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The mutual influence of aircraft aerodynamics and ship hydrodynamics in theory and experiment

Larrie D. Ferreiro

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Abstract As early as 1784, sharp-eyed engineers and scientists noted striking similarities between the dynamics of seagoing vessels and aerial vehicles. By the early twentieth century, naval engineers and scientists were developing and designing airplanes and dirigibles using empirical principles derived from naval architecture. Several key researchers in aerodynamics began their career as naval architects (David A. Taylor, William F. Durand and Jerome C. Hunsaker) and carried out their experiments in ship testing facilities. By the 1930s, however, the transfer of knowledge was irrevocably reversed as empiricism gave way to more fundamental, physics-based research. The rapid evolution of complex aircraft systems and flight envelopes led to new theoretical developments in aerodynamics and maneuvering, which quickly found their way into naval ship design. The theoretical and experimental results for airfoils, rigid airships and fixed-wing aircraft developed by Ludwig Prandtl, Theodore von Kármán, Max M. Munk and Hilda M. Lyon were employed in the hydrodynamic development of surface ships and submarines. This paper examines how the ideas, concepts and data from one discipline influenced the other and explores the processes by which that knowledge was transferred between disciplines.

1 Introduction

Naval architects were heavily involved early in the development of aircraft design. In the early twentieth century, when the great steam-turbine passenger liners and dreadnoughts were unquestionably the most advanced machines of the age, their designers

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were regarded as among the most sophisticated of all engineers, and their services were called upon in developing novel technologies like the airplane and dirigible.[1] The reverse was also true: aviation had a profound impact upon the evolution of ships, not only in the adoption of esthetically "streamlined" forms like that of the 1930s passenger liner *Normandie*, but also in the development of lightweight aluminum alloys that found their way into marine construction (Peter 1996; Shatzberg 1999; Forrest 1947).

But it was in the rapid progress of theoretical developments in fluid resistance and dynamics that the connection between ships and aircraft was most profound. At the dawn of aviation, the development of aircraft aerodynamics was informed by empirical studies of stability, propellers and control surfaces derived from many years of practical and experimental studies. Within a few years, however, this flow of information reversed, and it was the theoretical developments in aircraft aerodynamics (e.g., laminar and turbulent flow, circulation theory and maneuvering equations) that now found their way into ship hydrodynamics, a state of affairs that has persisted to this day. This article discusses the flow of information between the two disciplines and examines the reasons for this reversal of flow.

2 Initial flow: from ships to aircraft

A cursory glance at any aircraft designer's drawing board or computer screen reveals the design heritage in the discipline of naval architecture. The body of an aircraft is sometimes referred to as the "hull" (especially in airships), and its left and right sides are designated as *port* and *starboard*. As with ships, the geometry of an aircraft is defined by a series of transverse *body stations*, by *buttock lines* that run vertically down its length and by *waterlines* that cut horizontally across it. The *vertical reference plane* at the nose corresponds directly to a ship's *forward perpendicular*, and the longitudinal cross-section for both is called the *inboard profile*. The aircraft designer used the very same tools as the naval architect to draw these lines, including *ships' curves* (similar to *French curves*) and *splines* or *battens* held in place with lead weights called *ducks* or *whales*. Aircraft motions are referred to by the nautical terms *roll*, *pitch* and *yaw*. The calculated surface of the aircraft is even called the *wetted area*, a direct reference to naval practice (Raymer 2006). This naval heritage of aircraft can be traced all the way back to the very first balloon flights of the late eighteenth century.

2.1 "Two faces of the same problem": the ship and the aircraft, 1784–1910

The first balloon flights of the Montgolfier brothers in 1783 ignited the interest of the scientific community to solve the various problems the inventors had experienced. The French Academy of Sciences quickly identified the primary concerns of making

[1] Naval architects did not just work on aircraft: during World War I, Winston Churchill specifically requested that his Director of Naval Construction, Eustace Tennyson d'Eyncourt, head up the creation of complex new armored vehicles he called *landships*, but which were later renamed *tanks*; to this day, tanks sport very nautical *hulls* and *turrets* (Stein 1919, p. 11).

balloons practical, the most important of which was to find a way of steering them. Many observers noted the similarities between balloons and ships, quickly coining the term *aeronautical* to describe the naval qualities of airborne craft. In 1784, several inventors proposed and built rudder systems to guide *dirigible* (steerable) balloons, although the concept ultimately proved ineffective for non-propelled balloons (Carra 1784; Gillespie 1984).

It was not until 1852, when the French engineer Jules Henri Giffard successfully demonstrated a steam-powered balloon that the possibility of a dirigible air vehicle became a reality. By that time, numerous inventors had demonstrated man-powered submersibles that could be controlled both horizontally and vertically through the water (Roland 1978). In 1854, the mining engineer (and inventor of the modern turbine) Claude Burdin submitted a memoir before the French Academy of Sciences that outlined in some detail the methods that could be used to propel and direct either a submarine boat or an airship, arguing that the mechanisms for one—i.e., propellers, rudders and horizontal planes—would be directly applicable to the other (*Comptes Rendues* 1854).

This link between airships and submarines was reaffirmed by the French naval constructor Stanislas Charles Henri Dupuy de Lôme, famous for building the first ironclad warships. In 1870 during the Siege of Paris, he constructed and tested a propeller-driven dirigible balloon as a means of escaping the surrounding Prussian troops, although the city fell before it could be used (Leclert 1872). In the 1880s, he began work on the *Gymnote* electric submarine, which was completed after his death by his colleague Gustave Zédé. Dupuy de Lôme used his experience from his aerial experiment to guide his submarine one, frequently noting that "the question of aerostats and that of submarine boats are intimately linked; the day that the first is solved, the second will be nearly so" (Zédé 1886).

The first heavier-than-air powered flights of Clément Ader and the Wright brothers showed both the great advances in the technological understanding of aircraft, and the vast deficit in knowledge of how to control and maintain dynamic flight. French Army captain Ferdinand Ferber, who had been experimenting with gliders at the same time as the Wright brothers, had developed his understanding of the longitudinal stability of aircraft from examining torpedoes and submarines, which have fins and control surfaces mounted at the tail. Carefully analyzing both the theoretical and practical aspects of the problem, he modified the Wright brothers' glider configurations (which all had forward canards that rendered them longitudinally unstable) by adding a fixed tail to provide inherent longitudinal stability. This practice was quickly followed by other aircraft builders (Ferber 1908).

In 1910, the technology journalist Henri Noalhat took his inspiration from Ferber to examine the problems of aviation in a small book *Aerial Navigation and Submarine Navigation: Two Faces of the Same Problem*, in which he compared stability, equilibrium and directional control for aerial craft (both heavier and lighter than air) with those of submarines and torpedoes. Noalhat pointed out several then current problems in manned flight that he believed could be rectified using marine technologies. Noting that single-propeller airplanes tended to pull to one side due to propeller torque, he suggested solutions following the practice for counter-rotating propellers as on torpedoes, or by using two opposite-hand propellers as on submarines. Noalhat also suggested the use of gyroscopes to stabilize airplanes, as such devices had been used in torpedoes since the 1890s (Noalhat 1910). In 1913 Elmer Sperry, who had made his name in naval gyroscopes, adapted the technology for aircraft, used first in a gyro-stabilized, radio-controlled "aerial torpedo" (Hughes 1971, pp. 243–272).

2.2 Naval architecture in aircraft design, 1911–1939

Within a decade of the Wright brothers' first flight, enthusiasts and professionals around the world were designing, building and testing airplanes. Many of those early aeronautical engineers had begun their careers as naval architects, transferring their skills in stability and dynamics from one fluid to another. Naval architects dominated the early days of aeronautics because they were familiar with the wide range of problems inherent in aircraft design. They appreciated the role of weight and buoyancy (or lift) on aircraft configuration and strength. They also understood how to apply practical hydrodynamic principles of pressure distribution, potential flow and streamlines to aircraft aerodynamics (Roenne 1913; Hunsaker 1916; Wyn-Evans 1921; Hovgaard 1927; Richmond 1929a).

Much of this knowledge had been derived empirically from ship experimental model basins, which had been pioneered in the 1870s and 1880s by the British father-and-son engineers William and Robert Froude in Torquay and Haslar. The Froudes were the first to develop a coherent theoretical basis for using small-scale models to simulate full-scale performance of ships. In particular, they developed a method to separate ship resistance into two components, viscous (frictional) and non-viscous (primarily wave making) components. Similar techniques were developed to simulate the performance of propellers behind a ship. Using the appropriate non-dimensional scaling laws for each component, model test results could be used to predict the speed and power of ships (Wright 1983; Brown 2006). By the turn of the twentieth century, a dozen experimental model basins had opened across Europe and the USA. The engineers and scientists working on naval topics soon turned their attention to the skies.

