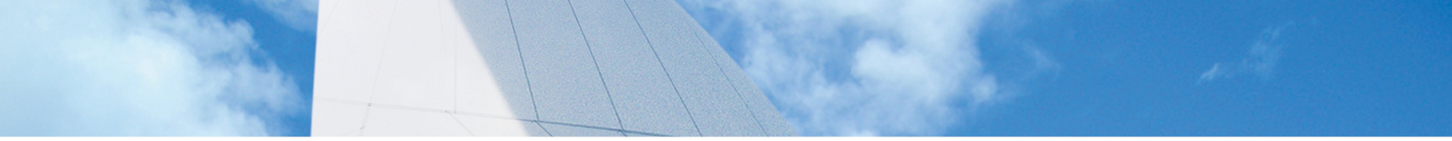

FIFTH EDITION

PRINCIPLES OF YACHT DESIGN

LARS LARSSON, ROLF E ELIASSON AND MICHAL ORYCH

ADLARD COLES

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ADLARD
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PREFACE

The first edition of *Principles of Yacht Design* was published in 1994. Since then there have been three new editions, and the book has been translated into German, Japanese, Korean, Chinese, and Polish. A special edition is published in the United States. The book has thus been very well received, and in this fifth edition we have kept the structure and the main contents of the previous editions. The basic idea is to cover all aspects of yacht design, from the specification, through the hydro- and aerodynamic design, structural assessment, and layout, to the final evaluation. Emphasis is placed on concept descriptions, but formulae, separated from the text, are included in sufficient depth for a complete design of a new yacht. An important feature of the book is the example yacht, used in the book to exemplify the use of the formulae. This is now the YD–41, which replaces the original YD-40 in the fourth edition. Since that edition, the YD–41 has been built and can be seen sailing on the cover. Several pictures of the boat are also included in the book.

In this fifth edition there are minor revisions in many chapters, but the two main updates are a new chapter on foiling and a completely rewritten chapter on scantlings, following the new ISO 12215 standard. The authors owe great thanks to Nimal Sudhan Saravana Prabahar, who carried out all computations reported in the foiling chapter. Heikki Hansen, Laura Marimon Giovannetti and Adam Persson are also gratefully acknowledged for reviewing the chapter. The new ISO scantlings standard was developed under the chairmanship of Gregoire Dolto and the authors are indebted to him for his support.

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LIST OF SYMBOLS

In general, the symbols used in this book are those recommended by the International Towing Tank Conference (ITTC). However, in the chapters on scantling determination (hull dimensioning) and the Nordic Boat Standard (rig dimensioning) other symbols have been used. This is to simplify the later use of these standards by readers.

$A, A_{(i)}$	area, general
a	elongation
$a_{(i)}$	distance from neutral axis to centre of area
A_0	area of propeller disk
a_1	distance from L_{WL} to T1
a_2	distance from L_{WL} to T2
ABS	American Bureau of Shipping
A_D	design area under consideration
A_F	foretriangle area
A_f	flange area
a_k	distance from keel centre of gravity to canoe body
A_{lr}	projected rudder area
A_M	mainsail area, or midship section area below designed waterline
A_{min}	keel/hull area
AOA	angle of attack
AP	aft perpendicular
A_R	aerodynamic driving force
AR, ΔAR	aspect ratio and change in aspect ratio, respectively
AR_e	effective aspect ratio
AR_E	aspect ratio of extended keel
AR_{Ee}	effective aspect ratio of extended keel
A_S	sail area (main + foretriangle) or aerodynamic side force
A_W	area of water plane
A_X	maximum section area below designed waterline
b	short edge of panel
B	beam of hull amidships, or centre of buoyancy, hull upright
B_C	chine beam of hull
BD	boom height above deck
b_e	effective width of plating
BG	distance between centre of buoyancy and gravity
B_H	moulded beam of hull
BM	metacentric radius
B_{MAX}	maximum beam of hull
B_u	Taylor thrust coefficient
B_{WL}	beam of waterline
C	chord length, or crown width of stiffener, or compressive strength (see also list of Indices)
$C_{1,2}$	spreader compression force
c	curvature height of panel
CB	centreboard
C_B	block coefficient
C_D	drag coefficient
C_{DI}	induced drag coefficient
C_{D0}	drag coefficient at zero angle of attack, or drag coefficient of mast, rig and topsides
C_{DP}	viscous (parasitic) drag coefficient of sails
CE	aerodynamic centre of effort
CF	centre foil
C_F	skin friction coefficient
CFD	computational fluid dynamics
C_H	heel resistance coefficient
C_L, C_{Lmax}	lift coefficient and maximum lift coefficient, respectively
C_L^{2D}	two-dimensional lift coefficient
C_L^{3D}	three-dimensional lift coefficient
C_{Lr}	rudder lift coefficient
CLR	hydrodynamic centre of lateral resistance
C_M	midship section coefficient
C_P	prismatic coefficient, or pressure coefficient
C_R	residuary resistance coefficient
C_S	aerodynamic side force coefficient
c_u	curvature height of stiffener
D	depth of yacht, or drag, or propeller diameter
D1,2,3	diagonal shrouds
d_{kb}	core diameter of keelbolt
DWL	designed waterline
E	modulus of elasticity, or base of mainsail (ISO)
E_C	compressive modulus of elasticity
E_F	flexural modulus of elasticity
E_T	tensile modulus of elasticity
E_{TC}	average modulus of elasticity
F	flat factor of sails, or flexural strength, or flange width of stiffener, or design head reduction factor
$F_{1,2,3}$	dimensioning transverse rig forces
F_a	freeboard aft
F_f	freeboard forward
F_h	hydrodynamic side force or horizontal boom force
F_i	impact force
F_n	Froude number
FP	forward perpendicular

