
CLIPPERS, YACHTS, and the false promise of the wave line

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**John Scott Russell's 19th-century theory
of ship design promised speed and delivered
elegance. But, ultimately, it didn't hold water.**



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Today's naval architects predict the speed and power of ships using scaling laws developed in the late 1800s by British engineer William Froude. But long before Froude, ship designers and shipbuilders knew that the proportions and shape of a ship's frame, or hull, affect its speed through water—and they sought out rules that governed those relationships.

In the late 1500s, a British shipbuilder named Mathew Baker famously circulated a drawing of a hybrid fish—with the blunt head of a cod and the tapered tail of a mackerel—superimposed on the hull of an Elizabethan warship. Devoid of any scientific or experimental basis, the idea that such natural principles should dictate the shape of a ship's hull was nonetheless widely accepted.

Throughout the 17th and 18th centuries, the scientific revolution spawned new ideas about hydrodynamics and resistance, which define the forces acting on a vessel moving through water. Navies around Europe, looking to build faster sailing warships, commissioned scientists and inventors to test those ideas. The arrival of steam power on the maritime scene in the early 1800s introduced an additional, financial incentive to minimize resistance: A steamship's operating costs were directly tied to its coal consumption, which in turn depended on its resistance. Early steam-powered ships were faster and more dependable than sailing vessels, but their engines were inefficient. Shipbuilders therefore sought fast, efficient hulls to get the most out of each ton of coal.

It was in that era of industrial upheaval, at the dawn of the Victorian age, that a mathematically minded British engineer named John Scott Russell, pictured in figure 1, set out to discover a universal law of shipbuilding: a set of design principles that would yield a hull of minimal resistance. The resulting theory, called the wave-line theory, dominated the world of naval architecture for nearly half a century. It guided the design of not only steamships but prize-winning yachts and record-setting clippers. The wave-line theory eventually fell out of favor, replaced by Froude's more rigorous theories, but its story is an instructive history lesson about the often-complicated relationship between science and technology.

Making waves

A well-respected shipbuilder, Russell studied mathematics at the University of Glasgow from 1821 to 1825 and subsequently

learned the mechanical trades by building steam carriages and marine steam engines. His combination of theoretical and practical training was almost unmatched in Britain.¹

In 1835 he began developing his wave-line theory while searching for ways to improve the newly developed steam canal boat. By then, scientists had identified hydrodynamic pressure and friction as key components of ship resistance. Russell argued, correctly, that wave making was another important factor. However, he incorrectly attributed wave making solely to the shape of the hull; in reality, any body of any shape moving through water creates waves. Russell contended that because a conventional hull has a blunt waterline—that is, the front of the hull, the bow, is convex

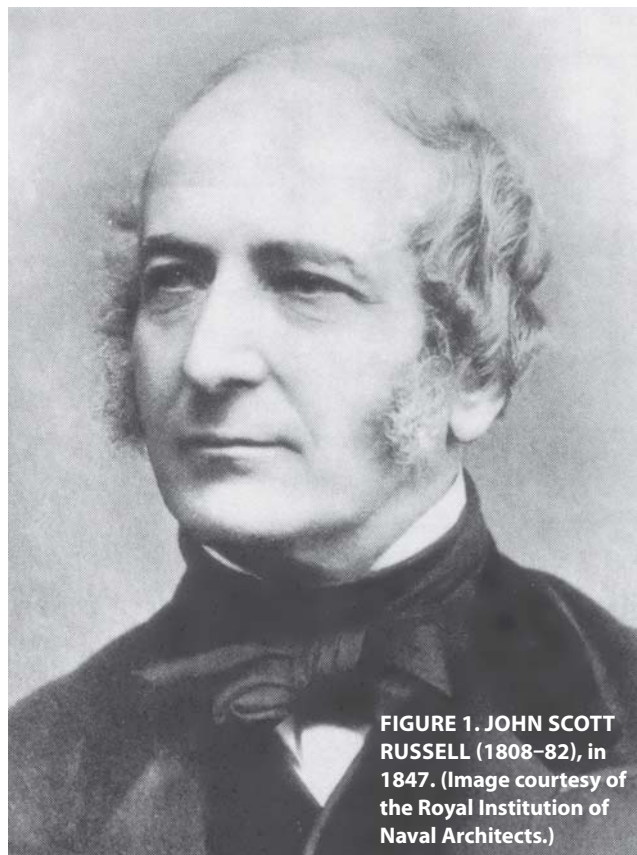


FIGURE 1. JOHN SCOTT RUSSELL (1808–82), in 1847. (Image courtesy of the Royal Institution of Naval Architects.)