This was particularly evident in the USA, where the US Navy took an early leading role in aeronautical research under the influence of David W. Taylor. Taylor was a naval architect who in 1898 created the US Experimental Model Basin (EMB) in Washington, D.C. to develop fundamental principles of hydrodynamics and test warship designs. Starting in 1911, Taylor built the experimental wind tunnel at the site to serve the same purposes for aircraft. He and his assistant William McEntee, also a naval architect, established a formal Aircraft Division within the Bureau of Construction and Repair (the Navy's ship design organization) and quickly populated it with 35 naval architects to perform aircraft design and conduct experimental work. These men, at once naval and aeronautical engineers, were instrumental in developing the hull and pontoon designs for seaplanes that dominated much of early naval aviation (Fulton 1963; Carlisle 1998; Trimble 2002; Stein 2007; Haas et al. 2011).

One of these "crossover" engineers was Jerome C. Hunsaker, who designed the *NC-4 Flying Boat* that made the first transatlantic crossing. In the 1920s, Hunsaker pointed out where aeronautical engineering had borrowed from naval architecture (Hunsaker 1920, 1924):

- Methods for controlling weight and center of gravity
- The Froude method separation of resistance analysis
- The use of small models and scaling laws in experimental facilities to test full-sized craft, largely following the Froudes' practice
- The design of propellers, also following the Froudes' practice
- The development and use of streamlined forms
- Buoyancy, trim and strength calculations for airships
- The design of floats for seaplanes

In Britain, the Admiralty's Airship Design Section was established in 1915 during World War I and populated with ten naval architects, including Charles I.R. Campbell (head of the design section), Harold Butler Wyn-Evans and Steven Payne, most of whom were on loan from the submarine design section. Several went back to ship design (notably aircraft carriers) in 1921 after the design section was transferred to the Air Ministry, but Campbell tragically died that year in the notorious crash of the R38 airship (Higham 1961, p. 176).

In Germany, a similar pattern emerged. Albert Betz was originally trained as a naval architect at the Technische Hochschule Berlin-Charlottenburg and succeeded Ludwig Prandtl as director of the Universität Göttingen aerodynamics research institute. Johann Schütte, while serving as a professor of naval architecture at the Technische Universität Danzig (Gdansk), became co-founder of the famous Schütte-Lanz Airship Company (Lehmann 1999, pp. 135, 458).

It is unsurprising that these early naval-turned-aviation engineers would bring their body of knowledge with them and apply well-known naval architectural concepts, notably the metacenter and propeller theory, to the design of aircraft. The concept of the metacenter as a measure of ship's stability dates back to the eighteenth century. The basic concept states that for positive stability at small angles of roll or pitch, the vertical couple formed by the ship's upward buoyancy (passing through the centroid of volumetric buoyancy B) and downward weight (through the center of gravity) produce a net restoring force. For the ship to be stable (i.e., to have a positive righting moment), the center of gravity G cannot rise above a certain point, called the metacenter M (which is a function of displacement, ∇, and the righting moment at the waterplane, I_T), beyond which the couple turns negative and the ship will overturn if heeled. The metacentric height is the distance between the center of gravity and the metacenter; the larger the value, the greater the inherent stability.[2] The formula for a ship's metacenter GM is thus:

$$GM = BG - \frac{I_T}{\nabla}$$

In 1911, William McEntee proposed that a similar concept be employed for assessing the stability of aircraft. In his formulation, the weight of the aircraft W is supported by the "buoyancy," i.e., the upward lift, acting through the centroid of surface area P. The aircraft metacenter GM (also called the "neutral point") is a function of the

[2] Note that the righting and pitching moments in the following equations have the dimension of [weight] × [distance]. See Nowacki and Ferreiro (2003).

dynamic pitching moment of pressure about its center of gravity, defined as V_m. The resultant equation becomes:

$$GM = PG - \frac{V_m}{W}$$

As with ships, the greater the distance between the aircraft center of gravity and the metacenter, the greater its inherent stability. Early aircraft designers found this simplified mathematical model useful in defining longitudinal stability. It was soon replaced by more complex dynamic stability formulae that better accounted for aircraft motions, though the metacenter formula is still found in aerodynamics textbooks as a convenient way to explain the concept of aircraft stability (McEntee 1911; Mises 1992, pp. 517–529).

In Germany and France, naval architects were also closely linked to developments in aviation. When the Technische Universität Berlin-Charlottenburg opened its new course for aircraft construction in 1925, it stipulated that candidates must "have acquired sufficient knowledge of the basics of ship-building" to be admitted (Eckert 2006, p. 131). In France, when the Service Technique Aéronautique was established in 1916, its ranks were quickly filled by naval architects like Emile Leroux from the Génie Maritime, who also taught aerodynamics at its Ecole d'Application. So closely did the two disciplines evolve together that in 1924, the naval professional society Association Technique Maritime (ATM) became the Association Technique Maritime et Aéronautique (ATMA). ATMA devoted many pages of its annual *Bulletin* to aeronautical research, for example comparative studies by Leroux on ship and aircraft propellers (Leroux 1925, 1927; ATMA 2013).

In the USA, the naval architecture community was closely involved in the establishment of the National Advisory Committee for Aeronautics (NACA) in the early days of World War I. Originally conceived by the aeronautical pioneer Washington Irving Chambers (who worked closely with Taylor's naval architects) as a scientific research center, it was finally created along the lines of the Navy's experimental facilities as articulated by David Taylor and aimed at providing practical engineering data for the design and construction of aircraft. From the beginning, naval architects were a strong presence within NACA and guided its agenda; Taylor was Secretary in the 1920s, while Hunsaker was Chairman in the 1940s and 1950s. Its first permanent headquarters was housed from 1920–1941 in the Main Navy Building in Washington D.C. (Roland 1985).

Perhaps the strongest technical influence that naval architects had upon aircraft aerodynamics was in the domain of propeller design. One of the first proposals to NACA, to conduct systematic tests of airplane propellers, came from William F. Durand at Stanford University. Durand had previously been a marine engineer with the US Navy, then head of the Department of Naval Architecture at Cornell, and was intimately familiar with both the theory and practice of ship propeller design. While at Cornell he had tested a series of propellers to gain comparative results across a range of design parameters (pitch, curvature, etc.). These tests, the results of which were published in 1905, were soon emulated in the UK, France and at David Taylor's Experimental Model Basin. In 1916, Durand teamed with fellow Stanford professor, and former naval architect, Everett P. Lesley to carry out similar parametric testing on airplane propellers, funded by NACA. The NACA Secretary Holden C. Richardson, himself a naval architect who developed one of the earliest models of hydrofoil boats, was the liaison for this project until Durand was appointed NACA President in 1917.

The experiments conducted by Durand and Lesley were a classic example of the transfer of methods, knowledge and expertise from the field of ship hydrodynamics to that of aircraft aerodynamics. The two men selected the design parameters for testing—rotational speed, distribution of pitch ratio, diameter—based upon their experience testing ship propellers, then created 48 model airplane propellers and systematically varied them. The tests results graphically detailed the performance data (efficiency, slip, etc.) for the entire family as functions of the parameters. These highly successful experiments gave aircraft designers a ready tool for matching desired propeller characteristics to their aircraft (Vincenti 1979, 1990, pp. 137–169; Durand 1953).

Although most of maritime influence on aircraft occurred within military and governmental bodies, the connection between naval architecture and aircraft design extended into civilian aviation as well. Since the mid-nineteenth century, rules for designing, building and surveying merchant ships had been established, not by governments, but by independent classification societies such as Lloyd's Register (Britain), Bureau Veritas (France), Det Norske Veritas (Norway) and the American Bureau of Shipping (United States). In the early days of aircraft design, aviation companies, insurance agents and government ministries turned to these societies to develop rules for construction and survey of aircraft, and for the issuance of airworthiness certificates. These classification societies created independent aeronautical branches to help the fledgling aircraft industry develop and codify new procedures and practices. In 1929, the Aircraft International Register (AIR) was established, which a contemporary announcement stated "will be to commercial aircraft what Lloyd's Register is to shipping," intended to provide an internationally accepted set of classification rules ("Aircraft International Register" 1929; 1978, pp. 17–20; Anderson and Collett 1989, pp. 104–106; American Bureau of Shipping 2006, p. 28; Watson 2010a, pp. 196–199).

The use of a ship-based classification scheme for aircraft was never a good fit and was ultimately short-lived. Classification societies were principally staffed by naval architects and marine engineers, and the criteria they developed for ship design and construction were based on empirical, rules of thumb lessons garnered over a century of practice. For example, requirements for plate thickness and hull stiffness were not based on any explicit structural loading cases, but rather as a simple function of ship's length and hull form. Aircraft designers, driven in large part by the need to minimize weight, quickly began employing first principles of physics and mechanics to develop loading and strength criteria that were used to establish minimum acceptable skin thicknesses and girder dimensions (Younger 1935, pp. 11–17). Within a few years of their establishment, most classification societies shuttered their aeronautical branches, and by 1939, the AIR was disestablished as governments took on the role of issuing airworthiness certificates.