F_r	rudder side force
F_s	design head reduction factor
F_S	freeboard at mast
F_v	vertical boom force
F_Φ	side force at right angles to (heeled) centre plane
FRP	fibre-reinforced plastic
g	acceleration of gravity, or girth length, or ballast weight
G	centre of gravity, or empty weight of yacht
GM	metacentric height
GRP	glass-reinforced plastic
GZ	righting arm
H	floor height or ride height
$H_{1/3}$	significant wave height
h	roughness height, rudder height, height of stiffener, local height from L_{WL} or chine, mast height from deck or superstructure to the highest sail carrying forestay
h_u	distance between rudder bearings
HA	heeling arm
h_b	pressure head for watertight bulkhead or integral tank
I	height of foretriangle (ISO), or moment of inertia
I_L	longitudinal moment of inertia of water plane area
IACC	International America's Cup Class
IMS	International Measurement System
IOR	International Offshore Rule
ISO	International Standards Organization
I_T	transverse moment of inertia of water plane area
I_{yy}	mass moment of inertia around a transverse axis through G
I_x	transverse moment of inertia for the mast
I_y	longitudinal moment of inertia for the mast
J	base of foretriangle (ISO)
k	gyradius in pitch, or aspect ratio factor
k_{2b}	aspect ratio factor
k_{AM}	assessment method factor
k_{AR}	area pressure reduction factor
k_{BB}	boatbuilding factor
k_c	curvature correction factor
k_{DC}	design category factor
k_{DYN}	dynamic load factor
k_L	longitudinal impact factor
K_Q	torque coefficient
k_{SH}	aspect ratio factor
k_R	structural component and boat type factor
k_{SA}	stiffener shear area factor
k_{SHC}	sandwich core shear coefficient
k_{SLS}	slamming factor for light, fast sailboats
k_{SUP}	superstructure pressure reduction factor
K_T	thrust coefficient
k_1	bending stiffness coefficient
k_2	aspect ratio coefficient for bending strength
k_3	aspect ratio coefficient for bending stiffness
l	long edge of panel
L	length, general, or length rated, or lift
L_F	floor length
L_K	Keel root length
$l_{1,2,3}$	rig panel lengths
l_a	distance from L_{WL} to top of aft stay
l_c	distance from leading edge to centre of effort
l_u	unsupported length of stiffener
LCB	longitudinal centre of buoyancy
L_H	length of hull
L_{OA}	length overall
L_{pp}	length between perpendiculars
L_{WL}	length of waterline
m	mass displacement, mass (general), or mast material factor
m_K	mass of ballast keel
m_{LA}	mass in loaded arrival condition
m_{LDC}	loaded displacement mass
M	bending moment, or metacentre
Mb_{hull}	hull bending moment
M_{fl}	floor bending moment
M_{kl}	floor bending moment, from grounding
M_{kt}	transverse moment from keel
m_{MO}	mass in minimum operating condition
M_r	rudder bending moment
M_s	spreader bending moment
N	rudder force factor
NBS	Nordic Boat Standard
n	number of persons on board, or rate of revolutions, or number of floors in way of keel
n_{cg}	dynamic load factor, g:s
n_{kb}	number of keelbolts
OF_{bolt}	keel bolt offset
ORC	Offshore Racing Congress
O_x	transverse fractional mast top length
O_y	longitudinal fractional mast top length
P	height of mainsail (ISO), or propeller pitch, or load, general
P_a	dimensioning aft stay load
P_{ah}	horizontal part of aft stay load
P_{av}	vertical part of aft stay load
P_b	bottom pressure
P_{BMD}	displacement powerboat bottom pressure
P_{BMP}	planing powerboat bottom pressure
P_{BS}	sailboat bottom pressure
P_c	composite property
P_{crit}	critical load
P_D	delivered power, or design pressure
P_{deck}	compression force in deck
P_{DM}	powerboat deck pressure
P_{DS}	sailboat deck pressure
$P_{D,V}$	dimensioning shroud load
P_{fh}	horizontal part of forestay load
P_{fi}	dimensioning inner forestay load
P_{fo}	dimensioning outer forestay load
P_{fv}	vertical part of forestay load
P_{hd}	horizontal component of stay forces
P_{kb}	keel bolt load tension
P_{kt}	total keel bolt load
P_m	mat property
P_{mast}	mast pressure
PT	dimensioning mast load
P_r	grounding load
P_{SMD}	displacement powerboat side pressure

P_{SMP}	planing powerboat side pressure
P_{SS}	sailboat side pressure
P_{SUPM}	powerboat superstructure pressure
P_{SUPS}	sailboat superstructure pressure
P_{TB}	design pressure, integral tank
P_{WB}	design pressure, watertight bulkhead
Q	torque
R	resistance, general, or reef factor of sails
R_A	windage
R_{AW}	added resistance in waves
R_F	frictional resistance
RB	rubber board
RF	rubber foil
R_H	heel resistance
RM	righting moment
RM_1	righting moment at 1 deg heel
RM_{30}	righting moment at 30 deg heel
RM_{90}	righting moment at 90 deg heel
R_n	Reynolds number
RORC	Royal Ocean Racing Club
R_R	residuary resistance
r_t	nose radius
R_{vc}	rudder centre of effort, vertical distance from top
RYA	Royal Yachting Association
s	spacing of stiffeners
$S_{(n)}$	length of spreader
SA	total triangular sail area
SAF	sail area, foretriangle (ISO)
SAM	sail area, mainsail, triangular (ISO)
SL	length of spinnaker leech (ISO)
SM	section modulus
SM_{fl}	floor section modulus
SM_{hull}	hull girder section modulus
SM_i	section modulus to inside of panel
SM_k	section modulus increase in way of keel
SM_o	section modulus to outside of panel
SMW	spinnaker width (IOR)
S_W	wetted surface area
S_{Wc}	wetted surface area of canoe body
t, t_{max}	thickness and maximum thickness, respectively
T	draft of yacht, or propeller thrust, or tensile strength
T_1	wave period, or transverse foresail force
T_2	transverse mainsail force
T_{boom}	transverse force at foot of mainsail
T_{bu}	upper boom force
t_c	core thickness, chine thickness
TCG	transverse centre of gravity
t_f	face thickness
T_{head}	transverse force at top of mainsail
t_k	keelstrake thickness
T_{hl}	lower shroud force
T_{hu}	upper shroud force
T_K	draft of keel below canoe body
T_R	taper ratio
Tr	rudder torsional moment
Ts	time to stop
t_s	skin thickness, stemstrake thickness
V	volume displacement, or yacht speed
V1,2	vertical shroud
V_{AW}	apparent wind speed
V_{AWe}	effective apparent wind speed, yacht heeled
VCB	vertical centre of buoyancy
VPP	Velocity Prediction Program
V_s	yacht speed
W	weight displacement, or fibre angle
w	fibre mass
Wf	fibre content, ratio
W_k	weight of ballast
X_0	position of neutral axis
x	distance of mid panel or stiffener from aft end of L_{WL}
x_{lc}	distance from leading edge to centre of rudderstock
X_m	ratio of mat in a composite
X,Y,Z	Cartesian coordinates. Origin at FP, X afterwards, Y to starboard, and Z upwards
y	deflection
Z	height of top of hull or deck above L_{WL}
Z_{CBk}	distance from water surface to keel centre of buoyancy
α	angle of attack, or scale factor
α_a	aft stay angle to mast
α_f	forestay angle to mast
β	leeway angle, deadrise angle
$\beta_{1,2,3}$	diagonal shroud angle to mast
β_{AW}	apparent wind angle
$\gamma_{1,2}$	vertical shroud angle
δ	Taylor parameter, or horizontal angle of spreader
δ_{RM}	additional righting moment from crew to windward
η	safety factor
η_0	propeller efficiency
Θ	trim angle
λ	wavelength
Λ	sweep angle
ν	kinematic viscosity
ρ	density
σ	normal stress, or cavitation number
$\sigma_{0.2}$	yield stress
σ_c	design stress for rudder stock
σ_d	design stress
σ_f	normal stress in sandwich face
σ_u	ultimate stress
σ_y	yield stress
τ	Burrill parameter, or shear stress
τ_d	design shear stress
τ_u	ultimate shear stress
Φ	heel angle
ω_φ	natural frequency (in roll)
ω_e	frequency of wave encounter
∇	volume displacement

