Rotating-Arm Model-Test Facility

An International Historic Mechanical Engineering Landmark

The American Society of Mechanical Engineers • October 14, 1981

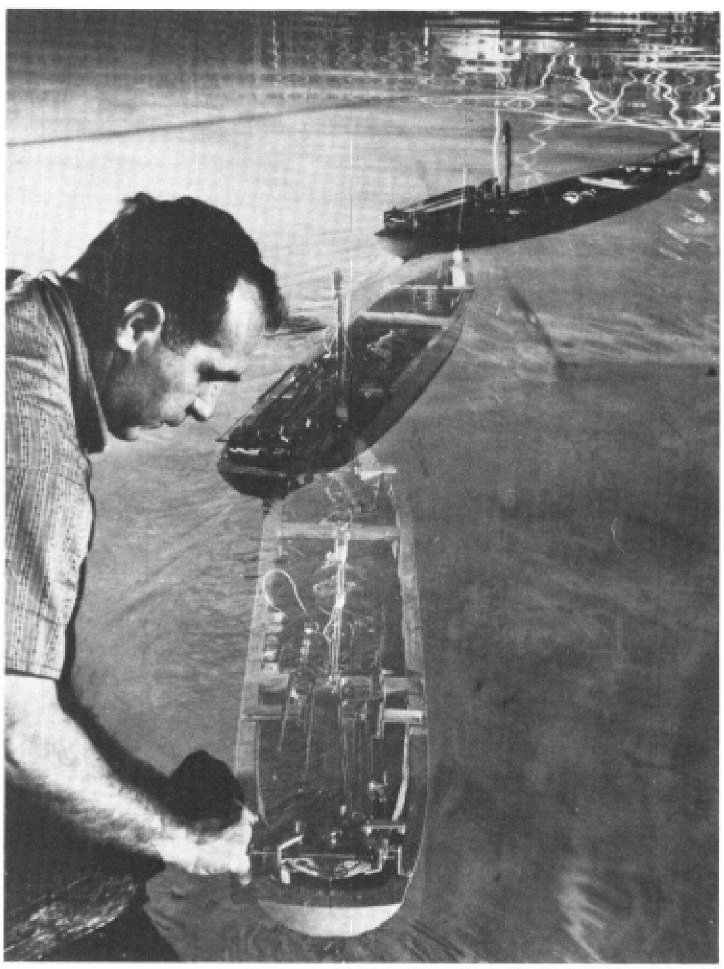
Davidson Laboratory
Stevens Institute of Technology
Hoboken, New Jersey

Landmarks

Back in the early 1930's, a grown man could frequently be seen towing small yacht models through the swimming pool at Stevens Institute of Technology. This was Dr. Kenneth S.M. Davidson, a professor of mechanical engineering and an ardent crewman on ocean sailing races. He was trying to find out why some yachts usually won and others regularly lost.

Through the efforts of this man, the Rotating-Arm Model-Test Facility at Stevens Institute of Technology, the first such facility in the world was, subsequently developed. This unique laboratory allows the researcher to obtain comprehensive measurements of those forces and moments necessary to predict the dynamic stability, maneuverability and control of surface ships, submersibles, and airships.

Pioneering work conducted at the facility has led to fundamental understanding of the hydrodynamics of ship control. Quantitative measures of the maneuverability and contrability of vessels are now possible, and hull designs can be developed and modified in order to achieve the desired performance.



Time-lapse photos of free-running model being tested at Davidson Laboratory prior to construction of the Rotating-Arm

On the Cover: Present configuration of the Rotating-Arm testing model of a container ship

Dr. Kenneth S.M. Davidson, founder of the laboratory which in 1959, following his death, was renamed in his honor

The Need/The Facility

When a helmsman turns his wheel to apply right rudder on a ship proceeding on a straight course, a stable vessel will almost immediately change heading angle to the right, then move laterally, heel or roll, and lose some speed at constant power. During this maneuver, several kinds of hydrodynamic forces and moments act on the ship, appendages and rudders. The most important of these forces result from combinations of translational velocities, rotary velocities and accelerations. At the Davidson Laboratory (DL) Rotating-Arm Model-Test Facility, where captive ship-model tests have been conducted since 1945, the dependence of these forces on hull geometry, hull orientation, turning radius and translational and angular velocities can be determined.

The facility, shown on the cover, consists of a 75-foot square, oblique sea basin, having a water depth of 5 feet, and a central, vertical shaft. The horizontal, radial structure, called the Rotating-Arm, is driven by the vertical shaft at prescribed turning rates, or angular velocities. The test model is mounted on a force and moment measuring apparatus, which is secured at various radial positions along this horizontal arm.