3 Flow reversal: from aircraft to ships

By the 1930s, much of the "normal science" of ship hydrodynamics had reached its limits. The physical and empirical rules developed over the previous half-century were proving inadequate to explain what researchers were finding in their test results and full-scale predictions. By that time, the insights from naval architecture were also becoming irrelevant to aircraft designers, who themselves were developing increasingly sophisticated research tools to deal with the practical problems of trying to reduce drag, extend lift and improve maneuverability at higher and higher speeds. These involved scale effects and fluid compressibility problems not found in slow-speed ships traveling through water, an effectively incompressible fluid (Anderson 1997, p. 319).

One reason for the disparity in the extent of theoretical developments between these two fields was that governments were pouring far more money and resources into aircraft aerodynamics than into naval hydrodynamics. In 1930, the USA had just two ship model basins (EMB and at University of Michigan), while almost a dozen wind tunnels had already sprang up in around the nation, including six run by NACA. That same year, the EMB received less than $100,000 in appropriations, whereas NACA was being funded to the tune of $1.3 million (Davidson 1936, p. A41; *Annual Report*, 1930, p. 627; Mack 1998, p. 15).

At the same time, naval architects were faced with a crisis in predicting the performance of ships that were growing rapidly in size and speed. Simply relying on empirical scale-model test results and decades-old rules of thumb was proving increasingly inadequate to satisfy the increasingly onerous demands placed by navies and shipowners for accuracy in predicting speed, power and maneuverability. Naval architects sometimes found it "difficult to find two runs of the same model that yielded identical results," and maneuvering tests often returned results of "doubtful validity." What was clearly lacking, as explained by one naval architect, was a "solid foundation" of hydrodynamic theory, which was now based "on ridiculous assumptions... there should be less doctrine and more Physics" (Roop 1929; Carlisle 1998, pp. 114–115, 134).

Thus, by the 1930s, it was increasingly apparent that the "Physics" necessary to build a solid theoretical foundation for naval architecture was to be found, not simply by extending current work in ship hydrodynamics, but by borrowing insights from the adolescent discipline of aircraft aerodynamics. This change in fundamental scientific assumptions is often characterized as a "paradigm shift" (Kuhn 1962), but in this instance, it is more accurate to call it a "flow reversal" between the two disciplines.

Much of the theoretical work in aircraft aerodynamics originated in Germany, which in part due to its pioneering development of the research-oriented university and close ties between academia and industry, has always "punched above its weight" in terms of its worldwide impact on scientific developments. These developments were marked early on by strong mathematical and physical bases, supported by extensive empirical confirmation. This very systematic and organized methodology extended into its aerodynamic research and later into hydrodynamic research (Clark 2006; Watson 2010b; Timmermann 1979, pp. 83–120; Nowacki 2000). Apart from the more obvious applications to sailboats, seaplanes and air-cushion vehicles, three naval architectural domains in particular were the beneficiaries of aerodynamic research: frictional resistance; propeller theory; and maneuvering and stability theory. A fourth domain, submarine design, was heavily influenced by British work on airships.

3.1 Frictional resistance and boundary-layer theory, 1904–1957

Since the 1870s, scientists and engineers working in ship hydrodynamics (notably the aforementioned William and Robert Froude, the British scientist Osborne Reynolds and Dutch naval architect Bruno Tideman) had used model test data to establish reasonably accurate estimates of skin friction drag at full scale. The methods used for establishing frictional resistance in the early twentieth century had changed little over two generations: measuring the towed resistance of various lengths of wood planks coated with different varnishes to simulate surface roughness, then scaling up to full size using the non-dimensional Reynolds number (a function of length, speed and fluid viscosity) to simulate the skin of metal ships coated in paint. It was not a completely satisfactory approach, as it did not accurately portray full-scale surface roughness or hull form effects. A "crisis in ship-powering prediction" emerged, as explained in an internal EMB report in 1929, which noted that "model basin testing is a very uncertain process," yielding only an approximation to the resistance and powering of a ship accurate to within 10 percent. "This is a rather discouraging state of affairs," the report went on, arguing that the proper use of the model basin would be to bolster the theoretical side of the hydrodynamics of skin friction through rigorous and long-term experiments (Bailey 1995, pp. 62–63. Quotes: Carlisle 1998, p. 115).

The reigning problem in hydrodynamic theory at the time was that there was no significant understanding of what happened at the surface of the body which could be used to develop a more accurate picture of what contributed to frictional drag. Observant sailors and shipbuilders had known for ages that the water directly on the skin of the ship moved slower than the surrounding water, forming a sort of boundary layer: as one shipbuilder explained in 1836 "that portion of the water accompanying a ship which is immediately next to her body is not passed by so quickly as that a little distance further off, etc.; consequently, the velocity of a ship through the water is actually less than the velocity with which she moves forward."[3] British scientist William John Macquorn Rankine, writing in 1862, assumed that "the agitation in the water caused by the friction on the ship's bottom extends only to a layer of water which is very thin as compared with the dimension of the ship," although under certain conditions "this assumption is not fulfilled" (Rankine 1862). William Froude himself implicitly recognized this boundary layer, noting that "no particles of fluid can be strictly regarded as sliding past the surface, in the sense in which a solid slides past a solid" (Froude 1869; Brown 2006, p. 178). However, neither Rankine nor Froude exploited these observations in their work on skin friction, nor would naval hydrodynamicists systematically do so until the 1930s.

[3] Blackburn assumed that this fluid drag was a sort of added mass, a concept today used in analysis of the motion of aircraft and ships, stating: "A sphere in motion is said to drag with it as much of the fluid as is equal to six-tenths of the bulk of the sphere.... So the total resistance of a ship is more of a compound and diversified nature by the circumstance of an atmosphere of water accompanying her" (Blackburn 1836, pp. 39–43).

Instead, it fell to a new generation of scientists, using higher mathematical and physical tools, to develop a working theory of how fluids behaved right at the surface of a solid body. In 1904, when Ludwig Prandtl (then a professor of mechanics in Hannover) developed his concept of the boundary layer, his great insight was that there existed not one, but two separate regimes of fluid resistance which could be analyzed separately: (1) a thin viscous region, the boundary layer itself, where frictional effects were felt, with the fluid adhering to the surface and gradually increasing in velocity outward; and (2) the region outside the boundary layer, which was essentially inviscid flow. The boundary layer and nature of resistance differed depending upon whether the flow was laminar (generally at lower Reynolds numbers, i.e., smaller scale, slower speeds and lower specific resistance) or turbulent (larger scale, higher speeds and higher specific resistance). This concept completely changed prevailing theories of frictional resistance and would revolutionize fluid dynamics.

Although many of the experiments that confirmed boundary-layer theory were done in a hydraulic context, the aerodynamic community was, at first, the main beneficiary of the results. Prandtl, now at the University of Göttingen, directed an institute for applied mechanics and an expanding extramural aerodynamic research facility (which would become the Aerodynamische Versuchsanstalt in 1919) where he continued to work on the problems associated with the boundary layer. Over the next two decades, many of Prandtl's students (again, often using hydraulic experiments) extended the theory of the boundary layer. Heinrich Blasius worked primarily in the laminar flow regime, while Theodore von Kármán and Hermann Schlichting extended Prandtl's theories into the frictional effects of roughness and turbulence. Turbulent flow, it was soon realized, was the critical domain to explore; although small-scale models often experience laminar flow conditions (and therefore lower resistance), at the scale of full-sized ships and aircraft the flow of air and water at the surface quickly becomes turbulent. Understanding the formation and characteristics of boundary layers in turbulent flow was critical to accurate prediction of fluid skin friction.

Von Kármán, one of Prandtl's first students, continued his work on turbulent flow when he moved to the Aachen Technische Hochschule in 1912 and then at the California Institute of Technology after 1930. Schlichting, who came to Göttingen in 1927, worked directly with Prandtl during the crucial years of his research, later using turbulent flow theory to help the German Navy and Air Force to develop low-drag rivets that reduced the resistance of ships and aircraft, and became the author of seminal textbooks on boundary-layer theory (Eckert 2006, p. 186; Epple 2009, pp. 295–297).

A fierce competition over fluid skin friction arose between Prandtl's group and von Kármán. "The competition was gentlemanly, of course," von Kármán later recalled. "But it was first-class rivalry nonetheless, a kind of Olympic Games, between Prandtl and me, and beyond that between Göttingen and Aachen…The 'ball' was the search for a universal law of turbulence" (Eckert 2006, pp. 107–128). In other words, both men were searching for a single non-dimensional equation known as the "friction line" or "skin friction coefficient (C_f)" that relates drag force to surface area and Reynolds number (R_n), in order to predict fluid friction in turbulent flow. By 1930, it appeared as though both men had arrived at similar conclusions concerning the logarithmic form of the friction line, where k and C are constants (Eckert 2010):

$$\frac{k}{\sqrt{C_f}} = \log_{10}(R_n \cdot C_f) + C$$

The German aerodynamics community had thus made enormous progress during the previous twenty-five years in the understanding of the boundary layer and its application to fluid friction, despite the upheavals of World War I and the subsequent deprivations under the Treaty of Versailles. Their work quickly influenced the conduct of aerodynamic research around the globe. The naval architecture community, however, demonstrated little interest in or knowledge of the subject, apart from work being done by Günther Kempf at the Hamburg Ship Model Basin and Friedrich Gebers at the Vienna Model Basin. Outside of these two centers, there was almost no mention of boundary-layer theory or references to Prandtl and von Kármán in the papers of ATMA, the Institution of Naval Architects (INA, UK) or Society of Naval Architects and Marine Engineers (SNAME, USA) (cf. ATMA 1989; RINA 1960; SNAME 1946).