WAVE-LINE THEORY

where it meets the water surface—it generates a wave that the ship must continually push out of the way. Russell believed that a bow with an appropriately concave, or hollow, waterline would displace water to the sides of the vessel without creating a bow wave.

Russell worked for the next eight years to determine precisely what form that waterline should take. The British Association for the Advancement of Science (BAAS), a newly established competitor to the Royal Society, gave him £1132—equivalent to \$1 million today—to study the nature of waves at sea and to develop ship designs that reduced wave making. At the time, it was the second-largest sum the association had paid out.²

Russell built and tested more than 100 hulls, ranging from 3 ft models to 200 ft ocean-going ships. He exploited ingenious techniques developed in previous experiments, in which ship models and canal boats were towed by systems of pulleys and weights suspended from tall trestles. In those early experiments, the more efficient hull forms naturally went faster, but the precise relationship between resistance and speed remained difficult to quantify. So instead of simply timing the fall of a suspended weight, Russell used a relatively new apparatus, the spring dynamometer, to directly measure the force of resistance, which could be translated into the horsepower needed to propel the vessel. During the trials, Russell also observed curious solitary waves that propagated along canals with no decrease in speed; later dubbed solitons, the waves have become important in optics and communications.

By 1843 Russell reported to the BAAS that after thousands of experiments, he had discovered a new law of physics, dubbed the wave-line theory, “by which it appears, that each velocity [of the hull] has a corresponding form and dimension peculiar to that velocity.”³ In other words, Russell claimed to have uncovered the fundamental principles by which any ship’s hull should be designed, regardless of size.⁴

The geometry of the wave line

The premise of Russell’s new law was that a ship’s hull should have the same shape as the waves it generates. He assumed that two types of waves were relevant to ship resistance: sinusoidal waves of translation, generated ahead of a ship as it pushes through the water, and cycloidal waves of replacement, driven by wind to fill in the space vacated by the ship as it passes.

Russell focused most of his research on the wave of translation. From his experiments, he concluded that the length L of the sinusoidal waves should obey the formula $L = 2\pi V^2/g$, where V is the velocity of the ship and g is the acceleration due

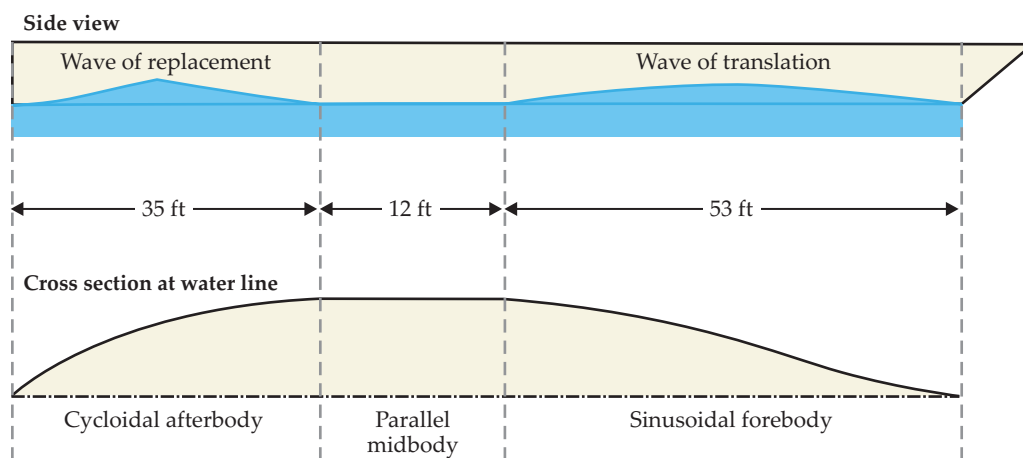


FIGURE 2. THE WAVE-LINE THEORY prescribes the geometries of three key elements of a ship’s hull: The forebody, or bow, should be sinusoidal to match the wave of translation that forms at the boat’s leading edge; the afterbody, or stern, should be cycloidal to match the trailing wave of replacement; and the midbody, where presumably there are no waves, should be straight and parallel to the centerline. The lengths of the bow and stern correspond to the lengths of the waves of translation and replacement, respectively, and the length of the midbody can be adjusted to yield the desired overall length of the vessel.

