9

Model experiments and scaling laws

9.1 Introduction

Hovercraft (ACV or SES), like ships, have a complex interaction with the surface they travel over. In previous chapters we have reviewed the theoretical background to hydrodynamic drag components and the response of these craft to waves. Many of the parameters in the equations are nonlinear, so creating complex problems for direct analysis.

Direct measurement of the drag or motions at model scale can be used as a means of identifying non-dimensional coefficients in the appropriate analytical equation. So long as a reliable relation between the model-scale behaviour and full-scale performance is available, the full-scale data can be generated and used to complete the craft design.

Since models are specific, if parametric data are required then a series of tests during which the parameter of interest is varied has to be carrried out. For example, tests may be with increasing cushion pressure, changes of centre of gravity, or perhaps changes to the skirt geometry, all for the same set of environmental conditions of speeds, sea conditions, etc.

Scaling criteria between model and full-scale craft have to be considered carefully during tests on hovercraft. There are many similarities as well as a number of differences in the scaling criteria for experimental data between hovercraft and conventional planing boats.

Similarly to conventional ships, it is difficult in model experimental conditions to scale all the needed parameters at the same time. A typical example is that many parameters follow Froude's scaling relationship (inertia-dominated loadings such as wave-making drag) while others follow Reynolds' law (skin friction and other velocity-dominated drag components). Experiments therefore have to be designed to scale the most important parameters and if necessary multiple tests carried out to investigate different loading components. An example is that the aerodynamic drag of a craft would be tested in a wind tunnel scaled according to Reynolds' law, while the wave-making drag would be investigated in a towing tank scaled according to Froude's law.

Hovercraft provide some additional challenges, since skirt wetting drag is rather complex, being an air-lubricated compliant surface, partly influenced by the generated spray. Such drag terms are generally treated as 'residuals' from experiments and a conservative approach to scaling adopted.

A (large) hovercraft design will usually require both 'static' testing and 'dynamic' testing. Examples of static tests are model skirts in skirt test boxes, static hovering models from which stability measurements are taken and fixed models of the above water part of a hovercraft in a wind tunnel used for aerodynamic drag and stability tests. Examples of dynamic tests are towing tank tests for drag in calm water or waves, trim, motions and accelerations. In addition dynamic tests may be carried out on a lake or the sea with radio-controlled models to obtain motions data in spread rather than unidirectional random sea states. Open sea testing can be very helpful to evaluate turning and control performance and if a fairly large-scale model is used, plough-in performance. Instrumentation becomes rather more complex than in a towing tank, as it requires on-board recording of the parameters, or remote telemetry.

We will consider first the scaling laws based on dimensional similarity, and then static and dynamic testing in turn, giving guidance on planning and analysis.

9.2 Scaling criteria for hovercraft models during static hovering tests

Test classification

There are three types of test normally carried out on hovercraft models or full-scale craft hovering statically and running on rigid surfaces as follows:

1. *Static hovering tests.* Static hovering tests of ACV or SES models and full-scale craft on rigid surfaces or platforms are carried out to investigate the static hovering performance at various fan speeds, including measurement of static cushion stability, internal air ducting characteristics, the geometry and tailoring of skirts, heave, stiffness, and craft pitch and roll damping.
2. *Experiments with skirts in skirt test boxes.* Testing scale model skirts of full scale craft or of models in small or large skirt boxes are carried out to investigate the static shaping, the dynamic response of skirts, flow and loss characteristics of air ducts, aerodynamic performance of the internal cushion, pressure head loss coefficients due to the skirt holes, heave motion characteristics of skirts, hysteresis effects and the heave attenuation characteristics of air control systems.
3. *Wind tunnel tests.* Wind tunnel testing is carried out to measure various coefficients of aerodynamic drag, static force derivatives, the performance of air propellers, the internal aerodynamic characteristics of models, and its influence on pressure distribution in the cushion.

Scaling laws and criteria

Table 9.1 shows the dimensional ratios for the main variables between the models and full scale craft based on the geometrical similarity, in which λ denotes the linear dimensional ratio.

