFULLY CARRIED OUT

Three government-aided projects were carried out in the field of Water-Train. The first project carried out in the Kerala State Science and Technology Museum, Thiruvananthapuram was a mini working model having eight bogies, as shown in Figures 1.1 and 1.2.

The energy efficiency of the Water-Train was investigated in the one-tractor-one trailer-system developed in the second project carried out at the Cochin University of Science and Technology. The system was operated and tested at KERI, Peechi. The energy efficiency test conducted showed that Water-Train requires only 24 BTU/ton-km where as diesel barges require 328 BTU/ton-km for transportation. Here an electric motor was used as the prime mover. Its energy requirements were found as 24 BTU/ton-km. But if the electric motor is replaced by a diesel engine the proportionate increase of energy is predicted as 37.7 BTU/ton-km \( (24 \times \frac{166.3}{105.76} = 37.7 \text{ BTU}) \) which is 11.5% of the energy requirement of diesel barges. The energy efficiency test was supervised by an expert team led by the Professor Dr. Walter Stovhase from Wilhelm Pieck University of Rostock, Germany.
4 1. INTRODUCTION

Figure 1.1: Water-Train front view.

Figure 1.2: Water-Train side view.
1.4 MAIN ADVANTAGES OF THE WATER-TRAIN

All the above tests and operations were carried out in calm water and some experts expressed doubts about how the Water-Train will respond to waves. So, a third project was carried out at the Indian Institute of Technology, Kharagpur. Flexible couplings, flexible driving arm, flexible guiding arms, and flexible transmission were developed for a larger-scale Water-Train having three bogies. The Water-Train was made to run in the towing tank on waves created by the wave maker. The test results of this third project proved that the Water-Train performed really well on waves.

1.4 MAIN ADVANTAGES OF THE WATER-TRAIN

- High traction/propulsion efficiency of above 90% compared to that of less than 15% for conventional propulsion in shallow water. Even though the propeller efficiency is 50%, the propulsion efficiency is less than 15% as mentioned earlier.

- Conventional screw propellers operating behind the ship increase the pressure resistance of the ship. The rail-connected traction mechanism used for propulsion in the Water-Train does not cause any increase in vessel resistance.

- Unlike conventional propellers operating in inland water, the propulsion system in the Water-Train located above the water line is not affected by water weeds and floating debris.

- The efficiency of a conventional screw propeller decreases as the thrust-loading coefficient increases. The efficiency of the Water-Train propulsion system is not affected by an increase in thrust requirement.

- The number of vessels can be increased or decreased depending on cargo or passenger availability as in the cases of locomotives.

- The train pattern of motion, vessels one behind the other and closely packed, reduces the overall wave making and skin resistances compared with that of the vessels moving independently. It provides further energy saving over and above the high traction efficiency.

- Ordinary water vehicles, especially speed boats, cause severe damage to the banks where Water-Train is friendly to the shore or banks.
1. INTRODUCTION

- Since the supporting pillars, monorail, etc., are fixed along the middle line of the waterway and at a convenient height of 3 meters, it does not create any impediment to the operation of other conventional vehicles and their use of the two banks and also for the crossing of barges having large width and height. Figures 5.10 to 5.12 provide the details. Also since the supporting pillars are 50 meters apart, criss-cross movements for the boats are permitted in the entire stretch.

- Water-Train vessels will not sink in water since they are connected with the monorail and so there is better safety.

- Water-Train can share the waterway with the conventional water vehicles like boats and barges as in the case of trams sharing the road with road vehicles like cars and trucks without causing mutual impediments.

- All the more, the great energy-saving advantage of Water-Train will decrease the global warming by reducing greenhouse gas emissions to a considerable extent.

1.5 PATENT