to gravity. Russell figured that to minimize resistance, the bow of a ship should also be sinusoidal in shape, with a length equal to L . His reasoning, never fully explained, was that such a correspondence would result in minimal disturbance of the water’s free surface—never mind that the water’s surface bobbed in the vertical direction and Russell’s hull was sinusoidal in the horizontal plane. The so-called wave-line bow would cleave rather than push oncoming water. To confirm that idea, Russell sailed such a vessel in a field of small floating balls. He observed that the balls did not strike the hull but were simply nudged aside.⁵

Likewise, Russell argued that the rear of the ship, the stern, should take the cycloidal form of the wave of replacement. Because that wave is $\frac{2}{3}$ the length of the wave of translation, the stern should be $\frac{2}{3}$ the length of the bow. The ship’s overall length could be adjusted by adding a parallel section in the middle. For example, a wave of translation generated by a ship moving at 10 knots (17 ft/s) would be 53 ft long. So a 100 ft ship designed to travel at that speed should have a 53 ft sinusoidal entrance; a straight, 12 ft middle body; and a 35 ft cycloidal run, as illustrated in figure 2.

It is important here to note what the wave-line theory did *not* do. It did not provide a way to estimate wave-making resistance; Russell simply assumed, quite incorrectly, that the wave-line hull form had zero wave-making resistance. The wave-line theory also did not have a basis in physics; despite his claims to have performed thousands of experiments, Russell had little data elucidating the mechanism of wave-making resistance. With its insistence on sine curves and cycloids, the wave line was less a physical theory and more a geometrically descriptive concept. Finally, contrary to Russell’s assertions, the wave line did not provide a surefire template for every ship. Ship design always reflects a compromise between speed, stability, strength, and dozens of other factors. In the case of the wave line, the need to immerse enough of the hull to counter-