That was about to change. In May 1932, Kempf and his colleague Ernst Foerster organized in Hamburg an international Conference on Hydromechanical Problems of Ship Propulsion (Konferenz über hydromechanische Probleme des Schiffsantriebs). It attracted enormous interest around the world, and the meeting room was filled with representatives from the major ship model testing basins in Germany, France, Sweden, Austria, the Netherlands and the USA (Bailey 1995, p. 95). This was the first time that the global community of naval architects received such wide exposure to the great theoretical leaps that had been made in the previous two decades by the German aerodynamic community. The primary subjects covered were frictional resistance and propeller hydrodynamics. This conference, more than any other event, served as the signal that a change in the direction of knowledge "flow" between the naval and aviation communities had begun, to where ship hydrodynamics began to be heavily influenced by aircraft aerodynamics.[4]

The first part of the two-day conference was devoted to current research on frictional resistance, the most advanced work being done at Aachen and Göttingen. Von Kármán, by then in California and unable to attend,[5] submitted a paper outlining his "rational theory of turbulence," in which he reiterated the logarithmic law and explained the effects of surface roughness on specific resistance, arguing that roughness "only commences to increase resistance when it projects outside the laminar boundary layer." This paper was commented upon by Prandtl, who did attend the conference but did not present any findings of his own. Kempf outlined his experiments which confirmed the theoretical formulations of von Kármán and Prandtl. The final paper was a short

[4] The papers referred to in the following sections were: Theodore von Kármán, "Theorie des Reibungswiderstandes," pp. 50–73; Günther Kempf, "Weitre Reibungsergebinsse an ebenen und rauhen Flächen,' pp. 74–82; Karl E. Schoenherr, "The Influence of Temperature on the Frictional Resistance Experienced by Plane Surfaces Moving in a Fluid," pp. 83–86 (Günther and Foerster 1932).

[5] Von Kármán, who was Jewish, had been increasingly concerned about the rise of official anti-Semitism in Weimar Germany. After several visits to the USA, he permanently left his post at Aachen in October 1930, just after the German Federal elections that helped vault the Nazi party into prominence, and assumed the directorship of the Guggenheim Aeronautical Laboratory at the California Institute of Technology in Pasadena.

discussion of the effect of temperature on friction by a relatively unknown American naval architect of German origin, Karl E. Schoenherr.

Schoenherr's short paper belied the much larger work that he was completing, just as the Hamburg conference was taking place. Schoenherr had already led an eventful life, having escaped a World War I prison camp by stowing away aboard ship to the USA. He became a U.S. citizen, attended MIT and began working at the EMB in Washington D.C. He became interested in the problem of turbulent flow and pursued his PhD at Johns Hopkins University with a dissertation on the subject, knowing full well that Prandtl and von Kármán were ahead in the race.

Through the years 1931 and 1932, Schoenherr could be found working at the EMB late into the night, long after his EMB colleagues had gone home, recording hundreds of experimental data points from model basins in the USA, Germany and elsewhere on massive sheets of graph paper, because (as he explained to his professors), "whoever comes out first with an answer that seems internationally acceptable, has something that builds a reputation" (Schoenherr 1989; Carlisle 1998, pp. 116–118). By 1932, he had completed his groundbreaking thesis and presented the results several months after the Hamburg conference, at the SNAME annual meeting in New York in November of that year. Building upon Prandtl and von Kármán's work, Schoenherr stated that the best fit to the reams of data would be represented by the equation (Schoenherr 1932):

$$\frac{0.242}{\sqrt{C_\mathrm{f}}} = \log_{10}(R_\mathrm{n} \cdot C_\mathrm{f})$$

Naval architects who examined the data found that Schoenherr's equation agreed well with the data. Even von Kármán was impressed: in late 1932, he wrote to Prandtl, saying that "Schoenherr has compiled the material very nicely and presented it in the previous meeting of the American Society [of Naval Architects]" (Kármán to Prandtl 1932).

The impact of the 1932 Hamburg Conference was almost immediately felt in the international naval architecture community, particularly in the domain of ship resistance and powering. In an after-dinner speech, consulting engineer Giovanni (John) de Meo, at the instigation of Dutch naval architect Lauren Troost, "pleaded strongly for international technical cooperation" in this domain. The following year, Troost hosted a meeting of model basin supervisors in The Hague to outline the framework for coordinating research and cooperation between model basins around the globe. The association, which became known as the International Towing Tank Conference (ITTC), continues to meet every three years to compare notes and coordinate work (Troost 1933, pp. 7–8). A parallel American offshoot, the ATTC, was created in 1938.

Naval architects scrupulously examined the friction lines developed by Prandtl, Kármán and Schoenherr. After careful analysis, in 1947, the ATTC adopted Schoenherr's equation as the standard friction line to be used for all resistance calculations in US and Canadian ship model basins. In 1950, the British Ship Research Association conducted full-scale hull friction tests on *Lucy Ashton* (a full-sized ship stripped of all underwater appendages, and fitted with above-water jet engines for propulsion) which showed that using Schoenherr's equation to calculate full-scale bare-hull frictional resistance was accurate to within 3 % of actual measurements, a vast improvement over previous methods. In 1957, a version of Schoenherr's equation, modified primarily by George Hughes at the UK National Physical Laboratory, was adopted by the ITTC (Lewis 1988, vol. 2, pp. 7–17; Grigson 2000; ITTC 2013).

Naval architects took notice of the work on turbulent flow and boundary-layer theory by Prandtl and von Kármán in other ways. Where before almost no naval hydrodynamic research had made reference to Aachen and Göttingen, now those findings on frictional resistance took on great importance in response to the "crisis" ship-powering predictions. One direct result was that model basins recognized the need to stimulate turbulent flow in small-scale models (which, operating at lower Reynolds numbers, often had laminar flow over significant portions of the hull) in order to accurately predict full scale, fully turbulent frictional resistance. Based on early work done by Kempf in Hamburg, model basins around the world began employing trip wires, pins, sandpaper and other mechanisms near the bow of the ship model to generate turbulent flow over the entire body, a practice that significantly improved the correlation of model test data with full-scale data, and which is now taught to every freshman-year naval architect (Hughes 1951, 1952; Saunders 1957, vol. 1, pp. 89–154, vol. 2, pp. 86–144).

3.2 Propeller design and circulation theory, 1915–1952

In addition to exposing naval architects to the work of Prandtl and others on boundary-layer theory and turbulent friction, the 1932 Hamburg Conference on Hydromechanical Problems of Ship Propulsion also re-introduced naval architects to the concept of circulation—also a product of Prandtl's research into aerodynamics—as a fundamental principle of lift and drag, with particular reference to the action of ship propellers. Prior to this conference, much of the research into shipboard screw propellers had been informed by two theories that were born late in the previous century—momentum theory and blade element theory. Neither proved satisfactory in calculating the actions of propellers in a way that allowed naval architects to overcome the "crisis in ship-powering prediction" that plagued them in the 1920s and early 1930s (Carlisle 1998, p. 115).

In 1865, the momentum theory of propellers was evolved by Rankine, who modeled the propeller as an infinitely thin disk (i.e., with an infinite number of blades) that instantaneously imparts momentum to the fluid flowing through it, providing thrust. Because he assumed an ideal fluid, the propeller did not experience energy loss due to frictional drag. Rankine originally assumed that the propeller did not produce any rotation in the fluid, a simplification later corrected by Robert Froude in 1887. The theory defined an ideal efficiency for a propeller, bounded only by the losses due to changes in momentum of the fluid (Lewis 1988, vol. 2, pp. 131–143; John 2007, pp. 169–172).

The deficiency in this model was that it did not provide any means of calculating the thrust and torque of real propellers, nor did it differentiate between a good design and a bad one. William Froude, in 1878, sought to remedy this by introducing the blade element theory, which accounted for the geometry of the propeller blades. In this formulation, propeller blades were divided into a large number of airfoil-shaped strips, for each of which the lift and drag could be calculated (with appropriate assumptions and approximations). Integrating the individual elements allowed for the direct calculation of thrust and torque for the propeller. It did not, however, provide any means of calculating the efficiency of the propeller, so that the results of momentum theory and blade element theory were inconsistent. (William Perring, an aeronautical engineer, unsuccessfully attempted to marry momentum theory with blade element theory; see Perring 1928.) Moreover, the calculated values derived from the two theories were often considerably different from the actual values of torque, thrust and efficiency of real-world propellers.

