4. RESISTANCE PREDICTION BY MODEL EXPERIMENTS

4.1 Model Preparation and Measurement

Conventional materials in building ship models are basically wood or paraffin. Recently composite materials are also used. The scale of the model should be as large as possible for the size of the towing tank which restricts model dimensions considering blockage and finite depth effects. Sometimes the dimensions of the stock propellers in the laboratory may be a factor in determining model scale. Ship's speed –if relatively higher- may restrict the model length depending on the maximum attainable speed by the towing carriage. Model mass should also be taken into account for dynamometer's capacity.

The model manufactured should have a surface finishing as smooth as possible in order to avoid roughness effect in experimentation. (Note that we don't have profound similarity laws for the roughness and thus the roughness effect is included in the power prediction by ship-model correlation formulae). On the other hand the flow regime around the model is generally laminar, as the model length is comparatively very shorter than the ship. So that, in order to have dynamically similar flow regime as that of the full scale, which is turbulent; turbulence stimulators are used in the model. For that purpose; pins, sand paper or thin wires are applied / placed in front of the model which are generally located at a distance of 5% model length from the fore-perpendicular.

The model is installed and attached to the towing carriage at the correct corresponding displacement and it is free to surge, heave and pitch. The tow force is expected to be applied in the line of the propeller shaft and at the LCB in order to avoid artificial trim.

The elements of a typical measurement system are given in the following figure. The quantities to be measured are; model's speed, total resistance, sinkage and trim and water temperature. Qualitative and/or quantitative recording of the wave deformations around the model may also be performed. Resistance can be measured by mechanical (Atwood) dynamometer or electronic dynamometers. The measurements should be taken when the carriage speed in steady and there should be sufficient waiting time between consecutive runs to eliminate free surface disturbances and residual currents.

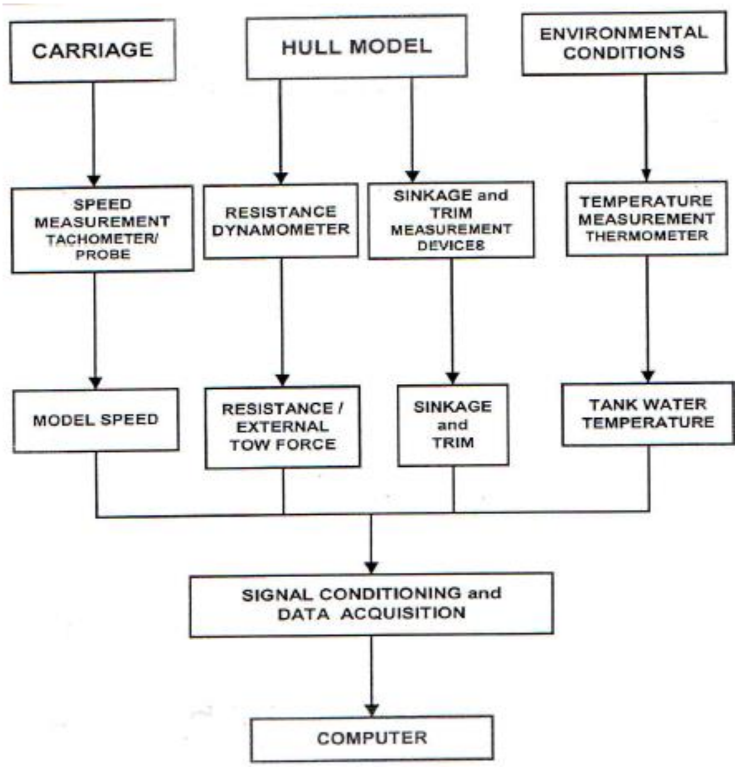

Fig. 4.1: Elements of a typical measurement system (Molland et al. 2011)