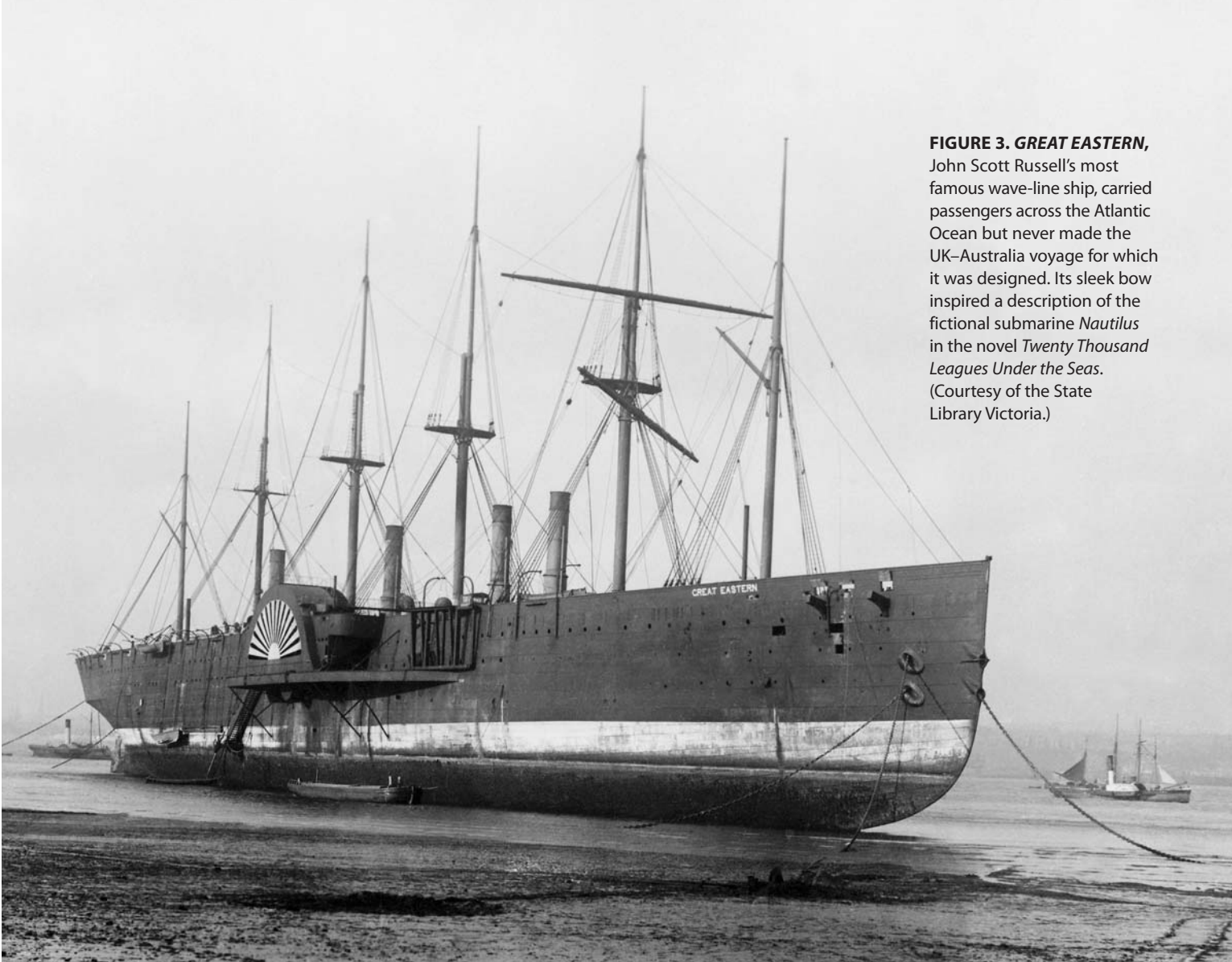


FIGURE 3. GREAT EASTERN, John Scott Russell's most famous wave-line ship, carried passengers across the Atlantic Ocean but never made the UK–Australia voyage for which it was designed. Its sleek bow inspired a description of the fictional submarine *Nautilus* in the novel *Twenty Thousand Leagues Under the Seas*. (Courtesy of the State Library Victoria.)

balance the ship's weight often meant that waterlines had to be revised away from the pure form that Russell envisioned.

By steam . . .

Once Russell began publishing the results of his BAAS-sponsored research, the wave-line hull found favor among builders of steamships, which were rapidly replacing sailing ships on trade routes in the English Channel, North Sea, and Irish Sea. Trading vessels in those waters had to cover short distances fairly quickly; shipbuilders saw the sharper hull form as ideal for speed, and after 1845 hollow waterlines boomed in popularity.

Although wave-line steamers generally served their captains well, the mere use of the wave-line formula did not guarantee a successful ship. For instance, Scottish shipbuilder James Napier constructed several Irish Sea steamers according to Russell's theory, but they were uniformly poor performers, and Napier lost money on each one.

In 1859 Russell, by then a prominent shipbuilder in London, lost a bid for the Royal Navy's first ironclad warship, HMS *Warrior*. But he did convince the navy's surveyor, Baldwin Walker, to adopt the wave-line concept for the new ship. Isaac Watts, *Warrior*'s chief constructor, followed Walker's lead and gave the ship a hollow waterline that certainly evoked the wave line. But

the rest of the hull was conventional, and Watts rebuffed Russell's later attempts to claim half credit for *Warrior*'s design.

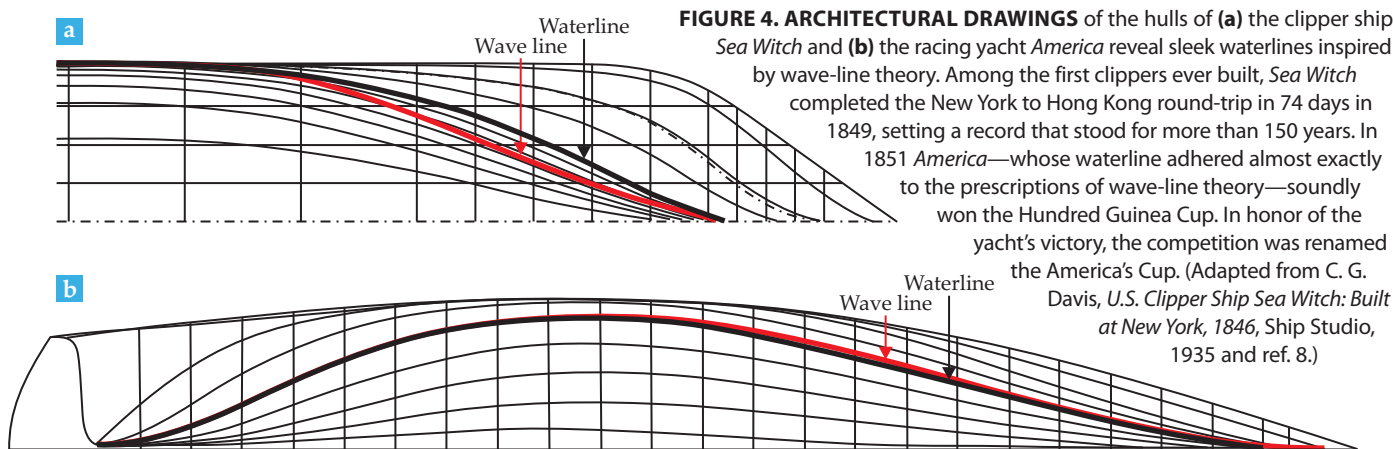
Russell did use the wave line for his most famous ship, SS *Great Eastern*, which entered service in 1859. (See figure 3.) It was the biggest ship of its day—600 ft long and displacing 27 000 tons—intended to take passengers from Britain to Australia. Despite its great size and advanced hull form, *Great Eastern* never made it Down Under. It only traversed the Atlantic Ocean a few times and never turned a profit.⁶