In 1907, British engineer Frederick Lanchester published a book entitled *Aerodynamics* in which he introduced the concept that the thrust of an airfoil is the product of what he termed "vortex emission" of fluid around the airfoil, and the resulting vortices that trailed from the edges and tips of the foil by the blades of the propeller. Lanchester had actually developed his ideas a decade earlier, but had initially failed to gain much attention in the scientific community.[6] In 1915, Lanchester introduced these concepts to the world of naval architecture, in a paper he presented before the Institution of Naval Architects on corrections to Robert Froude's momentum theory (Lanchester 1915). However, his concepts fell upon apparently deaf ears, for Lanchester's theory was barely referenced in any further work on ship propellers through the 1910s and 1920s.

The similar concept of "circulation" was developed independently and almost simultaneously by Wilhelm Kutta, Nikolai Joukowski, and most importantly, by Ludwig Prandtl (Darrigol 2005, pp. 302–322; Bloor 2011). The key insight into their theories is that a two-dimensional airfoil generates lift from two sources: (1) asymptotically rectilinear uniform flow and (2) non-vanishing circulation around the foil. The circulation around a three-dimensional airfoil also induces drag as the airfoil sheds vortices from the tips. Much of the important experimental work that verified these mechanisms of lift and drag was done at Prandtl's laboratory in Göttingen, from 1910–1918. Prandtl was ably helped by his assistant, naval-architect-turned-aerodynamicist Albert Betz, as well as by his doctoral student Max M. Munk. As with the boundary layer investigations, Prandtl's work on circulation was often conducted in friendly but fierce competition with Kármán's group in Aachen. Both groups maintained close connections with the hydrodynamic laboratories in Hamburg and Berlin, influencing naval architects such as Fritz Horn, Heinrich Helmbold and Fritz Gutsche (Lewis 1988, vol. 2, p. 206).

It was not until after World War I that the results in circulation theory derived in Göttingen and Aachen became widely known to the non-German scientific community. NACA was instrumental in this process, as part of a concerted effort to transfer technical and scientific knowledge out of Germany, which was by then recognized to be the world leader in aeronautical research and application. NACA paid Prandtl handsomely for a lengthy report that detailed the state of knowledge that had been achieved to date at Göttingen. In 1920, on the advice of Jerome Hunsaker, NACA also hired Max Munk to work in its headquarters and later in one of its laboratories.

[6] One early exception to this oversight was the work of the German engineer and physicist Hermann Föttinger, who in 1911 applied Lanchester's theory to turbine blades (Föttinger 1911). He later extended this research to ship propellers.

During his six-year stint at NACA, Munk conducted both theoretical and experimental research that married Prandtl's airfoil theory to practical design, resulting in many of the successful "NACA profiles," a systematic series of airfoil shapes that became widely used for aircraft wings as well as for ship and aircraft propellers (Prandtl 1923; Munk 1924a; Eckert 2005).

The wider community of naval architects was re-introduced to circulation theory as a result of the 1932 Hamburg Conference, this time bearing the imprint of Prandtl rather than Lanchester. The main problem for circulation theory addressed at this conference was the action of propellers in non-uniform flow behind ships. Unlike most aircraft propellers which are mounted at the front of the wing or nose (thus in a free stream), a ship's propeller is mounted behind the hull, so that the wake (flow into a ship's propeller) varies greatly across the disk. The Hamburg papers gave some early indications of how to use circulation theory to modify existing blade element theories in order to account for the non-uniformity of flow.[7]

In 1944, the British naval architect Leonard Burrill, building on Prandtl's theories and the work presented in Hamburg (especially that of Fritz Gutsche), developed an analytical method that combined blade element and momentum theories with circulation theory in order to properly account for non-uniform flow. Burrill's straightforward method could be performed by hand for quick-turnaround calculations of moderately loaded propellers. In 1952, Hermann Lerbs, formerly a colleague of Kempf at the Hamburg Ship Model Basin but by then working at the David Taylor Model Basin in the USA, developed a more rigorous lifting-line analysis for designing wake-adapted propellers. Complex to use, Lerb's method became more popular with the advent of computer-aided calculations and is now the de-facto technique found in countless propeller design software applications (Burrill 1944; Lerbs 1952. See also Lewis 1988, pp. 204–213; John 2007, pp. 174–182; and Saunders 1957, vol. 2, pp. 609–637).

3.3 Theory of maneuvering and course stability, 1911–1946

Early studies of ship maneuvering at the turn of the twentieth century were concerned with simple, straightforward measures such as tactical diameter, a measure of the ability to attack or avoid an enemy. Naval architects examined the kinematics of the problem, for example relating the diameter to speed, rudder angle and propeller rotations, but did not address the physics behind it (Clarke 2003, p. 2).

By contrast, from the earliest days, aeronautical engineers were modeling the aerodynamic forces on airplanes and airships, both mathematically and empirically. Even before the Wright brothers, aircraft designers understood the need for inherent aircraft stability in flight (that is, the ability of the aircraft to return to its original orientation after a perturbation) and attempted to model the forces on control surfaces. In 1911, a British mathematics professor, George H. Bryan, worked out the six-degree-of-freedom equations of motion for an aircraft. These equations calculated stability

[7] The papers dealing with circulation were by Alfred Betz, Fritz Weinig, Melitta Schiller (later to become the sister-in-law of Claus von Stauffenberg; she was involved in the 1944 plot to assassinate Adolf Hitler, surviving retribution only to be shot down in combat), Fritz Horn, Heinrich Helmbold, Einar Hogner and Fritz Gutsche. (Günther and Foerster 1932, pp. 161–217, 343–396).

derivatives based upon forces in straight-line motion as well as rotary motions of roll, pitch and yaw. The rotary forces were particularly difficult to resolve, but Bryan suggested a method using a whirling arm to measure them (Bryan 1911, pp. 45–46; Abzug and Larrabee 2002, pp. 91–12, 266–267).

The whirling arm—essentially a long rotating arm with the model fixed at the end—had initially been developed over a hundred years earlier as a way of measuring airflow in a contained environment. Most European aeronautical laboratories—e.g., at Saint-Cyr in France, Göttingen in Germany and the National Physical Laboratory at Teddington, UK—employed whirling arms, but they had problems with instrumentation and interference from the arm itself, so whirling arms were on their way out as labs built fixed wind tunnels to provide more accurate results (Zahm 1914).

The need to measure rotary forces breathed new life into the whirling arm. It became the principal method for developing rotary stability derivatives, which are the non-dimensional variations in forces and moments as a function of angular velocity in roll, pitch and yaw. In Britain, for example, Leonard Bairstow used it to develop equations for rolling during a banked turn (Bairstow 1920, p. 105; Hashimoto 2007).

In France, the whirling arm housed in the *manège* (roundabout) of Saint-Cyr became the focus of attention for aircraft stability. Maurice Roy built upon the work of Bryan and Bairstow to develop equations of motion that explicitly accounted for wind gusts (Roy 1931). Both the *manège* and Roy's work came to the attention of French naval architects, who were searching for a methodology to more rigorously calculate a ship's course stability, i.e., its ability to maintain course after a perturbation. In the 1920s, the planned expansion of the Paris model basin was to include a "*manège (bassin de giration)*" i.e., a rotating-arm basin, but it initially conflicted with the adjacent flying field at Issy-les-Moulineaux, so construction could not start until 1938 (DGA/DCN 1988, p. 23). That same year, Pierre Contensou applied Roy's equations of motion to a ship's course stability and turning characteristics (Contensou 1938, 1946).

The start of World War II in 1939 halted all work on course stability. The nearly completed rotating-arm basin—the first of its type in the world—was bombed during the German occupation of Paris in 1940. It was not rebuilt until 1945, after which course stability and maneuvering research (employing Roy's original concepts of aircraft motion) went into full swing. These experiments were most famously performed under the naval architect Jean Dieudonné,[8] who developed the eponymous spiral maneuver that is used to measure a ship's course stability (Bleuzen 1946; Dieudonné 1949).

A particularly telling example of the influence of aircraft aerodynamics is found in the evolution of maneuvering theory by Ken Davidson at Stevens Institute of Technology in Hoboken, NJ. Davidson was a former military pilot who initially used his knowledge of aerodynamics in yacht design.[9] In the 1930s, his work at Stevens had been largely funded through the Research Corporation for Science Advancement, but

[8] Dieudonné's internal reports on maneuvering and course stability were collected and translated into English by Harold Saunders at the David Taylor Model Basin (Saunders 1952). Note that the naval architect Jean Dieudonné (1900–1972) should not be confused with the mathematician Jean Dieudonné (1906–1992).