Cushion pressure ratio (H_q) (Euler number)

In order to correctly simulate air leakage from an air cushion and external aerodynamics of full-scale craft, as well as the spray caused by the cushion acting on the water surface, the scaling criteria of cushion pressure ratio H_q, the Euler number, can be written as

$$H_q = p_c/(0.5\, \rho_a\, V_a^2) \tag{9.1}$$

where p_c is the cushion pressure (N/m^2), ρ_a the air density (Ns^2/m^4) and V_a the velocity of air leakage, (m/s). According to Table 9.1, V_a can be written as

$$V_a \propto \lambda^{0.5} \tag{9.2}$$

If V_a denotes the velocity of the craft model, then expression 9.2 is similar to the Froude number, which is normally used for ship models running on water. Thus the dimension ratio of some corresponding variables can be given as in Table 9.2.

Reynolds number at jet nozzles, Re_j

In the case where hovering experiments are carried out on hovercraft models, the Reynolds number at the jet nozzles Re_j has to be in the range for turbulent flow, namely $Re_j = V_j\, t/\gamma \geqslant 1 \times 10^5$, as was described in Chapter 2, where γ denotes the kinematic viscosity coefficient, t the equivalent nozzle width and V_j the average velocity of the jet at the nozzle. In the case of $Re_j \geqslant 1 \times 10^5$ then the aerodynamic characteristics of the air jet at the nozzle can be considered independent of the Reynolds number.

Table 9.1 The dimensional ratio of various physical variables between the models and full-scale craft with geometric similarity

Physical variables	Nomenclature	Dimensional ratio
Length	l_c	λ
Cushion area	S_c	λ^2
Force and weight	F	λ^3
Acceleration of gravity	g	Constant
Air density	ρ_a	Constant*
Cushion pressure	p_c (height of water head)	λ
Time		$\lambda^{0.5}$

* Note: Air density can vary significantly with altitude and temperature. Take care to choose the appropriate value.

Table 9.2 The dimensional ratio of air cushion related physical variables

Physical variables		Dimensional ratio
Air flow rate	$Q = V_j\, S_j$	$\lambda^{2.5}$
Lift power	N_p	$\lambda^{3.5}$
Frequency	ω (s^{-1})	$\lambda^{-0.5}$

Non-dimensional characteristic curves of fans and air ducts

The Reynolds number for model air ducts is rather small because the dimensions of the model decrease with the dimensional ratio λ. This will influence the air duct friction drag. However the air friction drag losses are usually small; the main losses of air pressure in air ducts are due to the curved or sharp bends in the ducts and sudden expansion of air flow into the cushion. Thus the air pressure loss in ducts can be considered independent of *Re*. Calculation of losses is similar to analysis of heating and ventilating systems.

Hovering performance parameters such as heave stiffness, damping, etc. are closely linked to the fan characteristic curve. On small models the fan characteristic may be distorted, because of its small dimensions and thus small *Re* and non-similarity of fan-specific speed (which will be introduced in detail in Chapter 12, Fan design).

The non-dimensional pressure coefficient H_j and non-dimensional flow rate coefficient Q can be written as

$$\bar{H}_j = H_j/[\rho_a\, n\, D^2] \tag{9.3}$$

$$\bar{Q} = Q/[n\, D^3] \tag{9.4}$$

where $\bar{H}_j$ is the fan non-dimensional pressure coefficient, $\bar{Q}$ the non-dimensional flow rate coefficient, H_j the total pressure head (N/m^2), n the fan revolutions (1/s), D the fan diameter (m) and Q the flow rate (m^3/s). Thus the specific speed of the fan is

$$N_s = Q^{0.5}/H^{0.75} \tag{9.5a}$$

If H_j can be expressed by the height of water head, then this expression can be written as

$$N_s = n\, Q^{0.5}/[g\, H]^{0.75} \tag{9.5b}$$

For craft models, $[D] \propto [l]$, $[n] \propto 1/[s]$. Thus the speed of a model fan should increase compared with that of full-scale craft by a factor of $\lambda^{0.5}$, i.e. less than linear scaling. High-speed electric motors are often used as power units for hovercraft models, so the specific speed of models, N_{sm}, *Re* and consequently the fan characteristics, differ from that of full-scale craft.

While it would be possible to install reduction gears with some penalty in weight on a model, the local aerodynamics in a model fan creates further difficulties in scaling and thus normally some trial and error is used to manufacture fans which have pressure/flow characteristics as close as possible to the desired curve, rather than modelling the fan itself.

When a section of the craft skirt is mounted on a test rig as a test skirt, the corresponding flow rate at the test rig should be smaller than that on full-scale craft, i.e. $Q_{sb} = Q/n_{sb}$ where Q_{sb} denotes the air flow rate of the fan on the skirt test box, Q denotes the air flow rate on full-scale craft (or model if the scaling is between the box and a model) and n_{sb} denotes a given value of flow reduction, which is according to the size of test box.