Still, one of *Great Eastern*'s passengers, Jules Verne, was so impressed with the ship's wave-line hull that it inspired a passage in his novel *Twenty Thousand Leagues Under the Seas*. He describes his fictional submarine *Nautilus* as having "lines . . . sufficiently long and its run extensive enough for the displaced water to escape easily and to provide no obstacle to headway."⁷

. . . and by sail

Although wave-line theory was initially developed for steamers, it was put to greatest use in sailing ships, specifically the clippers and yachts of the mid to late 1800s. Clippers were built for fast transport of passengers and perishable goods; yachts were built to win races. Every aspect of their design and construction could be bent to the goal of speed.

The clipper was originally developed in the 1840s by John



Griffiths, a young employee at New York's Smith and Dimon shipyard. Griffiths looked to design a new type of ship to take advantage of the rapidly expanding tea trade with China. He was conversant in the latest theories of naval architecture and had studied the various reports on Russell's wave-line theory.⁸ His first clippers—*Rainbow* (1845) and *Sea Witch* (1846)—were inspired by Russell's hollow waterlines and cut almost two months from the US-China round-trip.⁹ Figure 4a shows the water line of *Sea Witch's* bow. Griffiths's clippers were some of the fastest ships ever to sail: In 1849 *Sea Witch* set a New York to Hong Kong record that wasn't broken until 2003.

The success of Griffiths's clippers spurred a surge in the construction of vessels with hollow waterlines at the shipbuilding ways of New York and Boston. Clipper builder Robert McKay put it succinctly when, during a visit to London, he told Russell, "I have adopted the wave principle in the construction of all my American clippers, and that is my secret. I first found the account of the wave line in the publications of the British Association."¹⁰

The wave line became an even more prominent fixture in the yacht community. Russell built the wave-line yacht *Titania* for British railroad engineer Robert Stephenson—the boat helped smooth Stephenson's entry into the prestigious Royal Yacht Squadron (RYS). In 1851, the members of the RYS invited their counterparts at the New York Yacht Club (NYYC) to Cowes, on the Isle of Wight, to compete for the Hundred Guinea Cup, the squadron's top racing prize.

Unbeknownst to the RYS, the members of the NYYC, led by George Steers, were readying their own wave-line yacht for the competition. Steers had been a shipbuilding colleague of Griffiths and learned wave-line theory from him. Steers built the schooner *America* in perfect adherence to that theory. (See figure 4b.)

On 22 August 1851, *America* soundly defeated a flotilla of 14 British boats in the regatta around the Isle of Wight. *America's* victory was so resounding that a few days later a cartoon in the *London Journal* depicted Queen Victoria asking which yacht

came in second, only to be told, "Ah, your Majesty, there is no second." A separate race a week later pitted *America* against Russell's own *Titania*. Again, *America* handily won.¹¹ Russell graciously acknowledged the victory but claimed that Steers made even better use of the wave line than he did.

