Tank tests, scaling and CFD

Objectives

After working through these notes you should be able to:

1. Describe the procedures used in tank tests
2. Scale tank test results using the ITTC 1978/Prohaska method
3. Outline the numerical/computational techniques for determining resistance, including their limitations

References:

Lewis E. (Ed.) (1988) Principles of Naval Architecture Vol 2. Society of Naval Architects and Marine Engineers, New York Chapter 5
Bertram, V. (2000) *Practical ship hydrodynamics,* Butterworth-Heinemann, Oxford, UK. Chapter 3
Harvald, S. A. (1983) *Resistance and propulsion of ships,* Wiley, New York. Chapter 5

1 Introduction:

The test tank is an essential tool for the hydrodynamicist and ship/boat designer. The traditional main role of the tank is the determination of resistance and hence power requirements for a vessel. However they are now increasingly used for investigating other phenomena such as seakeeping performance, directional stability and capsizing in waves.

2 Historical:

Tank testing of scale models has been carried out for many years. The earliest recorded experiments were conducted by Leonardo da Vinci (1452-1519) on three models of ships having different distributions of displacement. From the late 17th century onwards there was a steady growth of interest in model experimental work. Colonel Beaufoy, under the auspices of the Society for the Improvement of Naval Architecture, founded in London in 1791, carried out over nine thousand towing experiments between 1791 and 1798 in the Greenland Dock, using models of geometrical shape and flat planks.

Up until 1871, when William Froude persuaded the Admiralty to build a tank in Torquay, the method of gravity towing was utilised in all tanks. This revolutionary tank had a length of 84.7m, a width of 11m and a depth of 3.05m. It was equipped with a mechanically propelled towing carriage in tow the models, and because of this and its size it is considered the forerunner of the modern tanks.

At the end of the 19th century there were only five model experiment tanks in the world, now they number about 125.

3 Description of a Towing Tank:

Tanks around the world vary in size (lengths of 20m to 1000m) and setup considerably, in order to give an outline of an operating tank the following description is for Australia's largest towing tank situated at the Launceston node of AMECRC in Tasmania.

The tank has a constant rectangular cross section with the following dimensions:

Overall length	60m
Width	3.5m
Depth	1.5m

A steel carriage running on rails along the walls of the tank is used to tow the models. It is powered by two DC motors driving all four wheels and can achieve speeds of up to 4.5m/s.

At one end of the tank is a wet dock with Perspex sides used for ballasting models prior to testing. Situating at the other end is a single flap, hydraulically driven wavemaker, which is controlled by a microcomputer.

The tank is filled with fresh water, the temperature of which is closely monitored to avoid changes in viscosity. The temperature tends to vary only slightly since the tank is housed in the basement with no windows and a regulated environment.

For calm water runs, a retractable beach on one side of the tank and a swimming pool lane marker on the other are used to dampen the waves produced by the model. These are removed for wave tests, although the retractable beach is lowered between runs.

Models are usually one to two metres long and constructed with great accuracy. The hull surface is highly polished to ensure surface roughness is consistently repeatable.

The model is attached to the carriage via a dynamometer which measures the resistance by the use of a strain gauge. It is generally restrained in surge, sway, yaw and roll but free to pitch and heave. The pitch and heave motions can be measured using LVDTs (linear voltage displacement transducers) whilst a capacitance wave probe is used to measure the incident wave height.

4 Resistance Test

The model is initially ballasted to the correct waterline with the use of weights. It is then connected to the dynamometer - a two post system. At the bottom of the forward post is a strain gauge whilst the aft post attaches to a slider in the model.

The strain gauge is calibrated at regular intervals throughout the testing process.

Before each run zero readings are taken for the resistance, trim and heave. The carriage is then started, once it has accelerated up to speed the data recording begins. The data is processed using an analogue to digital converter and then recorded by an IBM-PC mounted on the carriage,

sampling at a rate of 100 samples per second. The speed of the carriage is also logged.
Video equipment is mounted under the carriage to enable filming of the model under way.
The water must be allowed to calm down completely between runs.
A series of runs are conducted at different speeds to obtain the resistance curve for the model, the model results can then be scaled up to give a full scale resistance.