[9] It is worth noting that in 1946, Stevens Institute brought another aviation specialist, Boris V. Korvin-Kroukovsky, former chief design engineer at Aeromarine and EDO Aircraft, into its hydrodynamics laboratory. There he made major contributions to ship theory, e.g., *Theory of Seakeeping*, (Korvin-Kroukovsky 1951).

the advent of World War II shifted the emphasis to naval work. In 1939, he began examining the turning performance of destroyers, but was hampered by lack of facilities to test small models in turns. Undaunted, he arranged to conduct self-propelled model tests in the swimming pools of Stevens Institute and Columbia University (nights and weekends). The results, published in 1944 as "On the Turning and Steering of Ships," examined the performance of hulls in turns, but made little headway in establishing quantitative control characteristics for course stability and maneuvering (Davidson 1940a,b, 1944).

The results of these investigations convinced Davidson that existing theory and experimental procedures were inadequate for the more demanding requirements of naval work and began a literature search for other solutions. He happened upon current research being performed by Leonard Schiff, a nuclear physicist who was working part-time on anti-submarine operations and torpedo maneuvering. Schiff alerted Davidson to the large whirling arm at the Guggenheim Airship Institute in Akron, Ohio, which had been built a decade earlier to examine the rotary forces on rigid airships. Davidson realized that he needed a similar capability for his own work and applied to the US Navy for funding. By 1945, a rotating-arm facility was up and running, which Davidson and Schiff used to further develop the theory of ship maneuvering and control (Bruno 1993, p. 13; ASME 1981).

The Davidson and Schiff paper which gave the results of these investigations, "Turning and Course-Keeping Qualities," explicitly shows the influence of the aerodynamics community. It was far more mathematically rigorous than the Davidson paper of just two years earlier, as they carefully followed aerodynamic practice in defining forces and moments acting on a ship, using essentially the same equations first employed by Bryan. The hydrodynamic forces developed experimentally using the rotating arm provided systematic, quantitative results for control derivatives. This marked a turning point in the assessment of ship maneuvering and control; within a few years of the facilities at Paris and Stevens Institute, rotating-arm basins became standard fixtures at major naval architecture research establishments, and the aerodynamics-based representation of ship motions invoked by Davidson and Schiff became the ITTC worldwide standard (Davidson and Schiff 1946; Lewis 1988, vol. 3, pp. 191–422; ITTC 2013).

3.4 Airship influence on submarine design, 1924–1953

The modern submarine, with its streamlined body-of-revolution hull design, directly traces its roots to airship design, in particular the British *R*101 program of the 1920s. The early experimental submarines and submersibles of the nineteenth century—*Ictineo*,*Gymnote* and *Holland*, to name a few—were generally streamlined, following the concept of a fishlike form. The later U-boats, fleet boats and other submarines of the World War I and World War II eras were generally ship-shaped, as they operated for long periods at high speed at the surface, with only short stints of underwater operation, limited by battery power to low speeds, typically 6–8 knots.[10]

[10] One notable exception to ship-shaped submarines was the German V80 submarine (1939) with an "outer casing shaped like a fish," designed by Hellmuth Walter with a closed-cycle engine that could give high speeds underwater (Rössler 1981, pp. 168–172).

The streamlined airship was a product of the aerodynamic research conducted at Göttingen for companies like Luftschiffbau Zeppelin GmbH, before World War I. A series of experiments using the newly established wind tunnel confirmed Prandtl's boundary-layer theory and further established that the optimal body of revolution (i.e., one that produces minimum resistance) had a blunt nose and pointed tail. Prior to this research, many airships resembled blunt-ended sausages. Afterward, all had the now-commonplace airfoil shape (Eckert 2006, pp. 46–49).

After World War I, British aeronautical engineers were under pressure to produce results comparable to or better than their German counterparts (Richmond 1929a, p. 174). The *R*101 project was begun in 1924 as the Air Ministry side of a government–commercial competition to develop a troop-carrying fleet of airships (immortalized in Shute 1954). The design team developed a series of minimum-drag hulls based on elliptical forms, before settling on a slender form with no parallel middle body (Richmond 1929b, p. 687; Cox 1929, pp. 800–809).

One of the team members, Hilda M. Lyon, was instrumental in the structural design of *R*101 and contributed to the aerodynamic development of the craft. Her interest in aerodynamics soon drew her to attend the MIT Department of Aeronautics from 1930 to 1932. Her Master's thesis "The Effect of Turbulence on the Drag of Airship Models" examined these effects on a pair of *R*101 models with different fullness ratios and highlighted how initial test conditions affected experimental results (Lyon 1930, 1932; Baker 1932, vol. 1, p. 210). Lyon subsequently studied under Prandtl at Göttingen and was working on boundary layer theory and stability before her untimely death in 1946.[11]

*R*101 crashed in 1930 after just a few flights. Subsequent accidents such as those which befell *Akron* and *Hindenburg* effectively ended the airship era by 1940. But the airship hull form was resurrected by the US Navy after World War II in its search for a submarine with high-speed submerged performance. In 1949, the Committee on Undersea Warfare submitted an initial report on the optimum shape for a research submarine that could exceed 20 knots submerged. When several conventional submarine forms were compared with a streamlined hullform based on *R*101, the results were startling; the *R*101 shape required less than half the power of the World War II fleet submarine for the same speed. The *R*101 airship thus became the starting point for the model research that led to the USS *Albacore*, the US Navy's prototype for the streamlined, body-of-revolution submarine. This submarine owed more than just its hull form to the world of aerodynamics; several models of *Albacore* were tested in the large NACA wind tunnel at Langley (Largess and Mandelblatt 1999, pp. 20–22; Gertler 1950; Polmar and Moore 2004, p. 128). The equations of motion for the submerged hull were developed directly from airship equations of motion first elucidated by Max Munk.[12]

USS *Albacore*, commissioned in 1953, was the forerunner of all modern submarine hulls. The diesel boat *Barbel* and nuclear boat *Skipjack* were closely based upon it,

[11] Additional information on Hilda Lyon is from the author's correspondence and telephone interviews with her niece Enid Greenwood, November 2009.

[12] Note that the pitch destabilizing force of a submarine moving at an angle of attack is referred to as the "Munk moment." See Munk (1924b).

both of which became the model for many Western submarines, both conventional and nuclear. Even the Soviet Navy copied the *Albacore* design from public and intelligence sources, beginning in 1957 with $K-3$ *Leninsky Komsomol* (Polmar and Moore 2004, p. 74).

Interestingly, the Committee on Undersea Warfare report, which started it all back in 1949, labeled the airship shape as the "Lyon Form," in honor of Hilda Lyon's contributions to *R*101. It is therefore the name of aeronautical engineer Hilda Lyon that has subsequently been used to describe the shape of the modern submarine.

4 Conclusions

From the earliest days of flight, practitioners have noted the many similarities between ships and aerial vehicles and sought to apply the principles and technologies used for centuries at sea to the newfangled dirigibles and heavier-than-air craft. When the development of airplanes and airships swung into high gear, naval architects initially led the way, applying their theoretical knowledge and experimental techniques to their design and production, along the way giving us the nautical terminology we use to describe aircraft—port, starboard, roll, pitch and waterlines.

In less than a generation, the roles were reversed. Naval architects, faced with a "crisis in ship-powering prediction," as well as the need to design wake-adapted propellers and to accurately develop quantitative control characteristics for course stability and maneuvering, quickly turned to the insights derived from aircraft aerodynamics (frequently originating in Germany) to inform their research and engineering, leading to a more formal approach to ship hydrodynamics. This culminated in the development of the modern submarine hullform, based upon airship design and corresponding equations of motion.

The connection between aircraft aerodynamics and ship hydrodynamics is as strong in the twenty-first century as it was in the early twentieth century. Modern day submarine designers continue to use airship and missile experimental data to examine flow separation at angles of attack. The methods and techniques of computational fluid dynamics, originally created as a joint effort between the hydrodynamic and aerodynamic communities, are continuously developed, improved and shared across both aircraft and naval fields.[13] Planing boats, hydrofoils, air-cushion vehicles and surface effect ships (and more recently wing-in-ground effect craft or ekranoplans) are all representative artifacts of this crossover engineering and scientific discipline (King 1966). Perhaps the most elegant example of the connection between aerodynamics and hydrodynamics is in the world of yacht design, notably that of the hi-tech America's Cup. In 2010, the *USA-17* trimaran handily won the competition, sporting not a traditional sail but instead a rigid wingsail (Wolverton 2010), and the AC72-class catamarans in the 2013 America's Cup all carry wingsails that would not look out of place on a modern airliner.

[13] For example, a fundamental and highly cited study on three-dimensional flow that formed the basis for computational fluid dynamics (Hess and Smith 1962) was carried out by Douglas Aircraft under the US Navy Bureau of Ships fundamental hydromechanics research program NS 715-102, administered by the David Taylor Model Basin.

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References

Abzug, Malcolm J., and E. Eugene Larrabee. 2002. *Airplane stability and control*. New York: Cambridge University Press.

Aircraft International Register. 1929. *Flight*. 8 Aug, 1929, p. 863.