However, the overall pressure head has to comply with the linear dimension, i.e. $[H_j] \propto [l]$. Thus there is a great difference in the specific speed between the fans of a skirt box and full-scale craft. In fact, a test rig fan cannot be suitable for all craft (models), due to its fixed characteristic. Normally the fan system in a skirt test box is not changed for each test! For this reason, the skirt test box is more suitable for experiments to optimize static shaping of skirts and will create large errors needing correction in the case of skirt dynamic response characteristic testing unless the fan and air speed system are also specially modelled.

Skirt weight per unit area

Skirt weight is directly related to its static geometry and surface area, since it is essentially a membrane, so scaling between model and full scale has to satisfy

$$W_{ss}/W_{sm} \propto \lambda \tag{9.6}$$

where W_{ss} is the weight per unit area of skirt (including the connections) of full-scale craft (N/m^2) and W_{sm} the weight per unit area of skirt (including connections) of models (N/m^2). The problems concerned with the elastic aerodynamics of skirts have to be considered during the investigation of the dynamic shaping of skirts; however, this does not greatly affect the skirt shaping and can therefore be neglected.

Strouhal number S_r

Strouhal's number is closely related to the elastic aerodynamic characteristics of the skirt fingers. It characterizes the ratio of inertia force due to the air pressure and the elastic modulus of skirt materials and can be expressed as

$$\begin{aligned} S_r &= \sqrt{[\rho_a V_a^2/E]} \\ &= V_a/\sqrt{[E/\rho_a]} \\ &= V_a/a \end{aligned} \tag{9.7}$$

or

$$\omega\, l/\sqrt{[E/\rho_a]} = \omega\, l/a \tag{9.8}$$

where v is the velocity of air flow (m/s), a the velocity of sound in skirts or other structural materials (m/s), ω the vibration frequency of skirts (1/s) and l any linear length.

In the case where the skirt material of the full-scale craft has the same characteristics as those of the model, then the model skirts' S_r is not scaled correctly compared to the full-scale craft. Thus it may be noted that in the calculation of skirt shaping described in Chapter 7, the skirt bag membrane tension and stresses of both the model and craft are not similar, even though the skirt geometric scaling with the same specific weight can be satisfied.

The tension in the skirt bag membrane is represented by $T = p_t R \propto \lambda^2$, where p_t denotes the bag pressure and R the radius of curvature of the skirt bag at that position, i.e. the dimensions of $[T] = $ [N/m]. Meanwhile the tension stress of the skirt membrane $\sigma = T/\delta$, where δ denotes the thickness of the skirt material.

According to this theory, the elastic modulus E of a full-scale craft skirt should be λ times E of the model skirt, i.e. $[E] \propto [l]$, but actually the experiments demonstrate rather different results as shown in [81]. The elastic modulus of skirt material for both model and full-scale craft are shown in Table 9.3.

In general the linear ratio between full-scale craft and models is approximately equal to 10, but Young's modulus of skirt materials for both models and full-scale craft are much closer (model skirts are too stiff relative to the linear scale). In addition, the thickness of model skirt materials is usually too great in comparison with

Table 9.3 The elastic modulus E and coefficient of elongation ε for both models and full-scale craft

Skirt material	E_{warp} (N/cm^2)	E_{weft} (N/cm^2)	ε_{warp} (%)	ε_{weft} (%)
6408 (for full-scale craft)	3 970	1 770	5.5	12.1
1533 (for models)	12 700	6 900	7.3	13.3
9514 (for models	10 900	10 900	6.0	10.0

that of full-scale craft on a basis of direct scaling, i.e., $\delta_s/\delta_m < \lambda$, and the materials are also relatively stiff.

This will affect the test results for inertia drag and frequency of vibration, especially for seaworthiness tests. Reference 9 recommends the parameter Γ which characterizes the ability to straighten the skirt under pressure of the air cushion. Γ can be written as

$$\Gamma = E\delta\, l_s/[\rho_a\, v^2\, S] \tag{9.9}$$

in which δ denotes the skirt cloth thickness, E, l_s and S denote Young's modulus, equivalent length and skirt material area respectively. Due to the fact that $E_s \approx E_m$, $\Gamma_s < \Gamma m$, the deformability of model skirts is less than that of a full-scale craft skirt. For this reason, skirt bag bounce and the flagellation motion of the skirt fingers in the water, which occurs at full scale and is also observed in the bag skirt test box, seldom happens to model craft and to skirts in small skirt test boxes.