Data are obtained over a range of angles of attack, angular velocities and turning radii. The facility can determine the distinct dependence of force and moment coefficients on each separate motion variable, while all other variables are held fixed. It provides data at large magnitudes of the motion variables, allowing non-linear effects to be measured and identified.[1]

Towing Tank Development Prior to the Rotating-Arm

In 1935, with a $5,000 grant from the Research Corporation in New York City and a $100-a-month subsidy from an interested sportsman, Prof. Davidson built a towing tank — the

1. Forces and moments arising from lateral and angular accelerations cannot readily be secured from the Rotating-Arm Model-Test Facility, but these can be calculated from hydrodynamic theory.

maritime equivalent of a wind tunnel — on the Stevens campus.[2] Studying the designs of some sailing yachts, he demonstrated that naval architects were designing excellent hulls as long as their sailboats stayed on an even keel, but that the hydrodynamic performance of such hulls was often deficient when the yachts heeled over.

Davidson's most outstanding early success was scored with Commodore Harold S. Vanderbilt's America's Cup defender, *Ranger*. This yacht trimmed the British *Endeavour II* by large margins in four straight races to capture the America's Cup off Newport in 1937.[3] The *Ranger* victory was not only a final triumph for U.S. Class J yachting, but it also gave substance to Davidson's theory that relatively small towing tanks, employing 6-foot instead of 20- to 25-foot models, could be immensely useful to naval architects.[4]

By 1939, U.S. Navy interest in the steering, transient maneuvering and control of ships, submarines, high-speed craft, and the porpoising of flying-boat hulls, brought Davidson and his staff back to the swimming pool. The limitations of his makeshift facilities, which involved the use of simple rotating-arms, led to the design and construction of a second testing tank. This new 75-foot square basin, funded by the National Defense Research Council was built in 1942 and was destined soon after to house the pioneering Rotating-Arm.

During its first three years of existence, the new basin was the test site for many free-running models of Navy combatants. The models were tested to determine their trajectories under action of rudders whose forces were measured by an on-board dynamometer. However, only a limited number of forces could be measured in this way. It became apparent that, to quantify the maneuvering performance and dynamic stability of vessels, models would have to be towed in a captive mode, using special instruments that could measure all the required hydrodynamic forces and moments acting on the hull, appendages and rudders.

Rotating-Arm Designed and Built

Consequently, in January 1945, the design of the Rotating-Arm for the new testing basin was undertaken by Walter Fried and Alfred Muley, both Davidson Laboratory staff members and Stevens alumni. A contract was let to the New Jersey Machine Corporation for working drawings and construction. By October 1945, the Rotating-Arm was installed and in operation. The U.S. Navy provided financial support for the design of the Arm, its construction and installation.

In his report to the Navy in February 1946, Fried stated that the operation of the Arm had "not only been quite satisfactory but exceeded expectations . . ." There was immediate great interest in applying this unique facility to assist in the solution of maneuvering and control problems of all forms of vehicles, including surface ships (both naval and commercial), submarines, torpedoes, underwater missiles, hydrofoil craft, planing boats, airships, and even automobiles and trucks.

The original Arm provided for towing models in circular paths whose radii could be varied from 5 to 32.5 feet at speeds of rotation from one to six revolutions per minute. The initial design has been upgraded over the years; the basic principles of its operation, however, remain unchanged since its introduction by Dr. Davidson in 1945.

Earlier "Rotating Arms"

It may be of interest to note the existence of fundamentally different mechanisms referred to as "rotating arm" facilities beginning as early as 1746. In that year, a Mr. Rouse of Harborough demonstrated a 4-foot radius rotating arm before the Royal Society in London. Later in the 1700's, John Smeaton used an ingenious combination of Rouse's ideas and work by Benjamin Robins to study the characteristics of windmills. In 1763, Jean Borda used a rotating arm to conduct resistance tests in water. In all these cases, however, the function of the rotating arm was only to provide a controlled translational velocity for a reasonable time period in a small test area and, except for the windmill studies, to measure the resistance of projectiles, cannonballs, various geometric forms, etc. In effect, these 18th-century rotating arms, which are described by Rouse, were inexpensive, approximate substitutes for straight towing tank facilities.

