THE DEVELOPMENT OF HYDRODYNAMICS: 1860 – 2010

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In the early 1860s, little was really understood about ship resistance and many of the ideas on powering at that time were erroneous. Propeller design was very much a question of trial and error. The power installed in ships was often wrong and it was clear that there was a need for a method of estimating the power to be installed in order to attain a certain speed. However, over the following 150 years, significant development was made in estimating ship propulsive power.

The Early Years

In 1870, W. Froude initiated an investigation into ship resistance using models. He noted that the wave configurations around geometrically similar forms were similar if compared at corresponding speeds, that is, speeds proportional to the square root of the model length. He propounded that the total resistance could be divided into residuary, mainly wavemaking, resistance and skin friction resistance. He derived estimates of frictional resistance from a series of measurements on planks of different lengths and with different surface finishes. Specific residuary resistance, or resistance per ton displacement, would remain constant at corresponding speeds between model and ship. His proposal was initially not well received, but gained favour after full scale tests had been carried out. HMS Greyhound (100 ft) was towed by a larger vessel and the results showed a substantial level of agreement with the model predictions. Model tests had been vindicated and the way opened for the realistic prediction of ship power. In his 1877 paper, Froude gave a detailed explanation of wavemaking resistance which lent further support to his methodology.

In the 1860s, propeller design was hampered by a lack of understanding of negative, or apparent, slip, naval architects being not fully aware of the effect of wake. Early propeller theories were developed to enhance the propeller design process, including the momentum theory of Rankine in 1865, the blade element theory of Froude in 1878 and the actuator disc theory of Froude in1889. In 1910, Luke published the first of three important papers on wake, allowing more realistic estimates of wake to be made for propeller design purposes.

Cavitation was not known as such at this time, although several investigators, including Reynolds, were attempting to describe its presence in various ways. Barnaby, in 1897, goes some way to describing cavitation, including the experience of Parsons with *Turbinia*. During this period, propeller blade area was based simply on thrust loading, without abasic understanding of cavitation.

By the 1890s the full potential of model resistance tests had been realised. Routine testing was being carried out for specific ships and tests also being carried out on series of models. A notable early contribution to this is the work of Taylor, closely followed by Baker. It is a tribute to Taylor that the results of his work, including the re-analysis by Gertler, are still in common use today.

The Middle Era

The next era saw a steady stream of model resistance tests, including the study of the effects of changes in hull parameters, the effects of shallow water and to challenge the suitability and correctness of the Froude friction values. There was an increasing interest in the performance of ships in rough water and the need to assess this performance. Several investigations were carried out to determine the influence of waves on motions and added resistance, both at model scale and from full scale ship measurements. Following the earlier work of Michell and Havelock, Wigley presented the first of several papers on the mathematical calculation of ship resistance together with supporting experimental results.

The 1920s saw much interest in improving propeller efficiency and, in 1928, vortex theory applied to propellers was introduced by Perring. This was basically a combination of momentum and blade element theories, generally following the approach for airscrews used by Lanchester, although there were shortcomings due to the wide blade of the marine screw.

In 1927, Telfer introduced a fundamentally new method of extrapolating model resistance values to full scale ship values which does not entail breaking down the resistance into its components. Experiments are carried out on a family of models, which Telfer termed 'Geosims', and the slope of the extrapolator determined experimentally in the region of the model values. The method has a sound scientific basis and is valuable as a research tool, but is found not to be cost effective for routine commercial testing. Several other families of Geosims have been tested since the early work of Telfer.

The 1930s saw the publication of work on cavitation by Lerbs and Kempf, based on results from their new cavitation tunnel, which greatly improved the understanding of cavitation. In 1937, Gawn published a series of tests on wide bladed propellers and, in 1938, Troost published the first results for a series of propellers that were to become the Wageningen B–Series. The mid1940s saw the description of the Kort nozzle (ducted propeller), together with a description of supercavitating propellers by Posdunine.

The presence of transitional and laminar flow on hull models had long been suspected, even from the days of the anomalies in the Froude data. In 1937, Lackenby re-analysed the Froude data. He plotted the data to a base of Reynolds number and showed clearly that mixed transitional and laminar flow did exist. Allan and Conn carried out tests in the late 1940s that also clearly proved the presence of laminar flow and the need for turbulence stimulation on models. From about that time, turbulence stimulation has been applied to all models.

The Modern Era

In the 1950s there was a renewed interest in friction lines. As well as the Froude values, other proposals over the years had included those of Tideman (using Froude data), Gebers, Prandtl, Schlichting, von Karman and Schoenherr. All were aware by now that the extrapolation process depended on the level and slope of the friction line, and that the Froude values were not explicitly defined in terms of Reynolds number. Also, the increasing size and speed of ships was leading to significant errors in power prediction, particularly when using the Froude friction coefficients. The predominant friction lines in use at the time were those of Froude and Schoenherr, whose line had been adopted by the ATTC in 1947. After much experimentation at the National Physical Laboratory, Hughes proposed a new formulation, and a modified form of his equation was adopted by the International Towing Tank Conference (ITTC) in 1957. This, together with a form factor to estimate the total viscous resistance, is the basic format of resistance extrapolation still in use. This era also saw the start of formal model-ship correlation, where correlation factors or coefficients were introduced to take account of the differences in the model and full-scale predictions that might arise due to such aspects as scale effects and levels of hull surface roughness.