4.2 Data Analysis and Extrapolation Methods

4.2.1 Froude's Method

Froude (1868), in his first formulation, expressed the resistance in two components as

$$R = KL^2V^2 + f(L,V)$$

The first term represents frictional effects irrespective of wave generation where V is the ship speed and L is the characteristic length and L^2 can be replaced by the wetted surface of the ship. Model speed can be determined from Froude's law of similarity:

$$V_m = \frac{V_s}{\sqrt{\lambda}}$$

where the scale ratio λ is taken as $\lambda = L_s / L_m$

In summary, total model resistance is formulated as;

$$R_{T_M} = R_{F_M} + R_{R_M}$$

Here R_{F_M} may be calculated by assuming that a ship form has frictional resistance equal to that of a flat plate having the same wetted area. Froude proposed a frictional resistance formula of the form:

$$R_F = fSV^n$$

which was then changed (by his son R. E. Froude) finally to:

$$R_F = \frac{\gamma \lambda_t}{1000} S V^{1.825} \text{ and } \lambda_t = \left(0.1392 + \frac{0.258}{2.68 + L} \right) [1 + 0.0043(15 - t)]$$

where γ density of water [kg/m^3], L is the ship length [m], V is the speed [m/s] and t is the water temperature in degrees Celsius.

Calculation of R_{F_M} makes it possible to obtain R_{R_M} from model experiments. Obtained from $R_{T_M} = R_{F_M} + R_{R_M}$; the residual resistance component can be extrapolated to the corresponding ship resistance component by multiplying the force scale of λ^3 to give:

$$R_{R_S} = \lambda^3 R_{R_M}$$

Therefore the extrapolation to full scale can be written as;

$$\begin{aligned} R_{T_S} = R_{F_S} + R_{R_S} &= R_{F_S} + \lambda^3 R_{R_M} \\ &= R_{F_S} + \lambda^3 (R_{T_M} - R_{F_M}) \end{aligned}$$

This formulation is shown graphically in the following figure.

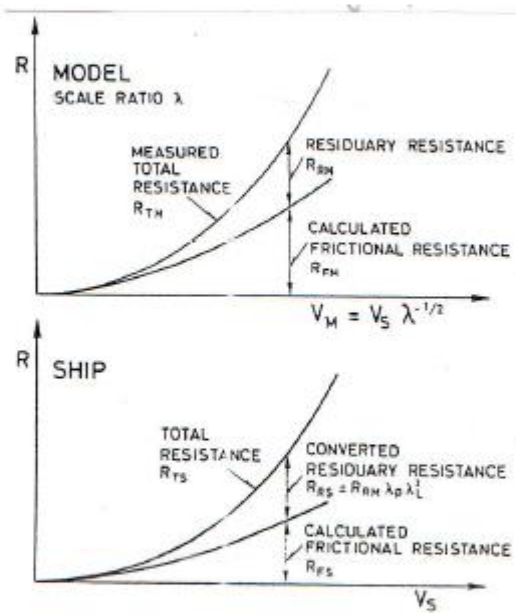

Fig. 4.2: Froude's extrapolation method (Harvald, 1991)

4.2.2 Telfer's Method

We will not examine the Telfer's Method (introduced in 1927) in full detail, but present its basic approaches to the problem. It was first Telfer who put forward clearly that the total resistance is a simultaneous function of Froude number and Reynolds number as;

$$\frac{R_T}{\rho S V^2} = f\left(\frac{V}{\sqrt{gL}}, \frac{VL}{\nu} \right)$$

This simultaneousness in Telfer's formulation requires a family of models to be tested. From these measurements, curves of constant (equi-) Froude numbers are obtained as a function of

Reynolds number (see the figure below). But there are some drawbacks in this method that extrapolation from the model region to ship scale may be very large so that extrapolated results may contain large errors and from practical point of view, performing experiments with a model family is very expensive and time-consuming.