Scaling conditions for wind tunnel model tests

In the case where the craft model tests are carried out in a wind tunnel to determine the aerodynamic resistance coefficients at various heading angles, the R_e of jet flow at nozzles has to be equal to or in excess of the critical R_e (i.e. the R_e for turbulent flow).

In addition, the linear velocity of any moving supporting plate in the wind tunnel has to be equivalent to the craft speed, namely $V_g \propto \lambda^{0.5}$, in which V_g denotes the linear velocity of the supporting plate. Otherwise, the wind tunnel tests cannot correctly simulate the internal and external aerodynamic characteristics. Unfortunately, these test conditions are difficult to satisfy.

In general, supporting plates representing the ground are static and are difficult to move with a high linear velocity to simulate the operational environment of craft. In order to investigate the external aerodynamics and static force derivatives during the wind tunnel tests, ACV models generally have to be in static hovering condition. It is also very difficult to model internal flows, because the flow and specific revolution of model fans are very difficult to scale, as has been discussed above.

For this reason, in general ACV tests in wind tunnels are carried out on solid models, perhaps also with fan and propulsor flows modelled according to Reynolds' law and not in static hovering condition. This certainly leads to errors in the data measured. Determination of the basic body drag and lift coefficients will be accurate enough for normal design purposes. Reference is also normally made to Hoerner's fluid dynamic drag [23] as a starting point. This book gives a wealth of information concerning aerodynamic modelling practice.

Air cushion adiabatic stiffness coefficient, C_b

The coefficient which characterizes the adiabatic stiffness of air cushion can be expressed by

$$C_b = V_c/(\gamma(p_a+p_c)) \tag{9.10}$$

where V_c is the cushion volume (m^3), p_a the atmospheric pressure (N/m), p_c the cushion pressure (N/m) and γ the adiabatic constant for air (m^2/N). This coefficient characterizes the adiabatic change of cushion air in compression due to the heaving, pitch and roll motion of hovercraft running at high speed, which affects heaving stiffness and damping.

The cushion pressure denotes the excess pressure of cushion air, i.e. the difference value between the absolute cushion pressure $|p_c|$ and the atmosphere. At model scale, $p_c \ll p_a$ and so $|p_c|$ can be neglected compared with atmospheric pressure, which suggests that the effect of cushion air compression is too small to change the air flow rate and fluctuate the cushion pressure. This is not true for full-scale craft, especially for larger hovercraft at high speed, because in this case the fluctuation of cushion pressure is large enough that $|p_c|$ is not a small value in comparison with p_a and therefore cannot be neglected.

In practice, therefore, it is very difficult to make the adiabatic stiffness coefficient of models equal to that of full-scale craft, so compressibility of cushion air for models is not similar to that for full-scale craft and will lead to some differences in the seaworthiness results for models compared with full scale. This difference should not be very important except in very large ACV/SES (displacements of several hundred tonnes).

9.3 Scaling criteria for tests of hovercraft over water

Test classification

There are three types of hovercraft test carried out hovering or running on a water surface:

1. *Static hovering test.* Static hovering tests, longitudinal/transverse stability tests of full-scale craft/models on water.
2. *Skirt tests in skirt test boxes with water supporting surface.* Static shaping and dynamic response tests of full-scale craft or model skirts on big/small skirt test boxes.
3. *Experiments of hovercraft in towing tank, etc.* Drag and seaworthiness tests.

Scaling conditions and criteria

Froude number Fn

According to Chapter 3, the wave-making resistance of hovercraft R_w can be written as

$$R_w = [p_c^2\, B_c/\rho_w\, g]\, f(F_{nl}, l_c/B_c) \tag{9.11}$$

or

$$R_w = p_c/[\rho_w\, g\, l_c]\, f(F_{nl}, l_c/B_c) \qquad (9.12)\ (3.3)$$

where F_{nl} is the Froude number, l_c the cushion length (m) B_c the cushion beam (m) and ρ_w the water mass density (Ns^2/m^4).

Equivalent to the methods used in fast boat research, the Froude similarity has to be considered at first during the tests in water tank, i.e. $F_{nls} = F_{nlm}$. Thus $V_s/V_m = \sqrt{\lambda}$, which is actually the same as the Euler similarity. The other scaling criterion p_c/l_c = constant is also to be considered in experiments.