5 The Scaling Problem:

Naked hull resistance essentially consists of three components:

- wavemaking
- skin friction
- viscous pressure

Wavemaking resistance is largely a function of Froude number whilst friction is Reynolds number dependent. Viscous pressure is Reynolds number dependent (as it is viscous in nature) but it is also affected by Froude number, and thus causes a few problems.
The ideal situation would be to run the model at the same Froude number and the same Reynolds number as the full size vessel, then the model resistance would be a simple, scale dependent ratio of the full size resistance. Unfortunately the laws of algebra do not allow this:

$$\text{Froude number} = \frac{v}{\sqrt{gL}}$$

$$\text{Reynolds number} = \frac{vL}{\nu}$$

where: v = vessel velocity (m/s)
L = waterline length (m)
ν = kinematic viscosity (m^2/s)

Assuming g and ν are the same for model and full size, then for constant Froude number:

$$v_m = v_s \sqrt{\frac{L_m}{L_s}}$$

whilst for constant Reynolds number:

$$v_m = v_s \frac{L_s}{L_m}$$

Therefore these two requirements are incompatible. A constant Reynolds number would result in ridiculously high speeds, so model tests are carried out at constant Froude number. This means that the model tests are carried out at very low Reynolds numbers.
This leads to two problems:
i) It is necessary to know how friction resistance varies with Reynolds number in order to scale the friction to full size. This problem has been addressed by the work of Froude and Hughes amongst others.
ii) If the Reynolds number is low the flow over the model may be laminar and not turbulent, this would have a large effect on the measured resistance. To avoid total laminar flow the boundary layer is artificially turbulated close to the bow of the model. This is achieved by placing studs or trip wires in a vertical orientation at the bow.

6 Scaling Methods:

There are several different scaling methods. The method generally considered most accurate is the **1978 ITTC Method**. (International Towing Tank Conference), which we will focus on. Other methods include the 1957 ITTC method and the Prohaska method.

note: suffix m = model value, suffix s = full size vessel

a) calculate C_{Fm} from old 1957 ITTC correlation formula:

$$C_{Fm} = \frac{0.075}{(\log_{10}Re - 2)^2}$$

b) find C_{Tm} from towing tank results:

$$C_{Tm} = \frac{R_{Tm}}{0.5\rho S_m v_m^2}$$

where: S = wetted surface area (m^2)

c) find the form factor (1+k) from the model test results at low Froude number. The assumption is that:

$$\frac{C_T}{C_F} = (1+k) + \alpha\frac{Fn^4}{C_F}$$

at low speeds where k is assumed to be independent of Re and Fn. Model tests at several Froude numbers (e.g. between 0.12 and 0.24) are used to find α and k.

d) determine C_{wm}

$$C_{Wm} = C_{Tm} - (1+k)C_{Fm}$$

e) find C_{FS} from ITTC formula using full size Reynolds number

f) since:

then:

$$C_{Ws} = C_{Wm}$$
$$C_{Ts} = (1+k)C_{Fs} + C_{Wm}$$

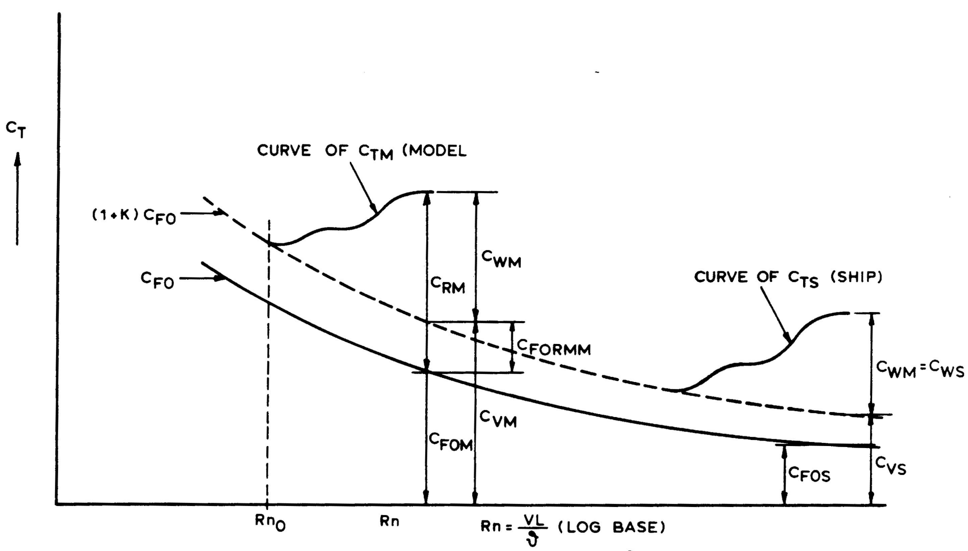
g) therefore the full scale vessel resistance can be found from:

$$R_{Ts} = C_{Ts} \times 0.5 \times \rho \times S_s \times v_s^2$$

note: ρ_m and ν_m are for fresh water
ρ_S and ν_S are usually for salt water

The Prohaska scaling method assumes $\alpha = 4$, enabling k to be determined by a linear plot.

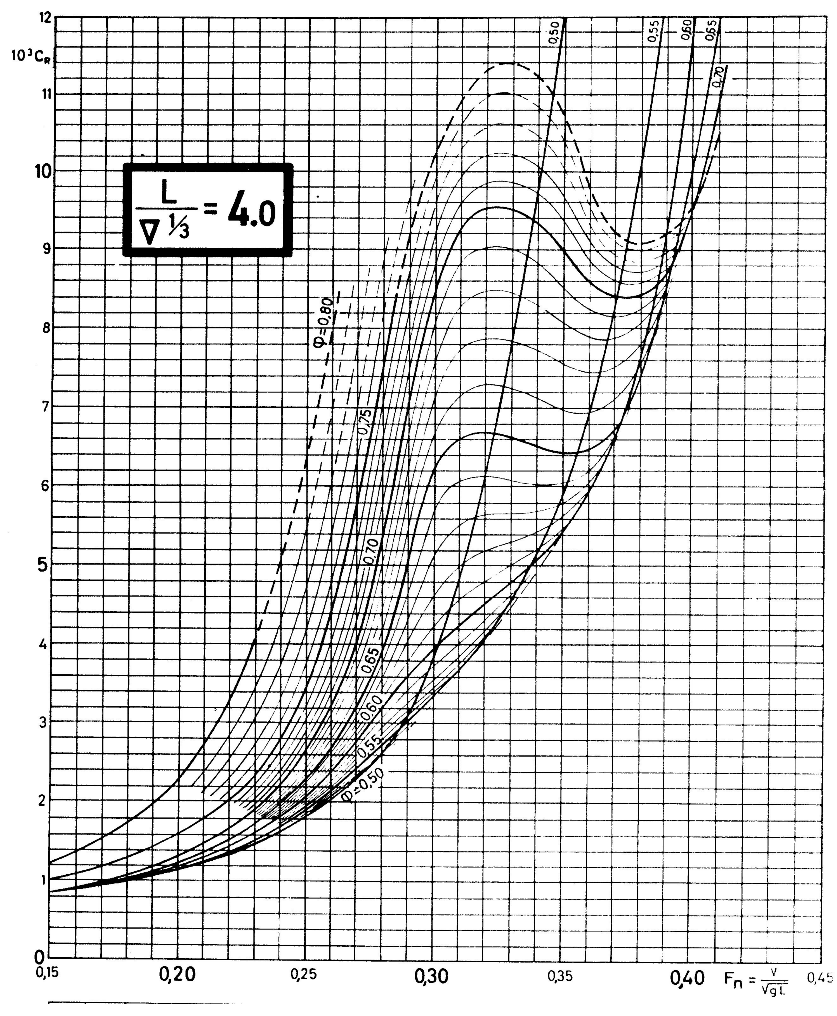
A graphical description of the ITTC 1978 and Prohaska scaling methods is shown below