Indices

c	canoe body
k	keel
r	rudder
u	upper
l	lower

CONVERSION FACTORS

To convert metric measures into imperial measures, multiply by x.
To convert imperial measures into metric measures, multiply by y.

Metric	Imperial	x	y
Length			
Millimetres (mm)	Inches	0.039	25.40
Centimetres (cm)	Inches	0.394	2.540
Metres (m)	Inches	39.37	0.025
Metres (m)	Feet	3.281	0.305
Metres (m)	Yards	1.094	0.914
Kilometres (km)	Geographic miles	0.621	1.609
Kilometres (km)	Nautical miles	0.5397	1.8532
Area			
Square millimetres (mm^2)	Square inches	0.0016	645.10
Square centimetres (cm^2)	Square inches	0.155	6.452
Square metres (m^2)	Square inches	1550	0.000645
Square metres (m^2)	Square feet	10.764	0.0929
Square metres (m^2)	Square yards	1.196	0.836
Volume			
Cubic centimetres (cm^3)	Cubic inches	0.061	16.39
Cubic metres (m^3)	Cubic feet	35.315	0.0283
Cubic metres (m^3)	Cubic yards	1.309	0.764
Litres (L)	Cubic inches	61.024	0.0164
Litres (L)	Cubic feet	0.0353	28.317
Litres (L)	US gallons	0.264	3.785
Litres (L)	Imp. gallons	0.220	4.546
Mass, weight and force			
Grams (g)	Ounces	0.0353	28.350
Kilograms (kg)	Pounds	2.2046	0.4536
Tonnes, metric (T)	Pounds	2204.6	0.00045
Tonnes, metric (T)	Tons, long	0.9843	1.0160
Newton (N)	Pounds	0.2247	4.450
Kilonewton (kN)	Pounds	224.73	0.0044
Density			
Kilograms/m^3 (kg/m^3)	Pounds/cubic foot	0.0624	16.026
Pressure, stress, work, energy			
Newton/mm^2 (N/mm^2)	Pounds/sq inch	144.95	0.0069
Kilonewton/mm^2 (kN/mm^2)	Pounds/sq inch	144950	0.0000069
Pascal (Pa) (= 1 N/m^2)	Pounds/sq inch	0.00014	6899
Kilopascal (kPa) (= 1 kN/m^2)	Pounds/sq inch	0.14495	6.899
Megapascal (MPa) (= 1 N/mm^2)	Pounds/sq inch	144.95	0.0069
Gigapascal (GPa) (= 1 kN/mm^2)	Pounds/sq inch	144950	0.0000069
Newton-metres (Nm)	Foot-pounds	0.7370	1.3568
Kilonewton-metres (kNm)	Foot-pounds	737.00	0.0136
Horsepower (metric)	Horsepower (imp)	0.9860	1.0142
Kilowatts (kW)	Horsepower (imp)	1.3400	0.7463
Speed			
Metres per second (m/s)	Feet per second	3.2808	0.3048
Metres per second (m/s)	Knots	1.9425	0.5148
Kilometres per hour (km/h)	Miles per hour	0.6214	1.6093
Kilometres per hour (km/h)	Knots	0.5397	1.8532

INTRODUCTION

Yacht design is of interest not only to professional and amateur yacht designers; many other yachtsmen are interested in the principles behind the design of their yacht and the theory of sailing. In racing, such knowledge is important for the optimization of the equipment and the handling of the boat. Speed is also of interest in cruising; nobody is interested in a slow boat. Safety is a major issue in all kinds of sailing. Consequently, there is a need for a comprehensive book, covering all aspects of yacht design.

It is now more than 100 years since Skene wrote his now-classic *Elements of Yacht Design*, which was revised several times (see Kinney, 1973). For almost a century this book was considered the 'bible' in yacht design, but it is now obsolete. The most well-known books on sailing theory are the excellent ones by Marchaj: *Sailing Theory and Practice*, first published in 1964, *The Aero-Hydrodynamics of Sailing* in 1979, *Seaworthiness – the Forgotten Factor* in 1986 and *Sail Performance: Techniques to Maximize Sail Power* in 1996. Since the books deal with basic sailing theory, they are still mostly up to date, but they are not very useful for the designer, since they do not cover methodology, statistical data for existing yachts or design evaluation techniques. Furthermore, these books concentrate on the hydro- and aerodynamic aspects of the problem, while, for instance, loading, strength, and structural problems, as well as practical design considerations, are either not mentioned or treated very briefly.

By the time the first edition of the present book was published (in 1994), there was no modern textbook comparable to Skene's as a guide for the yacht designer. Trying to replace this classic text with a modern one was a great challenge, but the new book was well-received both by professional and amateur yacht designers and translations have been made into several languages.

Since the first edition, another three high-quality books have appeared. *Sailing Yacht Design* by Claughton, Wellicome and Shenoi (1998) is published in two volumes: *Theory* and *Practice*, respectively. *Aero-Hydrodynamics and the Performance of Sailing Yachts* by Fossati (2009) deals with the fundamental theory of sailing yacht design and may be considered a modern version of Marchaj's books. The same is true also for the most recent book by van Oossanen (2020): *The Science of Sailing*. This is an in-depth analysis of sailing physics in four volumes and around 1000 pages. As compared to Marchaj, and even Fossati, this book is more fundamental and goes into basic physics at a high academic level.

As the title suggests, the emphasis of this book is on yachts, rather than dinghies. However, most of the theories and concepts described apply to this class of boats as well. For specific aspects on racing dinghy design, see the excellent books by Bethwaite (1996, 2013): *High Performance Sailing* and *Higher Performance Sailing*.