Reynolds number Re

During hovercraft experiments, just as for conventional ships, the Reynolds similarity or $Re_m > Re_c$ (where Re_c denotes the critical Reynolds number) has to be satisfied in order to accurately predict the friction drag. For this reason, stimulation threads or pins should be mounted on the outside of the bow sidewalls during towing tank experiments with an SES to induce turbulent flow over the whole model sidewall. Such stimulation threads are difficult to mount on the side of the bow skirt of an ACV, but it is found that the disturbance due to jet air escaping under the skirt segment or finger tips creates very turbulent conditions close to the water surface; therefore it is impossible to build up a laminar boundary layer along the side skirt.

Weber number W_e

During consideration of skirt drag and spray formation, we have to estimate the relation between the inertia force of water flow and surface tension of water. The generation process of spray and its size as well as its direction can be determined by the Weber number, which can be written as

$$W_e = [\rho_w\, V^2\, l]/\sigma_t \qquad (9.13)$$

where V is the water flow velocity (m/s) and σ_t the surface tension of water (N/m). Due to the ρ_w and σ_t being constant for both model and full-scale craft, then $W_e \propto \lambda^2$ and $W_{es} \gg W_{em}$, therefore the spray induced by the full-scale craft will be greater than that by models, due to the size of spray particles caused by full-scale craft being relatively smaller than those caused by models.

In one respect, this suggests that the hump drag of full-scale craft will be less than that of models; in another, it demonstrates that a thicker mixed water-air layer might be blown out under the stern lower bag to reduce the stern drag. This spray layer can be seen on full-scale craft, but it cannot be found on models running in towing tanks because of the small Weber number.

Skirt weight per unit area

The dissimilarity of specific weight and Young's modulus of skirts between the full-scale craft and models will cause a distortion of skirt geometry, different skirt dynamic response and added wave drag predicted by the test results. For this reason the repeatability of test results by towing tanks can be poor.

The same craft model with same specific fan speed, tested by the same methods, will obtain different values of drag at different dates and with different test facilities. Sometimes the difference will be as high as 20%. Figure 9.1 shows experimental results

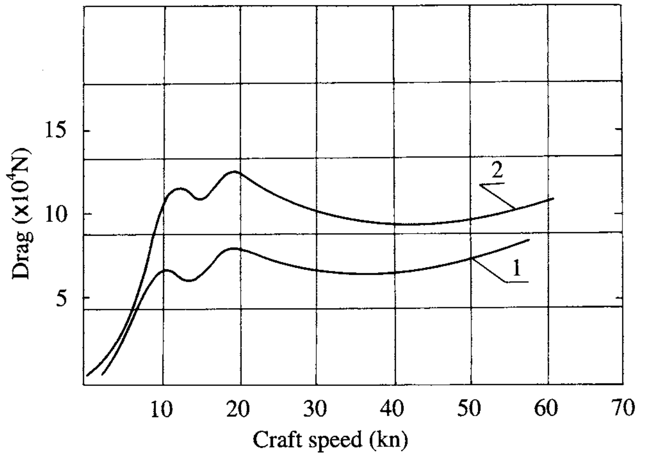

Fig. 9.1 Drag test results for US AALC 150-50 model in different towing tanks: (1) AALC 150-50 model in Davison Laboratory; (2) same model in DTNSRDC Laboratory.

for the same model in different towing tanks at different dates illustrating such differences. It is also possible for different experimental results to be obtained on the same model and same facility; the different condition might only be that the model skirt was straightened before later experiments.

This was also a troublesome problem which faced researchers during the early phase of study in China. In the 1970s, the plastic membrane which was used as model skirt material easily aged and changed the skirt geometry, thus affecting the drag of craft running on calm water and in waves. Thus it could be found that different test results were obtained from the same model, or might be obtained from a different towing tank and at a different date. This is not the case now, as polyurethane-coated fabrics of very fine nylon or aramid woven material are available. These are flexible while being very strong and stable. The scaling problem still remains to a lesser extent, but the ageing and stretching should not be a problem for model tests today.

Non-dimensional characteristics of fans and air ducts

Similar to the experiments with hovercraft models on rigid surfaces, owing to the difference of the non-dimensional characteristic of fans and air ducts, as well as the specific speed between full-scale craft and models, the damping coefficient and natural frequencies are rather different between full-scale craft and models. This affects the motion performance of craft in vertical, longitudinal and transverse directions.