Lewis (1988)

7 Standard Series Data:

One of the most important applications of tank testing to vessel design is in the generation of standard series data. It would be time-consuming and costly to tank test every design, so many research establishments have set up their own tank testing programmes. A basis hull shape is chosen, then several variations are designed to form a series of similar hulls. They are all tested and the results then indicate the effect of altering the shape in a controlled manner. The general trends shown in the results are then converted into an easily useable form (eg. computer program)
An example of standard series data is given below:



Harvald (1983)

where
φ = prismatic coefficient
∇ = displaced volume (m^3)
dotted lines are where data quality is poor

8 Statistical Analysis of Model Data:

ref. Holtrop, J. and Mennen, G.G.J. 'An Approximate Power Prediction Method'. International Shipbuilding Progress, Vol.29, July 1982.
In addition to the published results for methodical model series, there exists a vast store of resistance data for the many models tested for specific designs.
It is possible to select certain hull design parameters which are important in determining the resistance coefficient. Then regressional analysis techniques can be used to find the 'powers' of these parameters and hence result in formulae to calculate the resistance coefficient.
Holtrop, et al, published the results of a statistical analysis of the results of resistance and propulsion tests with 334 models of various types of ship carried out at the Netherlands Ship Model Basin. It was found that for 95% of cases the accuracy of the statistically derived formulae is satisfactory in preliminary design work if the range of variables is within broad given limits.

9 CFD and ship resistance

9.1 CFD solvers

	Navier –Stokes (N-S)	Solves the fundamental equations – impossible for practical ship problems
complicated ↑	Large Eddy Simulations (LES)	Solves large eddies directly, uses a turbulence model for small eddies in boundary layer. Requires small grid resolution (hence big computer) so not practical
	Reynolds-Averaged N-S eqns (RANSE)	Divides velocities into time-averaged and fluctuating, then uses a turbulence model to relate fluctuating velocities to Reynolds stresses. Turb models subject of great debate – they become the “tuning” button
	Euler	Solves inviscid N-S eqns. OK for lifting surfaces (foils) but not much use for ships – still needs high computer power
simple	Potential flow	Inviscid and irrotational means eqns are linear, so very easy to solve. Most commonly used CFD for ship resistance

As a general guide, current use is inviscid codes near the bow e.g. for bulbous bow shapes, and RANSE near the stern, where separated flow dominates. Potential flows are used for wavemaking resistance investigations, RANSE for detailed wake studies e.g. around the propeller region

9.2 CFD techniques

9.2.1 Boundary methods

Boundary Element Method BEM (panel method)

Used for potential flows therefore most common. Integrals over the 3-D volume can be transferred to integrals on the (2-D) boundary surfaces, simplifying the grid. It does not work for RANSE because you need a linear problem for BEM, so that you can apply superposition at joins etc.

9.2.2 Field methods

Finite Element Method (FEM)

Not much use in hydrodynamics. Unlike structures, weighting functions cannot be used for hydrodynamic properties to obtain residuals.

Finite Difference Method (FDM)

Derivatives of the base equations are approximated by finite differences. This results in cumulative errors, which leads to violation of conservation laws (mass, momentum), so not much use.

Finite Volume Method (FVM)

Same as FDM but conservation equations are integrated over the cell before the mid-cell values are approximated, thus retaining conservation. FVM is used in most RANSE codes.

9.3 The free surface

The biggest problem with most codes is how to deal with the free surface. If you put (and keep) the grid on the surface, then it has to move with the waves. This requires lots of computing power and is very difficult to mange where the moving surface meets the ship hull. An alternative is to fix the grid and allow the free surface to partially fill the grid spaces, using an estimate of the amount of water in the cell. This is called the Volume of Fluid (VOF) technique