For a book on yacht design to be successful, two conditions must be satisfied:

- It must cover all aspects of yacht design.
- Although it must be comprehensible for amateurs, it must be advanced enough to be of interest also to professional designers.

There follows a short presentation of this book and an explanation of the strategy adopted for satisfying these two requirements.

The book begins with a description of the methodology recommended in the design process. Specifications of the yacht and the design concept are discussed in Chapter 2, and Chapters 3 and 4 cover the geometric description of the hull and hydrostatics and stability in calm water and waves. The hydrodynamic design of the hull, keel, and rudder is explained in Chapters 5 and 6. Chapter 7 deals with foiling and Chapter 8 with sail aerodynamics. In Chapter 9 methods are introduced for finding the balance of the yacht. Chapter 10 deals with the selection of the correct propeller and engine, and in Chapter 11 planing hulls are introduced.

Structural aspects of design are treated in Chapters 12, 13, 14 and 15. Loads acting on the rig and hull are identified and methods for computing them introduced. Dimensioning according to the ISO standard is explained and complete calculations carried out for one example. There is also a discussion on different fibre-reinforced plastic (FRP) materials, including sandwich laminates. Practical matters, such as the layout of the cockpit, deck and cabin, are discussed in Chapter 16, and Chapter 17 presents different means for evaluating the design. A complete weight calculation is carried out in Appendix 2.

The different aspects of the design process are therefore well covered. To satisfy the second requirement above, the material must be well presented, and we have tried to accomplish this in several ways. Yacht design is by its nature a quantitative process. A designer, professional or amateur, is not much helped by qualitative reasoning. It is not enough to know that the hull can withstand a larger load if the skin is made thicker, or that stability is increased by more lead in the keel. What he needs to know, as exactly as possible, is the *minimum* skin thickness and the least amount of lead needed in the keel for the yacht to be safe under all possible conditions. If he is not able to compute these quantities the yacht may be slower and more expensive than necessary and, worst of all, it may be unsafe. Therefore, a basic principle of this book has been to provide formulae or diagrams for all aspects of the design process. The reader should be able to evaluate quantitatively every step in the design procedure.

We are fully aware that many potential readers may be intimidated by a text loaded with formulae and would reject the book as being too technical. To avoid this, the equations have been removed from the text and inserted into the figures. A serious designer will need to work through the formulae himself for the reasons just explained, but we believe that the book could also be of interest to yachtsmen in general, since many may have a keen interest in the basic physics of sailing. They will be able to read the text without digging too deeply into the quantitative aspects. On the other hand, the equations are not very complicated from a mathematical point of view. They are numerous, and they may be lengthy, but they are all of the algebraic type. Higher mathematics, such as integral or differential calculus, have been completely avoided, and everyone with a basic mathematical background from, say, secondary school should be able to understand them.

To help the reader understand the practical application of the principles and formulae presented, the design of a new yacht, called YD–41 (Yacht Design 41-footer) is followed throughout the book. Thus, most of the formulae presented are followed by the computed value for the YD–41, and most drawings (like lines plan, interior and exterior layout, rig plan and general arrangement) are for this modern cruiser/racer. This does not mean, of course, that the book is limited to this type of yacht. The material covers other cruisers and racers, traditional and modern designs, and different rig types. Dinghies are covered as well, particularly in Chapter 7 on foiling, but there is not much discussion on multihulls. Powerboats are addressed specifically in the chapters on high-speed hydrodynamics and scantlings, but much of the other material in the book applies to this type of craft as well. The YD–41 is specified in detail in Appendix 1, where all the data is given. There are two different sets of data. One is for the cruising condition, with all the necessary equipment and the tanks half full, while the other is for the light version, without cruising equipment. The latter version, or an even lighter one, is normally used in advertising material for new yachts. A weight calculation for the YD–41 is presented in Appendix 2, for different loading conditions. The boat can be seen under sail on the cover of this book.

To evaluate a new design and its qualities it is important to compare it with other yachts. Sections with statistical data are therefore included in many of the chapters. Median values for existing yachts are given and the scatter, within which approximately 95% of all yachts lie, is indicated. There is also a discussion on the effects of deviating from the median, which will enable the designer to create a yacht with special qualities. The position of the YD–41 within the statistical data is also shown and motivation for this position is given in the light of the yacht specification in Chapter 2 and Appendix 1. To satisfy the more qualified readers of the book, there are sections on advanced design, where the methods and tools described are not normally available to non-professionals. Also, throughout the book, the results of the most recent research in yacht design are presented. Much of this is not discussed in yachting literature.

Finally, some general remarks on the principles and style of the book. With a few exceptions, the International System of Units (SI) is adopted. The exceptions are parts of the rig and scantling chapters where we use standards that still rely on other systems. Otherwise, it is only the yacht speed that does not always follow the SI system; it is often given in knots. This is still standard in hydrodynamics when it comes to boat speed. However, in the discussion of wings of different kinds, like keels, rudders, and hydrofoils, the aerodynamic vocabulary is used. Here speed is expressed in m/s. Resistance and drag are two words with the same meaning but from the two different disciplines. Depending on the topic both words are used in the book. A conversion table between the SI and English units may be found on page 19.

Another standard adopted is the nomenclature specified by the International Towing Tank Conference (ITTC). This has been developed over a very long period and is agreed by all members of the ITTC, which include all reasonably sized towing tanks in the world, as well as most universities teaching naval architecture.

A list of references may be found at the end of the book. In the text, the references are identified by the name of the author, followed by the year of publication. It should be noted that there are more references in the list than are specifically referred to in the text.

1 DESIGN METHODOLOGY

Yacht design is an iterative 'trial and error' procedure where the final result has to satisfy certain requirements, specified beforehand. To achieve this the designer has to start with a number of assumptions and work through the design to see if, at the end, it satisfies the requirements. This will most certainly not be the case in the first iteration, so he will have to change some assumptions and repeat the process, normally several times. The sequence of operations is often referred to as a spiral, where the designer runs through all the design steps and then returns to the starting point, whereupon a new 'turn' begins. After several turns the process may have produced the desired result. We will describe the design spiral in more detail below.

If all steps are taken manually the procedure can be extremely time consuming, and it is tempting to stop the iterations before the initial specifications have been fully met. A huge saving in time and accuracy is possible if modern computer-aided design (CAD) techniques are adopted, and we will discuss this possibility in the second part of the chapter.

THE DESIGN SPIRAL

In Fig 1.1 the design spiral is shown. Eleven different segments may be identified, and each segment corresponds to an operation by the designer. Not all operations have to be carried out in each turn, and the tools used in each operation may vary from turn to turn. In principle, more and more segments are included, and better and better tools are used, as the process converges towards the final solution. The figure shows that each sector corresponds to a chapter (or possibly two) in this book.