American Bureau of Shipping. 2006. *The history of the American Bureau of Shipping 1862–2005*. Houston: ABS.

Anderson, Håkon, and John Collett. 1989. *Anchor and balance: Det Norske Veritas 1864–1989*. Oslo: Cappelens Folag.

Anderson, John. 1997. *A history of Aerodynamics*. Cambridge: Cambridge University Press.

Annual Report. 1930. *Annual Report of the Secretary of the Navy*. Washington DC: US GPO.

ASME. 1981. American Society of Mechanical Engineers Landmarks brochure H072, "Rotating-Arm Model Test Facility: An International Historic Mechanical Engineering Landmark".

ATMA. 1989. *Association Technique Maritime et Aéronautique Centième Anniversaire*. Paris: ATMA.

ATMA. 2013. "Histoire". http://www.atma.asso.fr/FR/histoire.htm. Accessed June 2013.

Bailey, David. 1995. *Ships in the making: A history of ship model testing at Teddington and Feltham, 1910–1994*. London: Lloyd's of London Press.

Bairstow, Leonard. 1920. *Applied Aerodynamics*. London: Longmans, Green.

Baker, George S. 1932. *Ship design, resistance and screw propulsion*, vol. 2. Liverpool: Charles Burchill.

Blackburn, Isaac. 1836. *The theory and science of naval architecture familiarly explained*. Plymouth: Bartlett.

Bleuzen, Jean. 1946. L'Etude de la Giration au Bassin d'Essais des Carènes. *Bulletin de l'Association Technique Maritime et Aéronautique* 45: 477–496.

Bloor, David. 2011. *The enigma of the aerofoil: Rival theories in aerodynamics, 1909–1930*. Chicago: University of Chicago Press.

Brown, David K. 2006. *The way of a ship in the midst of the sea: The life and work of William Froude*. Penzance: Periscope.

Bruno, Michael S. 1993. *The history of towing tank research at Stevens (pamphlet)*. Hoboken: Stevens University Davidson Laboratory.

Bryan, George H. 1911. *Stability in aviation*. London: MacMillan.

Bureau Veritas. 1978. Bureau Veritas 1828/1978: A record of 150 years. Paris: PEMA 2B.

Burrill, Leonard. 1944. Calculation of marine propeller performance characteristics. *Transactions of North East Coast Institute of Engineers and Shipbuilders* 60: 269–294.

Carlisle, Rodney P. 1998. *Where the fleet begins: A history of the David Taylor Research Center, 1898–1998*. Washington, DC: Naval Historical Center.

Carlton, John. 2007. *Marine propellers and propulsion*. Amsterdam: Elsevier.

Carra, Jean-Louis. 1784. *Essai sur la nautique aérienne*. Paris: Onfroy.

Clark, William. 2006. *Academic charisma and the origins of the research university*. Chicago: University of Chicago Press.

Clarke, David. 2003. The Foundations of Steering and Maneuvering. In *6th IFAC conference on maneuvering and control of marine craft*. Girona: University of Girona.

Comptes Rendues. 1854. *Comptes Rendues Hebdomadaires des Séances de l'Académie des Sciences*. 38: 953, 998–999.

Contensou, Pierre. 1938. Mecanique du navire en route et en giration. *Bulletin de l'Association Technique Maritime et Aéronautique* 42: 597–614.

Contensou, Pierre. 1946. Note sur la Cinématique Générale du Mobile Dirigé. *Bulletin de l'Association Technique Maritime et Aéronautique* 45: 323–368.

Cox, Harold Roxbee. 1929. The external forces on an airship structure. *Journal of the Royal Aeronautical Society* 33(225): 725–811.

Darrigol, Olivier. 2005. *Worlds of flow*. Oxford: Oxford University Press.

Davidson, Kenneth. 1936. An experimental towing tank for small models. *Journal of Applied Mechanics* 3(2): A41–A46.

Davidson, Kenneth, 1940a. Experimental Towing Tank 1940 Annual Report, no. 142, Research Corporation for Science Advancement (Tucson, AZ) Archives Box 42 fol. 528.

Davidson, Kenneth, 1940b. Memo of December 13, 1940. Research Corporation for Science Advancement (Tucson, AZ) Archives Box 36 fol. 503.

Davidson, Kenneth. 1944. On the turning and steering of ships. *Transactions of the Society of Naval Architects and Marine Engineers* 52: 287–324.

Davidson, Kenneth, and Leonard Schiff. 1946. Turning and course-keeping qualities. *Transactions of the Society of Naval Architects and Marine Engineers* 54: 152–200.

DGA/DCN. 1988. *1906–1988: Quatre-vingt-deux ans d'histoire du Bassin d'Essais des Carènes de Paris.* Paris: DGA/DCN.

Dieudonné, Jean. 1949. Note sur la Stabilité du Régime de Route des Navires. *Bulletin de l'Association Technique Maritime et Aéronautique* 48: 463–490.

Durand, William F. 1953. *Adventures in the Navy*. New York: McGraw Hill.

Eckert, Michael. 2005. Strategic internationalism and the transfer of technical knowledge: The United States Germany and aerodynamics after World War I. *Technology and Culture* 46(1): 104–131.

Eckert, Michael. 2006. *The dawn of fluid dynamics*. Weinheim: Wiley-VCH.

Eckert, Michael. 2010. A kind of Olympic Games: the Prandtl-Kármán rivalry on turbulent skin friction. In *Conference on Fluid Resistance from Newton to the Present*. Paris: Université Pierre et Marie Curie.

Epple, Moritz. 2009. Calculation, measurement and leadership: War research at the Kaiser Wilhelm Institute for Fluid Dynamics, 1937–1945. In *The Kaiser Wilhelm Society under National Socialism*, ed. Susanne Heim et al., 283–311. Cambridge, UK: Cambridge University Press.

Ferber, Ferdinand. 1908. *L'aviation: ses débuts, son développement: de crête à crête, de ville á ville, de continent á continent.* Paris: Berger Levrault.

Forrest, Matthew G. 1947. Application and use of aluminum alloys in ship construction. *Transactions of the Society of Naval Architects and Marine Engineers* 55: 305–331.

Föttinger, Hermann. 1911. *"Über die physikalischen Grundlagen der Turbinen- und Propellerwirkung", Zeitschrift für Flugtechnik und Motorluftschiffahrt.* Berlin: R. Oldenbourg Verlag.

Froude, William. 1869. On Some Difficulties in the Received View of Fluid Friction. In *British Association for the Advancement of Science (Mechanical Science Section) Report* Exeter: BAAS.

Fulton, Garland. 1963. The General climate for Technological Developments in Naval Aeronautics on the Eve of World War I. *Technology and Culture* 4(2): 154–165.

Gertler, Morton. 1950. *Resistance experiments on a systematic series of streamlined bodies of revolution for application to the design of high-speed submarines, DTMB Report C-297.* Washington, DC: DTMB.

Gillespie, Richard. 1984. Ballooning in France and Britain, 1783–1786: Aerostation and adventurism. *Isis* 75(2): 248–268.

Grigson, Christopher. 2000. Accurate friction lines: An essential to understanding hull flow. Royal Institution of Naval Architects magazine, *The Naval Architect*, 27–30.

Haas, David, et al. 2011. Birth of U.S. Naval Aeronautical Engineering and Phenomenal Rise to Excellence. Bethesda: Naval Surface Warfare Center Carderock Division, Report NSWCCD-50-TR-2011/068.

Hashimoto, Takehiko. 2007. Leonard Bairstow as a Scientific Middleman: Early Aerodynamic Research on Airplane Stability in Britain, 1909–1920. *Historia Scientarium* 17(2): 102–120.

Hess, John L., and Apollo Milton Olin Smith. 1962. *Calculation of non-lifting potential flow about arbitrary three-dimensional bodies*. Long Beach: Douglas Aircraft report ES 40622.

Higham, Robin D.S. 1961. *The British rigid airship, 1908–1931: A study in weapons policy*. London: G.T. Foulis.

Hovgaard, William. 1927. Deformations and stress distributions in rigid airships. *Transactions of the Institution of Naval Architects* 69: 314–339.

Hughes, George. 1951. Turbulence stimulation on ship models. *Transactions of the Society of Naval Architects and Marine Engineers* 54: 281–314.

Hughes, George. 1952. Frictional resistance of smooth plane surfaces in turbulent flow. *Transactions of the Institution of Naval Architects* 94: 287–322.

Hughes, Thomas. 1971. *Elmer sperry; Inventor and engineer*. Baltimore: Johns Hopkins University Press.

Hunsaker, Jerome. 1916. A review of hydrodynamical theory as applied to experimental aerodynamics. In *Transactions of the international engineering congress 1915*, 12 vols, vol. 11, 160–207. San Francisco: Neals Publishing.

Hunsaker, Jerome. 1920. Naval Architecture in Aeronautics. *Aviation and Aeronautical Engineering* 9(1): 10–14.