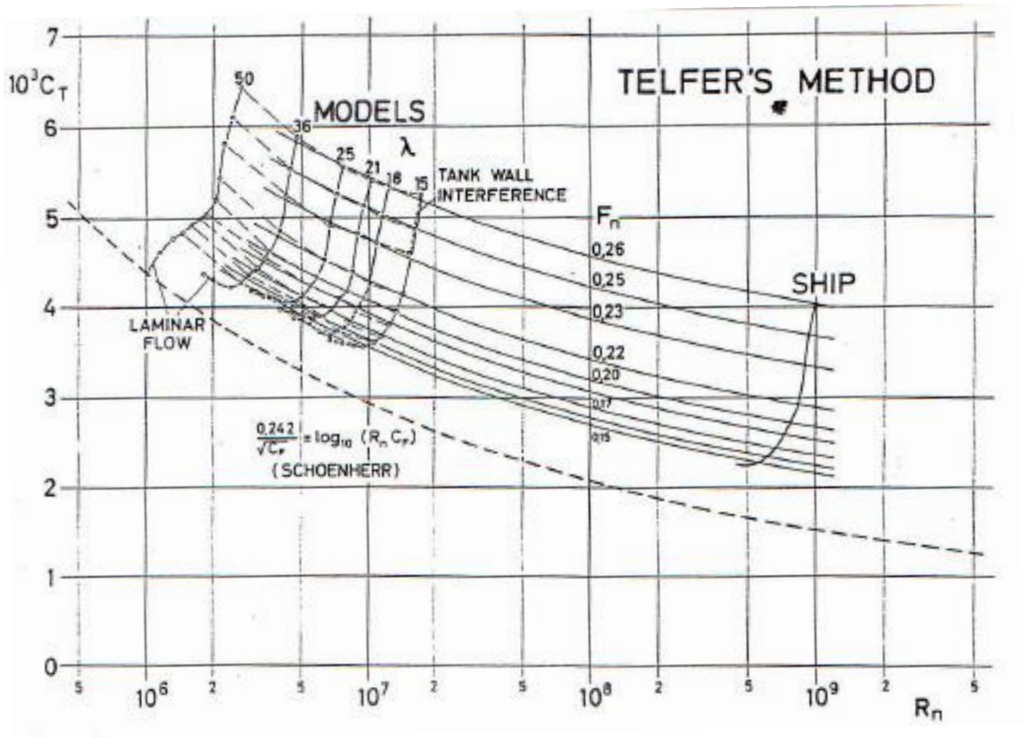

Fig. 4.3: Telfer's extrapolation method (Harvald, 1991)

4.2.3 ITTC 1957 Method

This method may be regarded as a well-established method of Froude's approach. In 1957 ITTC, the frictional model-ship correlation line was adopted as

$$C_F = \frac{0.075}{(\log \mathrm{Re} - 2)^2}$$

which takes the C_F as the equivalent plank resistance having the wetted surface area of the model or ship. The residuary resistance is then obtained from model experiments:

$$C_{R_M} = C_{T_M} - C_{F_M}$$

At this point, one can calculate the ship's frictional resistance by the ITTC 1957 frictional coefficient formula. According to Froude's hypothesis, the residuary resistance coefficient for the ship at the same Froude number is the same as for the model : $C_{R_S} = C_{R_M}$. Thus for the smooth ship:

$$C_{T_S} = C_{F_S} + C_{R_M}$$

As incremental resistance coefficient for model-ship correlation (includes roughness effect) C_A should be added to C_{T_S} to give:

$$C_{T_S} = C_{F_S} + C_{R_M} + C_A$$

The resistance coefficient is dimensionalized to give:

$$R_{TS} = C_{TS}(\frac{\rho}{2} S V^2)$$

4.2.4 Hughes' Method

Hughes proposed a method in 1954 to represent viscous pressure resistance (what he called as form resistance) by means of –what is called- form factor. According to Hughes formulation of total resistance, there are 3 basic components:

R_T = Basic friction resistance + Form resistance + Wave making resistance

In this method, basic friction resistance together with form resistance is expressed as "basic friction resistance × (1+k)", where (1+k) is the resistance ratio (of viscous resistance to flat plate resistance) and this ratio is assumed to be constant independent of Reynolds number and depends only on the form of the body. He proposed basic friction resistance coefficient C_F as:

$$C_F = \frac{0.066}{(\log_{10} \mathrm{Re} - 2.03)^2}$$

Form factor, k, can be determined from low-speed tests in which wave making resistance is thought to be negligible. This can be done by calculating first C_{F_M} and then $C_F(1+k)$ is determined having tangent common with the C_T curve, (see the representative graph in the following).