From the start the designer has only the specifications of the yacht, i.e. its requested capabilities. Based on his experience, or data from other yachts, he assumes the main data of the hull. Non-dimensional parameters such as displacement/length ratio, sail area/wetted arearatio, heeling arm and metacentric height may thus be computed, and a rough check of the performance may be made based on statistics from other yachts. The procedure is summarized in Chapters 2 and 17. In this first spiral turn the designer jumps from the first to the last segment directly, and the evaluation is very rough.

In the second turn, after having adjusted the main parameters, it may be time to begin the actual design of the hull, keel, rudder and sail plan. The theory for this is given in Chapters 3, 5, 6, 7, 8 and 9. A rough layout of the interior and exterior design (see

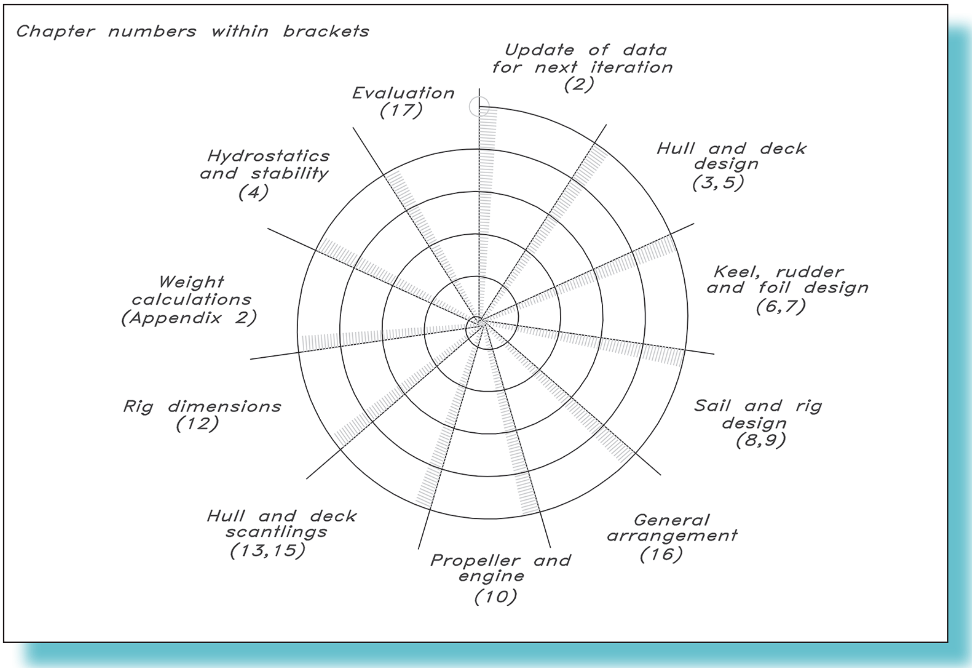


Fig 1.1 The design spiral

Chapter 16) may be made too, to give an initial weight estimate, needed for the stability calculation (see Chapter 4). It is likely that neither the weight nor the stability will be correct, so several turns may be required to satisfy these requirements reasonably. Of course, not all previous operations may have to be redone in each turn. Having found a reasonable weight and stability for the yacht, the next turn may include the detailed hull scantling calculations and the dimensioning of the rig, as well as the choice of the engine (see Chapters 10–15). Only at this stage can an exact weight calculation be carried out, as shown in Appendix 2.

As the designer approaches the final solution he may want to evaluate the design more carefully, and to do this a Velocity Prediction Program (VPP) is required. Such programs are described in Chapter 17, where other even more accurate techniques, such as towing tank testing and computational fluid dynamics (CFD), are also presented. The amateur designer may not have access to either of these tools, however, so his evaluation of the current design will have to be based on experience.

It should be pointed out that in some segments internal iterations are required. This is particularly the case in the hull design area. Here, requirements for volume and its distribution are probably specified beforehand, and it may take several iterations to satisfy them. If the process is manual, iterations between the different views to fair the lines are also required, as will be described in Chapter 3. In the hydrostatics and stability segment iterations are required to find the proper sinkage and trim when the hull heels at large angles.

COMPUTER-AIDED DESIGN (CAD)

Thanks to rapid development in recent years, computer-aided design (CAD) may be carried out efficiently on PCs or Macs. It is important to have a high resolution screen; special graphics software speeds up the process. A laser printer will produce reasonably good small-scale graphical output, but professional designers use pen plotters of various sizes to produce drawings up to full scale.

The most important module of a CAD system for yacht design is a powerful program for generating the hull lines, and such programs have been available since the early 1980s. In modern programs the hull surface is represented mathematically by one or more Non-Uniform Rational B-Splines (NURBS) patches. For a detailed description the reader is referred to the book *Computational Geometry for Ships* by Nowacki, Bloor and Oleksiewicz (1995). Any point on the surface may be found from the mathematical representation, or more precisely, if two coordinates of a point are given, the program computes the third one. Thus, if the user provides the distance from the bow, X, and the distance above the waterline, Z, the program computes the local beam, Y, at this location. Also, any cut through the surface may be obtained, for instance, any station or waterline.

There are principally two different problems in connection with the surface representation. The task can be either to generate a new hull, or to duplicate, as accurately as possible, an existing one. The latter problem is more difficult. It is certainly possible in an iterative process to approach a given shape, but it can be time consuming. Fortunately, the designer is normally interested in the first task: creating a new hull. To achieve this he has to work with a set of points, called vertices, located near the surface. By moving one vertex the hull surface is locally deformed in such a way that it is still smooth. In most programs the curvature of the surface may be plotted, thus enabling the designer to generate fair lines even on a small scale, and with the relatively low resolution of the screen. Some programs use points on the hull itself for defining its shape, but all the major programs on the international market use vertex points. There seems to be a consensus among yacht designers that this approach is very effective for creating fair lines. In Chapter 3 we will show how the hull is generated by vertex points.

Most hull geometry programs have the capability to rotate the hull and show it in different perspectives on the screen. The possibility of showing a perspective plot of the hull is important and is a major improvement from the manual approach, where only three standard views are employed (see Chapter 3). For example, the shape of the sheer line may look quite different in perspective compared with the side view, since the line that meets the eye is influenced also by the beam distribution along the hull. Hulls that look good in a side view may look quite ugly in reality.

Some of the more advanced programs include the deck and superstructure as for the hull model, i.e. these parts of the yacht are represented in three dimensions and may be displayed in perspective. In other programs they are treated separately. To compute stability at large angles of heel the deck, cabin and cockpit need to be modelled, and this is frequently done in a separate module where these parts are added relatively crudely, section by section.