In contradistinction to that early work, it is important to note, the DL Rotating-Arm Model-Test Facility was not designed to be a substitute for a straight line towing tank, but rather as a laboratory for subjecting towed models to angular velocities equal to the rotational velocity of the rotating-arm. Present rotating-arm model-test facilities, as used by the hydrodynamic researcher, provide a capability of in-depth analysis of the maneuvering and turning characteristics of vehicles as opposed to the limited resistance studies of the 18th-century facilities. The only similarity lies in the common use of the term "rotating arm."

Significant Accomplishments

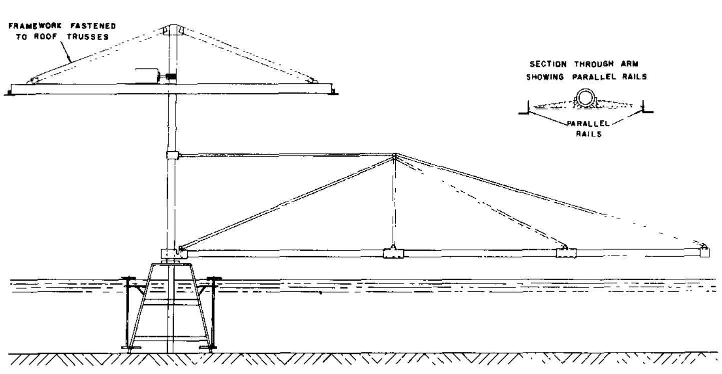
The past 36 years have seen the application of the Rotating-Arm to literally hundreds of projects related to the stability and control of diverse hull forms for both military and commercial application. Some of the highlights of this work are summarized below:

- *First definitive quantitative determination of the course-keeping qualities of displacement ships:* In the landmark paper "Turning and Coursekeeping," which Davidson and Professor Leonard Schiff of the University of Pennsylvania presented to the Society of Naval Architects and Marine Engineers (SNAME) in November 1946, excellent agreement between calculated and measured

2. Today the original tank has been replaced by two larger sister tanks; one is the high speed towing tank, and the other is the Rotating-Arm Model-Test Facility. Over the years, the three tanks undertook model tests of barges and speed-boats, yachts and destroyers, ferries and assault craft, trawlers and racing shells, submarines and ocean platforms.
3. Virtually every Cup defender since *Ranger* has had the benefit of model tests at the Davidson Laboratory. This activity seems especially appropriate for Stevens Institute in view of the fact that members of the founding Stevens family were instrumental in the design and the racing of *America* in 1851, when she first won the trophy that has long since become yachting's most renowned and coveted prize.
4. The towing tanks at the U.S. Navy's David W. Taylor Naval Research and Development Center outside Washington, D.C. is more than half a mile long. Yet the studies conducted with the smaller facility at Stevens have been highly useful to the Navy in contributing to and complementing its own research.

model-scale ship maneuvering qualities was shown. A reliable design method thus became available to naval architects concerned with the stability and control of ships.

- *Conception and development of the revolutionary 200-foot Albacore submarine:* This research vessel, which was the forerunner of the modern submarine hull form, was so maneuverable that its seated occupants had to wear safety belts! It was demonstrated that high-speed submarines could be designed so as not to broach while operating at snorkel depths and not to exceed collapse depth when maneuvering submerged at high speed. Modern submarines are true submersibles as compared with World War II submarines, which were essentially surface ships capable of submergence.
- *Development of computer driven simulators:* These devices predict ship trajectories while being controlled by a helmsman in either deep water, shallow water, in confined harbors and under the action of wind and currents. The so-called Computer-Aided Operations Research Facility (CAORF) ship handling simulator, operated at the U.S. Merchant Marine Academy at Kings Point, N.Y., relies heavily upon data obtained from the DL Rotating-Arm and upon analytical methods developed by the DL staff.
- *Tests of a family of ship hulls defined the influence of rudder size, block coefficient, draft, breadth, and section shape upon maneuvering qualities:* Correlations with results of linear and non-linear simulator equations with free-running models were found to be satisfactory. Extension to ships in quartering and following seas demonstrated the further utility of the rotating-arm technique.[5]
- *Safe transit of harbors studied:* Arm data secured with models of five tankers and a containership were incorporated into a digital computer-evaluated motion simulator which showed correlation with ship trial results. Applications were made to a variety of harbor configurations.[6]