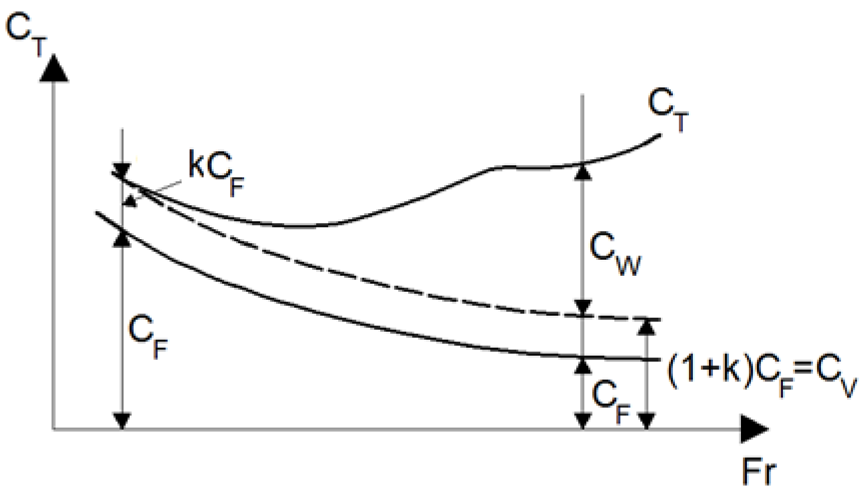

Fig. 4.4: The role of the form factor in Hughes' method.

Note that the coefficients of wave-making resistances for both the model and the full scales are the same for the same Froude's numbers, so that the extrapolation can be attained by;

$$C_{T_S} = (1+k)C_{F_S} + C_{W_M}$$

4.2.5 ITTC-1978 Method

ITTC found the Hughes' method as promising and recommended to improve it. 1978 Conference of ITTC advised to use ITTC-1957 frictional formula and to combine the Hughes' method with Prohaska's method to determine the form factor. Hence total resistance coefficient of a ship without appendages:

$$C_{T_S} = (1+k)C_{F_S} + C_R + C_A + C_{AA}$$

where k is the form factor obtained by means of Prohoska's method from low-speed measurements, C_{F_S} is due to ITTC-1957 frictional formula, C_R is the residual resistance but excluding viscous effects here (or namely wave resistance, C_w) as calculated from the tests:

$$C_R = C_{T_M} - (1+k)C_{F_M}$$

C_A is the roughness allowance (incremental resistance) coefficient:

$$C_A = \left(105 \left(\frac{k}{L_{WL}} \right)^{1/3} - 0.64 \right) x10^{-3}$$

If k is not known for the ship to be built, a standard roughness of $150x10^{-6}$m may be employed in the formula. C_{AA} is the air resistance which may be given by:

$$C_{AA} = 0.001\left(\frac{A_{VT}}{S} \right)$$

where A_{VT} is the transverse area of ship above the waterline, S is the wetted area.

Prohaska's method for determining form factor

By definition, the form factor, k;

$$k = \frac{C_V - C_F}{C_F}$$

where C_V is the total viscous resistance coefficient and C_F is the equivalent plank frictional resistance in 2D. If no flow separation is present or considered, the total resistance is written as:

$$C_{T_M}(Re, Fr) = (1+k)C_{F_M}(\mathrm{Re}) + C_{W_M}(Fr)$$

In Prohaska's analysis, wave resistance coefficient is assumed to be:

$$C_W = sFr^4$$

Dividing both sides of resistance equation by C_{F_M} gives;

$$\frac{C_{T_M}}{C_{F_M}} = (1+k) + s\frac{Fr^4}{C_{F_M}}$$

Here s is suggested as the slope of the straight line as understood from the following figure. (1+k) is the value when Fr^4 / C_{F_M} goes to zero.

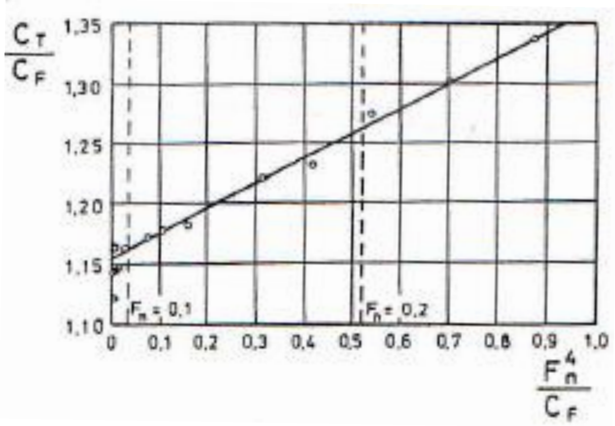

Fig. 4.5: Prohaska's plot for the form factor (Harvald, 1991).

C_{T_M} values employed in the graph should be from the low-speed region of 0.0<Fr<0.2. Note that uncertainty in the measurements in the low speed region is relatively higher and this requires care in the analysis. For full ships, it is recommended to use Fr^6 / C_{F_M} instead of Fr^4 / C_{F_M} as abscissa. Appropriate way to determine the straight line in the Prohaska's plot is the least-squares fit.