A keel/rudder module is often available in yacht CAD systems. The designer may choose between a number of different profiles for the cross-section and specify the planform of the keel/rudder. The code computes the volume, weight of the keel, centre of gravity and centre of effort of the hydrodynamic force. The latter is required in the balancing of the yacht, as explained in Chapter 8. For this the sail plan is also required, and some systems have a simple sail module which computes sail areas and centres, given the sail corner coordinates.

The total weight and centre of gravity location (in three directions) are computed in a weight schedule monitor, which accepts the weight and position relative to a given reference point of all items on board. Appendix 2 presents the input and output from such a monitor.

Very important modules of the yacht CAD system are the hydrostatics and stability programs. These compute all the quantities discussed in Chapter 4, including stability at small and large heel angles, weight per mm of sinkage, and moment per degree of trim. In the stability calculation the correct sinkage and trim are found for each heel angle – a very time consuming procedure if carried out manually.

The Velocity Prediction Program (VPP), mentioned earlier, may also be regarded as a module of the CAD system. As explained above, this program computes the speed, heel angle and leeway angle at all wind speeds and directions of interest, based on a set of dimensions for the hull, keel, rudder and sails. The very simple performance estimator, based on a few main parameters and used in the first iteration of the design spiral, may also be a module of the system.

Finally, more or less advanced programs for the structural design of the yacht may be included. Such programs can be based on the rules given by the classification societies: the American Bureau of Shipping (ABS), Lloyd's Register of Shipping (LR) and others or the ISO 12215 scantlings standard. The ISO standard will be described in Chapter 15. Other methods employed in the rig and scantling calculations may be based on basic strength theory or finite element techniques.

Computer-aided design may be extended to computer-aided manufacturing, which can be used in the production of the yacht. For example, the very time consuming lofting process, where the builder produces full-scale templates, may be eliminated. Traditionally, the builder receives offset tables from the designer. Based on these offsets the templates are drawn at full scale with a reduction in dimension for the skin thickness of the hull. This is necessary, since the templates are used internally during the building process. If the hull has been CAD designed, however, the full-scale templates with the proper reduction may be plotted directly, provided a sufficiently large plotter is available. Plate expansions may also be obtained from the CAD system, simplifying the production of steel and aluminium hulls.

2 PRELIMINARY CONSIDERATIONS

Before actually starting the design work, we must have a clear picture of the yacht's purpose: what are the requirements, limitations and objectives of the design? In this chapter we will list the considerations that form the starting point of the design.

CHOICE OF BOAT-TYPE

Regardless of whether the client is an individual owner or a boatbuilding firm, he will have definite ideas as to the type of boat he wants. Most people have a particular yacht in mind, which, with changes in dimensions, style, arrangement, rig or hull form, satisfies their demands. These preferences are often modified by other considerations, such as local conditions, economic considerations and intended use. Personal opinion often governs the choice of type to such an extent that the more logical and scientific arguments may become of secondary concern, if not set aside entirely.

INTENDED USE

The intended use of the yacht is a matter that comes first on the list of considerations. The first distinction is that between racing and cruising. For the racer we must naturally decide to which rule the boat should be designed, and in which class it will be racing. This gives us a good starting point regarding the size of boat and crew, rig size and type, by comparing it with existing successful designs. Having established the type and size of boat, we can proceed with the design process described in the following chapters, making adjustments so as to conform to the rule we are following.

For the cruiser the primary requirement influencing the type of design to adopt regarding hull, deck, accommodation and rig is the yacht's intended use in broad terms, i.e. unlimited ocean passage-making, open or restricted offshore use, or coastal or sheltered use. Obviously, it is easier to reach high standards of safety, stability and performance with a big yacht, provided there is sufficient crew to handle the vessel.

This brings us to the question of the need for compromise. The requirements of speed, seaworthiness, dryness, weatherliness, ease of handling, comfort and other qualities often conflict, but the fewer the compromises the better the design. We must decide at an early stage what particular qualities we desire most, or require to the greatest extent. By getting our priorities right from the start we know where compromises can be made with the least harm. Too many yachts are designed on the assumption that it is possible to achieve all of the qualities of the perfect yacht without regard for the limitations of the chosen type and its intended use. To achieve a good design it is crucial to define the intended use, weigh the requirements that these impose on the yacht and choose a type of yacht whose design elements fulfil that need. When the type of yacht is chosen we must stick to it throughout the whole design process. Of course there will be alterations along the way, but if we find that many major changes are necessary it will probably be best to start the design work from square one.

The intended use is not only about sailing area, performance, and range, but also about who is going to use the boat and under what circumstances. If we take a design intended for charter use, the requirement will usually be a large number of berths and a roomy cockpit to accommodate everyone when sailing. The time at sea will be restricted, most sleeping will be in harbour or at anchor and the handling systems must be understood by novices. By contrast, an experienced owner who wishes to make extended passages with a small crew will have the opposite requirements.

MAIN DIMENSIONS

It is generally agreed that by increasing the size of the boat a better design in terms of performance and comfort will be produced; on the other hand the boat might be more difficult to handle for a small crew. Size is also linked to the intended area of use: unlimited ocean use naturally places greater demands on a boat than sheltered water use. Not only will it need to withstand strong winds and heavy seas, but it will also need to carry more fuel, water and stores – all of which point to the bigger yacht. However, it is not self-evident that size in this respect means length; a better measure would perhaps be displacement, since this describes the volume of the boat. Take two boats of similar displacement: the longer one will usually have better performance but its carrying capabilities will be roughly the same as for the shorter one.

The requirements of engine, rig and deck equipment depend largely on size, weight and length as well as beam. To reach a certain speed with a limited power source the length–weight ratio is of vital importance, while the stability required to carry enough sail is more dependent on the beam and weight. In this context it is noticeable that the heeling moment increases with size to the power of 3, while the stability increases with size to the power of 4. So scaling a boat up linearly does not produce a design compatible with good performance and stability.