MARIN in Holland have found that for SES models, the dynamic characteristics of the cushion chamber can be modelled more accurately by adding a flexible membrane to what would normally be the hull hard structure between the sidewalls. This allows the cushion natural frequency and damping in heave to be tuned to the expected scaled response.

Table 9.4 Scaling criteria and conditions for use in hovercraft research, design and tests

Item	Scaling criteria	Applicable tests	Applicability of criteria	Influence	Remarks
1	Constant pressure ratio {1}	All tests	Possible	High	
2	Constant *Re* at the jet nozzle {2} or higher than 10^5	All tests	In general cannot be obtained	Low for craft with small flow rate	
3	Dimensionless characteristic of the air ducts	All tests	In general cannot be obtained	Medium	Usual method is to increase revolutions of the fan to make constant Q_i c.f. full scale, i.e. equal flow coefficient
4	Fan constant dimensionless characteristic, or constant fan revolutions {3}	All tests	Cannot be obtained for b, or SES models, but OK for ACV	Medium	As 3
5	Similarity for specific weight of skirt materials {4}	a, b, d, e	Possible	High, should make an effort to obtain it	If no suitable material available then thin glue may be coated on it as balance weight
6	Constant Strouhal number {5}	a, b, d, e	Impossible	Influences the dynamic response of skirt bag and finger so it is very difficult to simulate flagellation and bounce in small models	Also influences the seaworthiness quality of models
7	Constant Π {6}	a, b, d, e	Impossible	As for 6	As for 6
8	Constant *Re* above 10^5 for external flow	a, d, e	Possible	Medium	This condition has to be satisfied during wind tunnel tests
9	$V_g \propto \lambda^{0.5}$ where V_g is the speed of movable model support plate	e only	Impossible	High in the case of simulating internal and external aerodynamic characteristics, particularly at high speed	
10	Constant cushion air adiabatic stiffness coefficient {7}	d, e	Impossible	Less influence for craft with small weight and low speed, otherwise high influence	Tests of intermediate scale test craft have to be carried out if studying large hovercraft
11	Constant *Fn*	d, e	Possible	Serious influence on model test results	
12	Reynolds correlation	d, e	Possible	Serious influence on model test results	In towing tank tests, the Reynolds correlation has to be kept for predicting friction drag from model to full scale
13	Constant Weber's number {8}	d, e	Impossible	Serious influence on spray formation in model tests	

Test types: a static hovering; b skirt box; c wind tunnel; d towing tank, calm; e seaworthiness tests.

Scaling relations: {1} $H_q = p_c/(0.5\ \rho_a\ V_a^2)$ i.e. $V_a \propto \lambda^{0.5}$. {2} $Re_j = V_j t/\gamma$. {3} $N_s = n\ Q^{0.5}/(g\ H_j)^{0.25}$ = constant. {4} $\bar{W}_s = W_s/S \propto \lambda$. {5} $S_r = v/a = \omega l/a$ = constant. {6} $\Pi = E\ \delta\ l_s/\rho_a\ v^2\ S)$. {7} $C_b = V_c/(p_a+p_c)\ \gamma$ = constant. {8} $W_e = \rho_w\ V^2\ l/\sigma_v$ = constant.

Scaling conditions for model seaworthiness experiments

In general, test instruments for seaworthiness are used to measure the amplitude of pitch/heave/surge and the additional wave resistance during seaworthiness tests of hovercraft models in towing tanks. The other three degrees of freedom of yaw, sway and roll are generally fixed. In addition, during experiments the craft are towed at a constant speed but not free flying, therefore the running attitude of models may differ from that of full-scale craft.

When full-scale craft are running in waves, the direction of the propulsor thrust line is fixed with respect to the craft base-line. In the case of towing tank model experiments, the thrust line direction is actually affected by the trim angle of the craft and an additional trim moment acting on the craft may therefore exist, which is very difficult to regulate by balance weights, because the pitching angle of craft running in waves is variable. The result of all this is that motions measured on a model in a towing tank may be different from those measured from free running models in an open tank, or on a lake. Care is needed for interpretation of these results. In general it may be expected that the tank tests will give conservative results for heave and pitch. The surge motions may not be realistic due to the nominal constant speed of the carriage.

9.4 Summary scaling criteria for hovercraft research, design and tests

The scaling criteria and conditions, which should be followed in the experiments mentioned above, are summarised in Table 9.4, in which λ denotes the linear dimensional ratio.