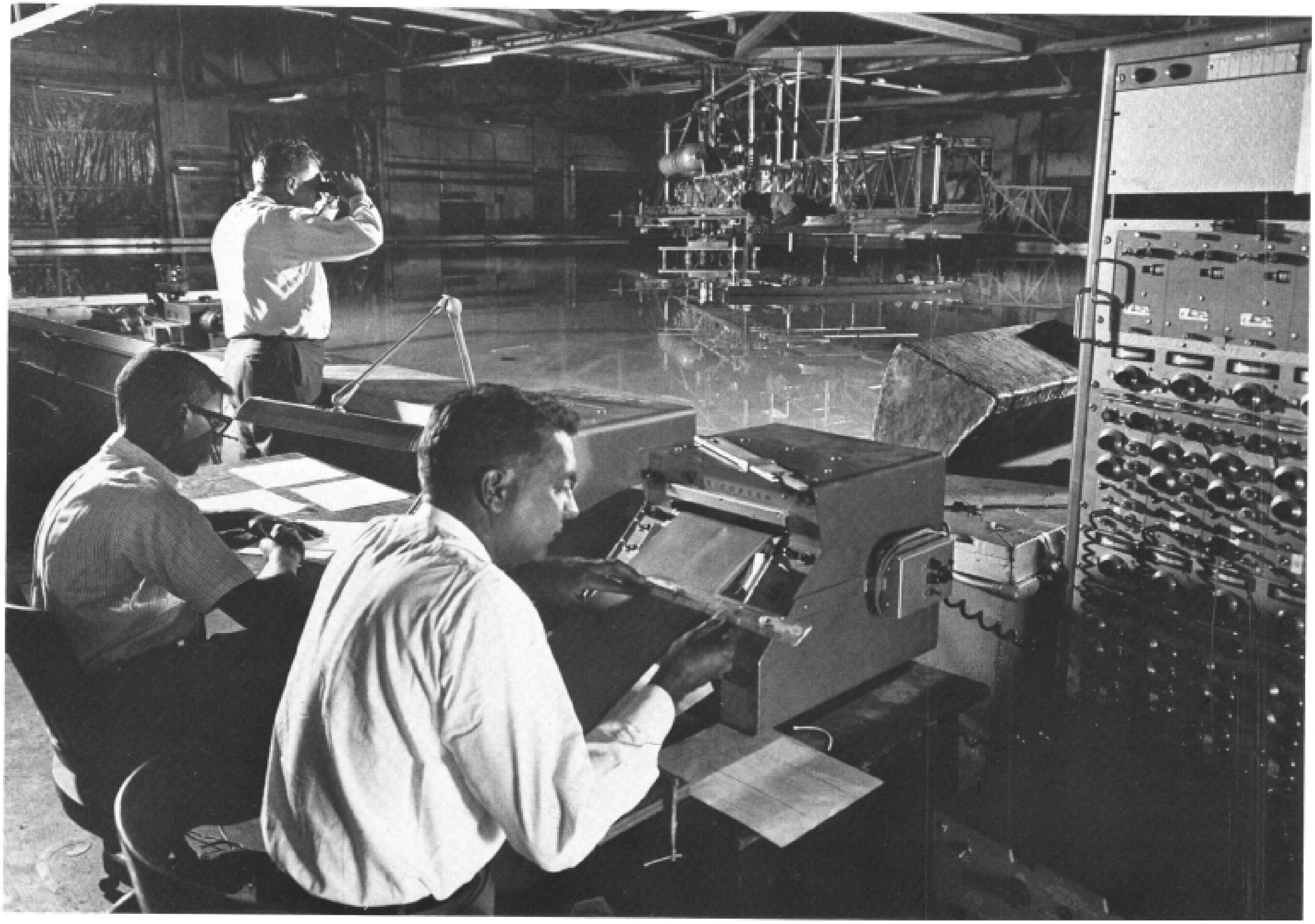
Sketch of the Rotating-Arm as originally configurated in October 1945

- *Quantitative definition of maneuvering characteristics of Great Lakes bulk carriers in critical channels and in ice-free and ice-covered conditions:* These studies revealed the magnitudes of reduced turning performance in ice-covered water.[7]
- *Study of the Presidential yacht, Williamsburg:* When the Navy took over the yacht, *Williamsburg,* for President Truman's use, it was discovered that she would probably be its worst steering ship. Understandably, the Navy was rather concerned about its image, lest the *Williamsburg* end up on some Potomac mud flat with Mr. Truman and assembled dignitaries aboard. While this matter could hardly be classified as a military secret, the Bureau of Ships requested a close-mouthed policy for fear that some Washington columnist would get wind of the unruly yacht and make great capital of it. Corrective measures were taken, and the *Williamsburg* thereafter managed to avoid the navigational hazards of the Potomac River for as long as she continued in Presidential service.