The changes in proportions with increasing size have been calculated for an allometric series of yachts from L_{OA} = 7m to L_{OA} = 19m by Barkla (1960) (see Fig 2.1). As we can clearly see, different dimensions and parameters scale differently with length. The scaling factors shown in the figure produce boats of similar behaviour regarding performance and 'feel' when scaled in either direction from a base model. The 'L' in Fig 2.1 refers to the length relation between the base model and the derivative. For example, if we increase the length of the boat by 50%, i.e. 1.5 times L, the beam, depth

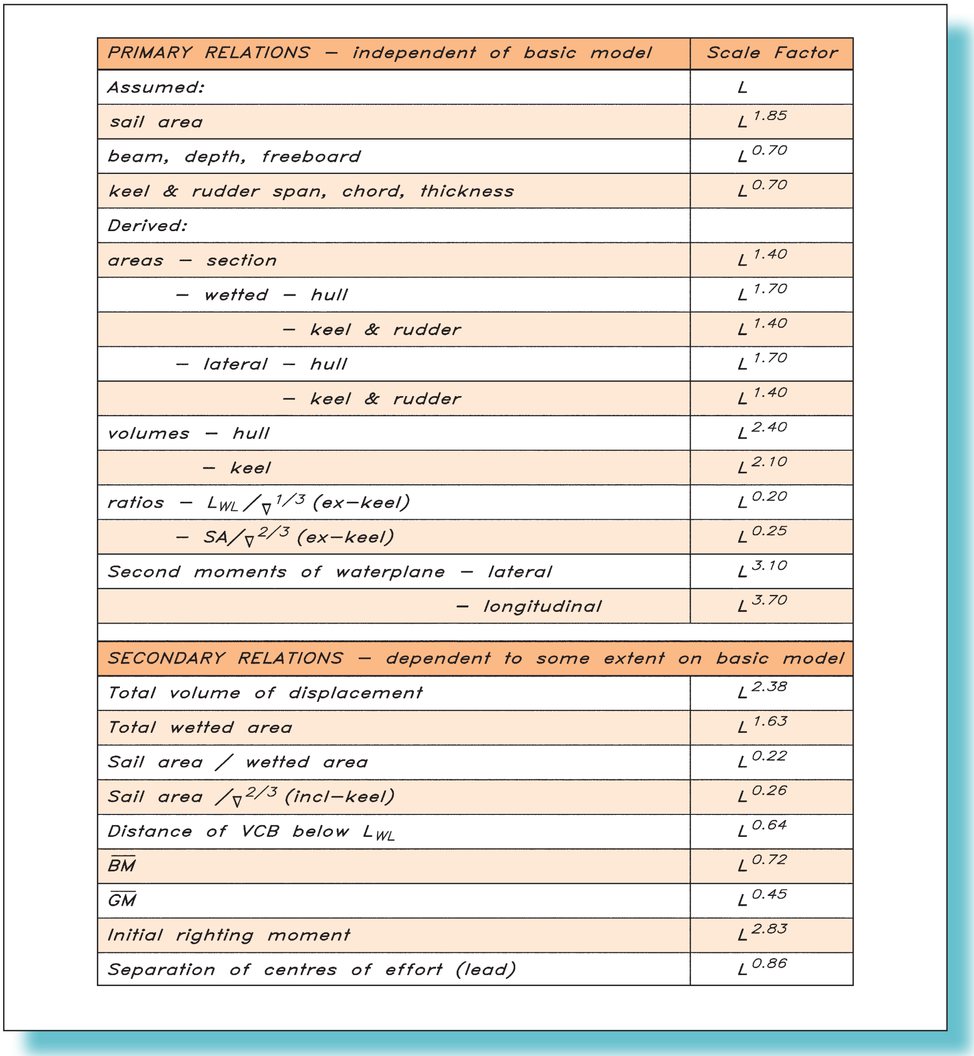
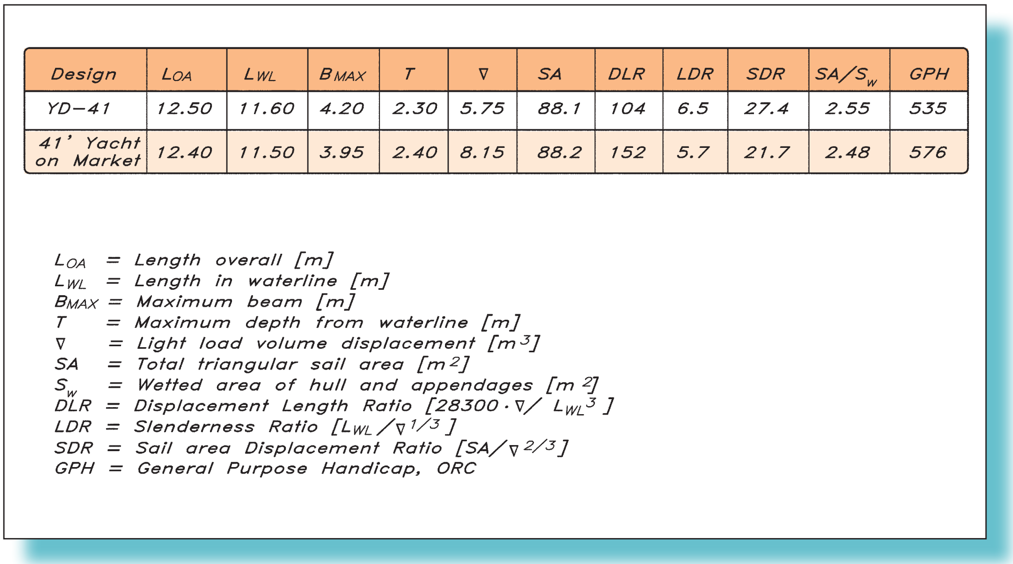


Fig 2.1 Proportions versus size (Barkla, 1960)

PRIMARY RELATIONS – independent of basic model	Scale Factor
Assumed:	L
sail area	$L^{1.85}$
beam, depth, freeboard	$L^{0.70}$
keel & rudder span, chord, thickness	$L^{0.70}$
Derived:	
areas – section	$L^{1.40}$
– wetted – hull	$L^{1.70}$
– keel & rudder	$L^{1.40}$
– lateral – hull	$L^{1.70}$
– keel & rudder	$L^{1.40}$
volumes – hull	$L^{2.40}$
– keel	$L^{2.10}$
ratios – $L_{WL}/\nabla^{1/3}$ (ex–keel)	$L^{0.20}$
– $SA/\nabla^{2/3}$ (ex–keel)	$L^{0.25}$
Second moments of waterplane – lateral	$L^{3.10}$
– longitudinal	$L^{3.70}$
SECONDARY RELATIONS – dependent to some extent on basic model	
Total volume of displacement	$L^{2.38}$
Total wetted area	$L^{1.63}$
Sail area / wetted area	$L^{0.22}$
Sail area $/\nabla^{2/3}$ (incl–keel)	$L^{0.26}$
Distance of VCB below L_{WL}	$L^{0.64}$
$\overline{BM}$	$L^{0.72}$
$\overline{GM}$	$L^{0.45}$
Initial righting moment	$L^{2.83}$
Separation of centres of effort (lead)	$L^{0.86}$

and freeboard will be increased by $1.5^{0.7} = 1.33$ times the original value to keep the boat within the same performance-family.