The wave line achieved international fame and was widely imitated in the years following *America's* victory.¹² By 1860 Russell had been appointed president of the Royal Institution of Naval Architects. But not all yachtsmen believed in wave-line theory. American Nathaniel Herreshoff, who was trained as an engineer at MIT, explicitly rejected the wave line—and

all other "scientific" theories—in favor of his seat-of-the-pants approach to hull design. His engineering intuition proved almost unerring; from 1893 until 1920, he designed and built five consecutive defenders of America's Cup (formerly

the Hundred Guinea Cup), including his 1903 masterpiece *Reliance*. None of those boats featured hollow waterlines.¹³

To many scientists and engineers who studied naval architecture, Herreshoff's remarkable run might not have been so surprising. Decades earlier a few of them had started pulling at the threads of wave-line theory. And it didn't take long for the theory to begin unraveling at the seams.

Wave line's demise

Among the scientists and engineers who doubted wave-line theory was William Rankine. Starting in 1857 he carried out a decade-long study of ship resistance and concluded that so-called frictional eddies, shed along the length of a ship—not just at the bow and stern—were the most important determinants of ship resistance. But Rankine's theory for computing resistance, later shown to be largely accurate, was too complex to be used in the day-to-day practice of shipbuilding.¹⁴

William Froude, who had worked on *Great Eastern* and knew Russell well, also began studying ship resistance. In 1865 he decided to compare Russell's sharp wave-line form with a more rounded form derived, as he stated, "by eye from water birds." He created two sets of ship models of varying sizes—a

THE PREMISE OF RUSSELL'S NEW LAW WAS THAT A SHIP'S HULL SHOULD HAVE THE SAME SHAPE AS THE WAVES IT GENERATES.

set of wave-line models named Raven and a set of blunt-ended models named Swan—and towed them behind a small launch. Not only did the Swans show less resistance, at higher speeds, than the Ravens, Froude also became convinced that resistance scaled predictably with size.

In 1868, the BAAS commissioned more research on ship resistance, and both Rankine and Froude participated. In its official report, the association argued against the use of small-scale models as an aid to predicting full-scale results. Froude disagreed, based on the results of his Swan and Raven investigations. With funds from the Royal Navy, he built a model test tank near his home in Torquay and began operating it in 1871. Over the next decade, Froude and his son Robert developed the ship-resistance scaling laws that now bear the elder's name.¹⁵

In Froude's formulation, subsequently validated by more than a century of theory and experimentation, total resistance is due to two factors that can be treated independently: pressure, which creates energy-dissipating wave systems along the entire length of the hull, and friction, a viscous resistance exerted by the water on the skin of the ship. The wave-line theory's premise that only the bow and stern were responsible for wave making was replaced with a more fundamental understanding of wave making as a transfer of energy from the entire hull to the surrounding water.

By the 1890s steam had surpassed sail as the primary means of propulsion in commercial ships. Ship owners began to place an even greater premium on coal and, later, oil efficiency. At the same time, small-scale model-testing tanks based on Froude's Torquay experiments were constructed around the world, and they confirmed Froude's formulation. The science of ship design quickly became the domain of the engineers and scientists working in those experimental facilities. (Figure 5 shows a modern-day model-testing tank.) The relative ease and low cost of experimenting with scale models, combined with the accuracy of Froude's scaling laws, made model testing a cost-effective way for shipbuilders and navies to develop efficient hull forms and lower their fuel bills.

The model tests also gradually revealed the importance of other factors influencing the speed and power of ships, including hull friction and flow patterns into the propellers, and they called into question the validity of all geometrically derived waterlines. In 1906 an article in the widely read journal *Engineering* opined,

The problem of finding “a form of least resistance,” which so much exercised the minds of early naval architects, is still unsolved, except to this extent—that scientific shipbuilders now know that no one form of ship will be most easily driven under all conditions; that “a form of least resistance” belongs to each speed, length, and other variables in ship-shaped bodies.

Mr. J. Scott-Russell deduced his celebrated “wave-line form of least disturbance and probable least resistance” from the . . . axioms he laid down.¹⁶

The subject, the article stated, “can only be elucidated with tank assistance.” Indeed, the influential 1893 work *Resistance of Ships and Screw Propulsion*, by US naval constructor David Taylor, focused almost entirely on model test results and made no mention at all of Russell's wave-line theory.

Up in the air

Although Russell's concept of the wave line didn't survive past the 19th century, the decidedly 18th-century ideal of a geometrical solid of least resistance did. Despite being shown to have no physical basis, the idea that such a solid could exist continued to hold sway even among some 20th-century engineers.