The preponderance of Rotating-Arm studies of underwater bodies have been conducted for the U.S. Navy, and because of security restrictions, they cannot be described. Those studies of underwater bodies that can be described have been conducted to stimulate advances in submarine and ship design. They attest to the use of the Rotating-Arm as more than a tool for evaluation of configurations that already exist. Several of the most notable of these exploratory programs on underwater bodies, providing a picture of their diversity and innovation, are described below:

- *First submerged body characterizations providing essential data for design of U.S. Navy Mark 13 torpedo:* Static and rotary derivatives were determined for the unappended body, and effects of conventional stabilizing surfaces, shroud ring tails with and without powered propellers. These tests permitted, for the first time, establishment of relationships between the rotary, or damping, derivatives and the static derivatives.[8]
- *First determination of the effects of a jet-propelled system on the dynamic stability and drag of an underwater missile.*[9]
- *First tests of an aerodynamic vehicle in water to secure the 6-degrees-of-freedom characteristics of an airship with various appendages:* These studies demonstrated that Arm data could be used directly to secure graphical evaluations of the dynamic stability of submersibles.[10]

5. H. Eda and C.L. Crane, *The Society of Naval Architects and Marine Engineers (SNAME) Transactions,* Vol. 73, New York, 1965
6. H. Eda, R. Falls and D. Walden, *SNAME Transactions,* Vol. 87, New York, 1979
7. H. Eda and F. DeBord, *Computer-Aided Operations Research Facility Symposium,* Kings Point, New York, 1980
8. A. Suarez, *Davidson Laboratory Report* 318, 1947
9. A. Strumpf, *Davidson Laboratory Report* 386 and 396, 1950
10. A. Strumpf, *Davidson Laboratory Report* 534, 1954



Recorded data is studied (foreground) while a technician makes adjustments to a cargo ship model (rear) undergoing tests in the Rotating-Arm Model-Test Facility

Other DL Ship and Marine Craft Studies

The pioneering studies of maneuvering qualities leading to, and including, the applications of the Rotating-Arm represent one facet of the Laboratory's many incisive studies of ship and marine craft. Its studies of water-based aircraft hulls led to extensive fundamental studies of families of prismatic planing hulls in the 1940's and '50's. These form the basis of design procedures developed at the Davidson Laboratory and used throughout the world today. The first seakeeping experiments with ship models were carried out at Stevens by Edward V. Lewis, and the results were used to guide Boris Korvin-Krovkovsky's development of the first theory for predictions of hull responses in waves. The first operational programs for unsteady propeller-generated velocity and pressure fields that produce ship hull vibration were devised and implemented at Davidson Laboratory.

All of these groundbreaking studies have been in keeping with Davidson's spirit of pursuit of untrammeled domains using simple, inexpensive model procedures adapted to simulate the significant effects present in the physics of the prototype operation.

Guiding Philosophy

Dr. Davidson's philosophy was admirably expressed in his 1946 account, *The Experimental Towing Tank Ten-Year Report:*

"There is no convenient rule by which the most efficient size of a research establishment can be determined. It is therefore, a matter of constant concern to avoid falling into the pitfall of thinking that enlargement of organization or facilities is necessarily followed by the accomplishment of more or better work. The basic philosophy, that knowledge and experience must be considered before facilities, must be continually safeguarded."

Looking ahead, he stated:

"The ultimate test of a research establishment will be the quality of the scientific knowledge it can produce. It must stand or fall on this basis. Clear, straight thinking of the highest type is required to achieve the necessary superior quality of work and, to that end, the Experimental Towing Tank is directing its energies."

These observations continue to provide the philosophical guide for the Davidson Laboratory's efforts.

INTERNATIONAL HISTORIC
MECHANICAL ENGINEERING LANDMARK
ROTATING-ARM MODEL-TEST FACILITY
1945
DAVIDSON LABORATORY
STEVENS INSTITUTE OF TECHNOLOGY

This facility was the first in the world to conduct experiments for obtaining comprehensive measurements of those forces and moments necessary to define the maneuverability and control of surface ships, submersibles and airships.

This and subsequent facilities throughout the world have been essential in the design of more responsive vessels. This installation at Stevens constitutes a tribute to the pioneering efforts of Dr. Kenneth S.M. Davidson (1898-1958), professor of mechanical engineering, and his colleagues in the Davidson Laboratory.

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The Rotating-Arm Model-Test Facility is the 65th Landmark designated by the Society. For further information on Landmarks write to the American Society of Mechanical Engineers, Public Information, 345 E. 47th St., New York, N.Y. 10017.

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