Hunsaker, Jerome. 1924. Aeronautics in naval architecture. *Transactions of the Society of Naval Architects and Marine Engineers* 32: 1–25.

ITTC. 2013. Website http://ittc.sname.org/ Accessed June 2013

Kempf, Günther, and Ernst Foerster (eds.). 1932. *Hydromechanische Probleme des Schiffsantriebs*. Hamburg: HSV.

King, Horace F. 1966. *Aeromarine origins: The beginnings of Marine Aircraft, Winged Hull, Air-Cushion and Air-Lubricated Craft, Planing Boats and Hydrofoils*. London: Putnam.

Korvin-Kroukovsky, Boris V. 1951. *Theory of seakeeping*. New York: SNAME.

Kuhn, Thomas. 1962. *The structure of scientific revolutions*. Chicago: University of Chicago Press.

Lanchester, Frederick W. 1915. A contribution to the theory of propulsion and the screw propeller. *Transactions of the Institution of Naval Architects* 57: 98–116.

Largess, Robert, and James Mandelblatt. 1999. *USS Albacore: Forerunner of the future*. Portsmouth, NH: Portsmouth Marine Society.

Leclert, Emile. 1872. M. Dupuy de Lôme's Aerial Ship. *Naval Science* 1: 280–285.

Lehmann, Eike. 1999. *100 Jahre Schiffbautechnische Gesellschaft: Biografien zur Geschichte des Schiffbaus*. Berlin: Springer.

Lerbs, Hermann W. 1952. Moderately loaded propellers with a finite number of blades and an arbitrary distribution of circulation. *Transactions of the Society of Naval Architects and Marine Engineers* 60: 73–117.

Leroux, Emile. 1925. Note sur un paramètre de similitude mécanique dans les mouvements des fluides. *Bulletin de l'Association Technique Maritime et Aéronautique* 29: 235–263.

Leroux, Emile. 1927. *Cours d'aéronautique*. Paris: C. Béranger.

Lewis, Edward (ed.). 1988. *Principles of naval architecture*, vol. 3. Jersey City: SNAME.

Lyon, Hilda M. 1930. The strength of transverse frames of rigid airships. *Journal of the Royal Aeronautical Society* 34(236): 497–556.

Lyon, Hilda M. 1932. *The Effect of Turbulence on the Drag of Airship Models*. Cambridge, MA: MIT Master's thesis; also published as British Aeronautical Research Council. Report no. 1151.

Mack, Pamela. 1998. *From engineering science to big science: the NACA and NASA Collier Trophy research project winners*. Washington, DC: NASA History Office.

McEntee, William. 1911. Some applications of the principles of naval architecture to aeronautics. *Transactions of the Society of Naval Architects and Marine Engineers* 19: 287–298.

Munk, Max M. 1924a. *Simplifying assumptions, reducing the strict application of classical hydrodynamics to practical aeronautical computations*. Washington DC: NACA Technical Note No. 207.

Munk, Max M., 1924b. The Aerodynamic Forces on Airship Hulls. Washington DC: NACA, Report 184.

Noalhat, Henri. 1910. *Navigation aérienne et navigation sous-marine: deux faces d'un même problème*. Paris: L. Geisler.

Nowacki, Horst. 2000. Zur Entwicklung der Schiffshydrodynamik im 20. Jahrhundert. In *100 Jahre Schiffbautechnische Gesellschaft: Jubiläumsveranstaltung an der TU Berlin*, ed. Eike Lehmann. Berlin: STG-Vortrag.

Nowacki, Horst and Larrie Ferreiro, 2003. Historical roots of the theory of hydrostatic stability of ships. In *Proceedings of the 8th international conference on the stability of ships and ocean vehicles*, ed. Luis Pérez Rojas, 1–30. Madrid: ETSIN, Reprinted as MPIWG Preprint 237, Berlin: Max Planck Institute for the History of Science.

Perring, William. 1928. The vortex theory of propellers and its application to the wake conditions existing behind a ship. *Transactions of the Institution of Naval Architects* 69: 226–238.

Polmar, Norman, and Kenneth J. Moore. 2004. *Cold War Submarines*. Washington DC: Brassey's.

Prandtl, Ludwig. 1923. *Applications of modern hydrodynamics to aeronautics*. Washington, DC: NACA Report No. 116.

Peter, Quartermaine. 1996. *Building on the Sea: Form and meaning in Modern Ship Architecture*. London: National Maritime Museum and Academy Group.

Rankine, William John Macquorn. 1862. Abstract of an investigation of the resistance of ships. *Journal of the Franklin Institute* 73: 22–29.

Raymer, Daniel P. 2006. *Aircraft design: A conceptual approach*. Reston, VA: AIAA.

Richmond, Vincent C. 1929a. Some modern developments in airship construction. *Transactions of the Institution of Naval Architects* 70: 173–209.

Richmond, Vincent C. 1929b. R101. *Journal of the Royal Aeronautical Society* 33(224): 686–723.

RINA. 1960. *Royal Institution of Naval Architects Index to the Transactions 1860–1959*. London: RINA.

Roenne, Baron A. 1913. Notes on Airship Construction. *Transactions of the Institution of Naval Architects* 55: 117–135.
Roland, Alex. 1978. *Underwater Warfare in the age of sail.* Bloomington: Indiana University Press.
Roland, Alex. 1985. *Model Research: The National Advisory Committee for Aeronautics 1915–1958.* Washington, DC: NASA.
Roop, Wendell, 1929. "Frictional Resistance of Ship Models", EMB Report 227, Washington D.C.; also in *Transactions of the Society of Naval Architects and Marine Engineers* 37, pp. 45–64.
Rössler, Eberhard. 1981. *The U-boat: The evolution and technical history of German submarines.* London: Cassell.
Roy, Maurice. 1931. Stabilité des Régimes de Vol des Avions. *Bulletin de l'Association Technique Maritime et Aéronautique* 35: 619–640.
Saunders, Harold. 1952. *Collected French Papers on the Stability of Route of Ships at Sea, 1949–1950,* DTMB translation 246. Washington, DC: DTMB.
Saunders, Harold. 1957. *Hydrodynamics in Ship Design*, vol. 3. New York: SNAME.
Schoenherr, Karl. 1932. Resistance of flat surfaces moving through fluid. *Transactions of the Society of Naval Architects and Marine Engineers* 40: 279–313.
Schoenherr, Karl. 1989. *Coming to the United States—The Hard Way.* New York: Vantage Press.
Shatzberg, Eric. 1999. *Wings of wood, wings of metal.* Princeton: Princeton University Press.
Shute, Nevil. 1954. *Slide Rule: Autobiography of an Engineer.* London: Heinemann.
SNAME, 1946. *Society of Naval Architects and Marine Engineers Index to Transactions, years 1893 to 1943.* New York: SNAME.
Stein, Albert G. 1919. *Tanks: 1914–1918.* London: Hodder and Stoughton.
Stein, Steven K. 2007. *From torpedoes to aviation; Washington Irving Chambers and technological innovation in the new Navy, 1876–1913.* Tuscaloosa: University of Alabama Press.
Timmermann, Gerhard. 1979. *Die Suche nach der günstigsten Schifform.* Hamburg: Gerhard Stalling.
Trimble, William F. 2002. *Jerome C. Hunsaker and the rise of American aeronautics.* Washington, DC: Smithsonian Institution Press.
Troost, Lauren (ed.). 1933. *International conference of Tank Superintendants Collected papers.* Wagenignen: Nederlands Scheepsbouwkundig Proefstation.
Vincenti, Walter. 1979. The air-propeller tests of W.F. Durand and E.P. Lesley. *Technology and Culture* 20(4): 712–751.
Vincenti, Walter. 1990. *What engineers know and how they know it.* Baltimore: Johns Hopkins University Press.
von Kármán, Theodore, to Ludwig Prandtl. 1932 (9 December). Archive of the Max-Planck-Gesellschaft, Berlin, III. Abstract Reports 61 (Prandtl papers), Number 793.
von Mises, Richard. 1992. *Theory of flight*, 2nd ed. New York: Dover.
Watson, Nigel. 2010a. *Lloyd's Register, 250 years of service.* London: Lloyd's Register.
Watson, Peter. 2010b. *The German Genius.* New York: Harper.
Wolverton, Mark. 2010. Winging it. *Invention and Technology* 25(1): 18–27.
Wright, Thomas, 1983. *Ship Hydrodynamics 1710–1880.* Ph.D. thesis, University of Manchester.
Wyn-Evans, Harold B. 1921. The standardization of data for airship calculations. *Transactions of the Institution of Naval Architects* 63: 131–162.
Younger, John, et al. 1935. *Structural design of metal airplanes.* New York: McGraw-Hill.
Zahm, Albert. 1914. *Report on European Aeronautical Laboratories.* Washington, DC: Smithsonian Institute.
Zédé, Gustave. 1886. Sur les navires sous-marins. *Comptes Rendues Hebdomadaires des Séances de l'Académie des Sciences* 102: 808.