In the most celebrated example, in 1934 the US aeronautical engineer David Davis patented a low-drag airfoil that used geometrical considerations based purely on the shape of the cycloid. In a throwback to Russell's contention that a cycloidal shape was optimal for the stern of a ship, Davis's patent claimed that his “most advantageous form of foil” was “developed from formulas based on the mechanical action of a rotor

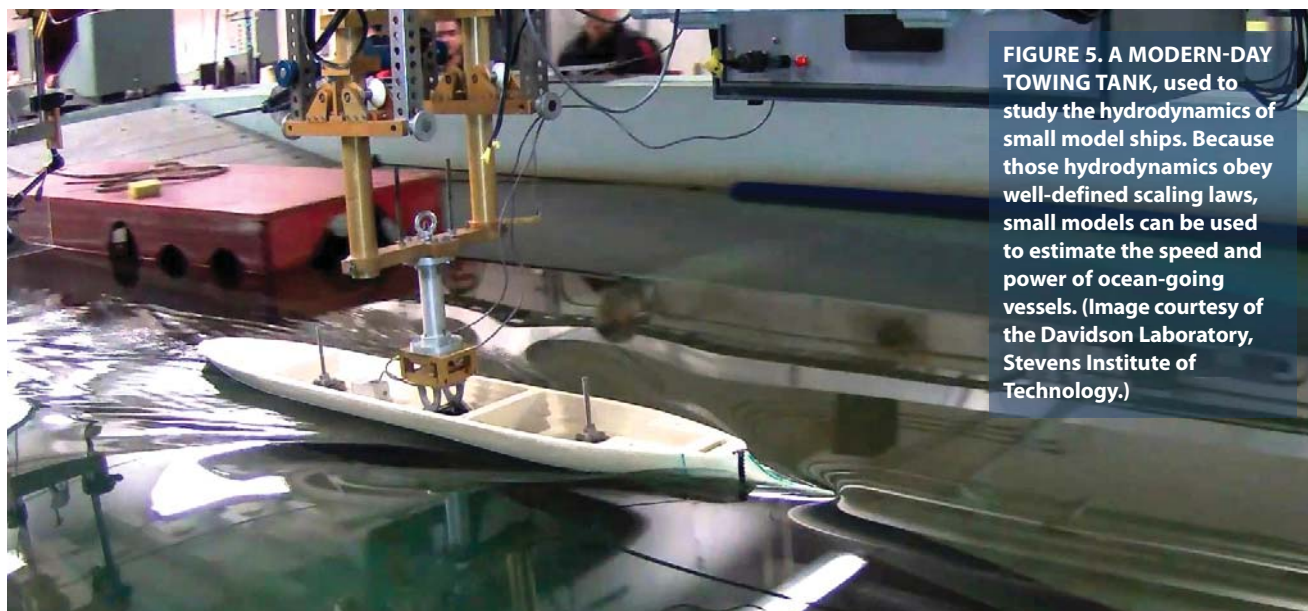


FIGURE 5. A MODERN-DAY TOWING TANK, used to study the hydrodynamics of small model ships. Because those hydrodynamics obey well-defined scaling laws, small models can be used to estimate the speed and power of ocean-going vessels. (Image courtesy of the Davidson Laboratory, Stevens Institute of Technology.)

WAVE-LINE THEORY

having rotation and translation through a fluid and giving the Magnus effect.”¹⁷

The claim of a Magnus effect—a phenomenon relevant only to spinning objects—was physically dubious considering that Davis’s airfoil was nonrotating. But the airfoil nevertheless caught the attention of Consolidated Aircraft Corp, which was developing a new long-range bomber that would become the B-24. When Consolidated tested Davis’s airfoil, it turned out to provide a largely nonturbulent, or laminar, flow over much of the surface and thus experienced considerably less drag. The company went on to manufacture the B-24 with the “Davis wing,” which was considered a great success. Not until some years later did the physics behind the low drag of so-called laminar-flow airfoils come to light. And only later still did engineers realize that Davis’s cycloid happened to fall almost exactly onto one of several laminar-flow airfoil shapes. Davis appears to have stumbled on his wing more by chance than by design.¹⁸

The same might be said of John Scott Russell and his half-century run of dominance in shipbuilding. Yet long after evidence emerged showing that his geometrical constructs were based on a foundation of sand, the fascination with his “form of least resistance” persisted. Part of the allure might have been his theory’s simplicity. But another factor behind the endurance of the wave line and other geometrically derived forms may be the visual beauty of the objects they produce. And few objects were more beautiful than the elegant hulls of the clipper ships and racing yachts of yesteryear.

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