The 1950s and 1960s saw the development of resistance tests for standard series models, including those for merchant ship forms, semi-displacement and planing forms. The basic results provide a comparator with other model tests and allow parametric variation of hull parameters for optimisation studies to be carried out and the refinement of the particulars of models to be used in future tests. The 1950s also saw the publication of the Gawn series of propellers, over-riding the earlier 1937 tests, and the Gawn/Burrill series, which included investigations into cavitation. These series, together with the extensive Wageningen series and other series such as those developed in Japan and elsewhere, have provided extremely useful tools for propeller design and continue to do so to the present time. Other propeller developments included the measurement of stresses in propellers using strain gauges and the effects of propeller surface roughness.

During the 1960s, much effort was also directed at measuring the individual components of resistance in order to provide a better understanding of the physical nature of the flow and the relative magnitude of the resistance components. This entailed measurements of the viscous resistance and wave resistance, which can be seen as energy dissipation, together with friction resistance and pressure resistance which comprise the forces acting on the hull. Such measurements allowed the division between components to be assessed better, including the distribution and magnitude of the skin friction and viscous resistance for the improved estimation of form factors.

The mid 1960s to mid 1970s saw a significant evolution of ship types, including container ships, chemical and gas carriers, RO-RO and car carriers, together with a general increase in size and speed. These developments called for a number of specific hydrodynamic investigations. The 1970s also saw increased attention to theoretical work, in particular the means of predicting wave resistance. Early CFD techniques were being developed in earnest.

Since the 1960s there have been many developments in propulsor types. These include various enhancements to the basic marine propeller such as tip fins, varying degrees of sweep, changes in section design to suit specific purposes and the addition of ducts. Contra-rotating propellers have been re-visited, cycloidal propellers have found new applications, waterjets have been introduced and podded units developed. Propulsion enhancing devices have been proposed and introduced including propeller boss cap fins, upstream pre-swirl fins or ducts, twisted rudders and fins on rudders. It can of course be noted that these devices are generally at their most efficient in particular specific applications.

The Computational Era

From the start of the 1980s, the potential of CFD was fully realised. This included the modelling of the flow around the hull and the derivation of viscous resistance and free surface waves. This generated the need for high quality benchmark data for the physical components of resistance necessary for the validation of the CFD. Much of the earlier data of the 1970s was re-visited and new benchmark data developed, particularly for viscous and wave drag. Much of the gathering of such data has been coordinated by the International Towing Tank Conference.

Propeller theories had continued to be developed in order to improve the propeller design process. Starting from the work of Rankine, Froude and Perring, these included blade element-momentum theories, such as Burrill in 1944, Lerbs in 1952 using a development of the lifting line, and lifting surface methods where vorticity is distributed over the blade. Vortex lattice methods, boundary element, or panel, methods and their application to propellers began in the 1980s. The 1990s saw the application of CFD and RANS solvers applied to propeller design together with CFD modelling of the combined hull and propeller.

Other numerical methods of a fundamental nature developed through this period include SPH (Smooth Particle Hydrodynamics). This is a numerical technique for the approximate integration of the governing partial differential equations of continuum mechanics. It is a mesh-less Lagrangian method that uses a pseudo-particle interpolation method to compute smooth field variables. Each SPH particle has a mass, Lagrangian position, velocity and internal energy. The SPH approach was initially developed for the simulation of astrophysics problems, with the critical development being a method for the calculation of derivatives without a computational mesh. Libersky and Petschek extended SPH to work with the full stress tensor, developing a 2D formulation.

More recently, SPH simulations have been further compared with published experimental results, an example being Scott Russell’s wave generator, with the SPH method in agreement with the experimental results. In these simulations an artificial equation of state to produce a quasi-incompressible fluid. SPH has also been used for wave mechanics with exact enforcement of incompressibility. This uses an implicit pressure update that allows a larger time step but requires more computational work per time step. Recently, SPH methods have been successfully applied to 2D simulations of green water overtopping and wave overtopping using rigid representations of the impacted structure.

The future

As to the future, as long as there continues to be changes in the economic and environmental operating conditions of ships, there will be a continuing need for hydrodynamic investigation. These changes might include movements in oil prices, an emphasis on reducing CO_2 and other emissions, environmental requirements such as the reduction of wave wash, the general drift to higher speeds, high speed commercial craft, large container ships and high speed cargo carriers.

All these topics tend to lead to the need to examine the hydrodynamics of the situation and to minimise ship propulsive power. This might include further investigations of hull shape, hull coatings, more efficient propulsors including energy recovery devices and hull-propeller interaction. Operational aspects will continue to be examined, such as optimum trim and ballast scenarios, developing a better knowledge of seakeeping and speed loss in waves, leading to enhancements in weather routing and minimising the average propulsive power. Many of these investigations will be enhanced and extended by the further development and use of CFD, together with the continuing support of physical experimentation, which is where it all began in a formal way 150 years ago.