A very good way of establishing dimensions for the hull and rig of a new design before there are any drawings or calculations is to decide on some vital dimensionless ratios that can be checked against known designs. Chapter 5 deals in more detail with this, and explains what factors are involved. Fig 2.2 shows, for the YD–41, the values of the ratios derived from first estimates of the main dimensions. Comparison is made with an existing yacht of the same size. Note that such a comparison is mostly done with several similar yachts and they do not necessarily have to be the same size. Using the relations of Fig 2.1 yachts of slightly different sizes may be scaled to the length of interest. Once we are satisfied with the numbers, we have a good starting point for the design.



Design	L_{OA}	L_{WL}	B_{MAX}	T	∇	SA	DLR	LDR	SDR	SA/S_w	GPH
YD–41	12.50	11.60	4.20	2.30	5.75	88.1	104	6.5	27.4	2.55	535
41' Yacht on Market	12.40	11.50	3.95	2.40	8.15	88.2	152	5.7	21.7	2.48	576

L_{OA} = Length overall [m]
L_{WL} = Length in waterline [m]
B_{MAX} = Maximum beam [m]
T = Maximum depth from waterline [m]
∇ = Light load volume displacement [m^3]
SA = Total triangular sail area [m^2]
S_w = Wetted area of hull and appendages [m^2]
DLR = Displacement Length Ratio [$28300 \cdot \nabla / L_{WL}^3$]
LDR = Slenderness Ratio [$L_{WL} / \nabla^{1/3}$]
SDR = Sail area Displacement Ratio [$SA / \nabla^{2/3}$]
GPH = General Purpose Handicap, ORC

Fig 2.2 Preliminary design parameters

COST

No one is interested in having a boat built more expensively than necessary.

Taking only that prerequisite into account, the obvious answer seems to be to build the boat as small as possible, since building costs relate directly to size (or rather weight). However, in going for light weight we might be forced to use exotic materials and advanced building methods which in turn might increase the cost compared with using heavier materials and a more conventional building technique. At the other end of the scale are the heavy building methods needed for steel and ferrocement, for instance, which certainly provide cheap materials but produce heavy boats that need much power (sail and engine) to drive them, and robust deck equipment for handling them, all of which cost money.

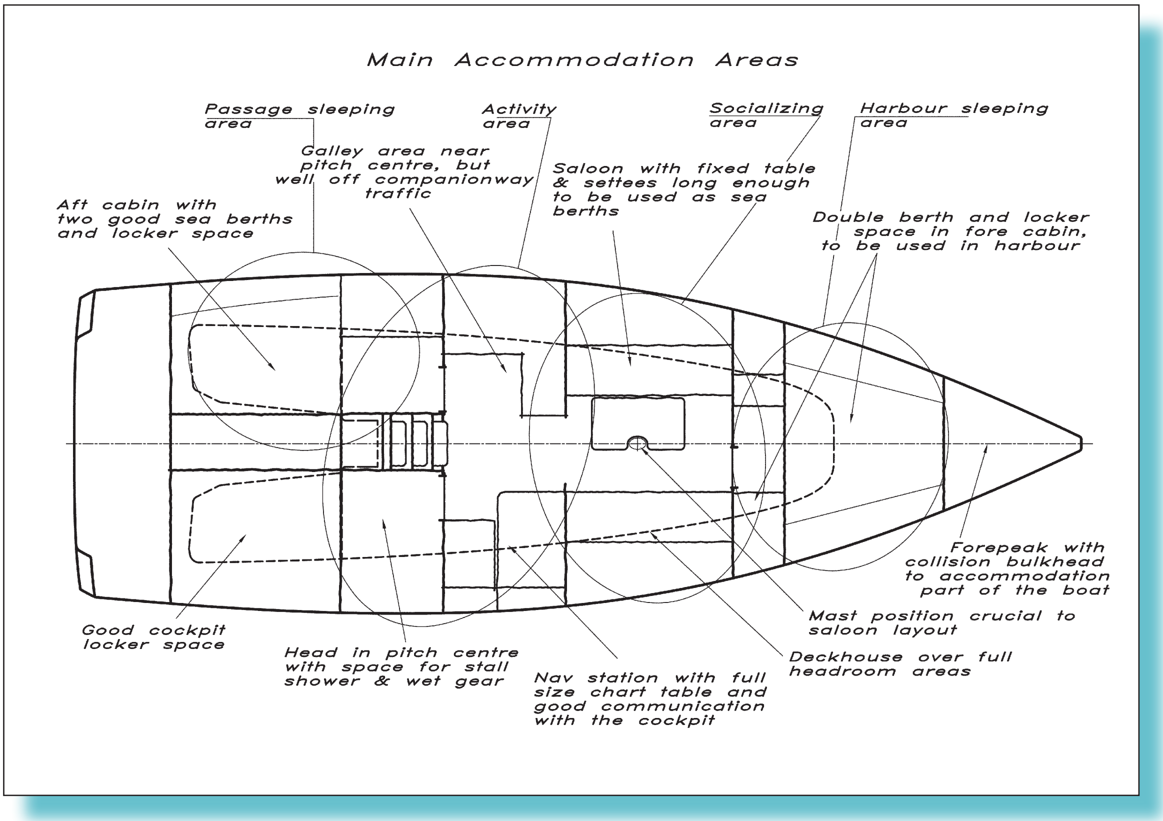
A common pitfall when designing a boat in the smaller size range to keep costs down, is to miniaturize. Everything might look well proportioned on paper, but in practice the design may not work because the human being cannot be scaled down. Moreover, trying to squeeze too much into a small volume would not produce a cost-effective design, not only because everything found in a bigger yacht would be there, but also because it would be so much harder to fit in, due to lack of space.

The hull form is basically derived from hydrodynamic and hydrostatic requirements, while the form of the deck is more open to the whim of the designer, to fashions and trends, and to what 'character' the design is intended to radiate. A deck with lots of angles and sharp turning points is much more difficult to build (FRP construction) than one with smooth areas and large radii in the corners. Here we have a choice that most definitely will affect the construction cost. Designing decks or parts of decks that require multiple moulds to make mould-release possible will also make the costs higher. We have to be quite sure that the benefits of such a design outweigh the increased cost that goes along with it.

To some extent the same reasoning can be applied to the accommodation. Obviously, a flat panel attached to another at a square angle is much cheaper to produce than a curved one attached at an oblique angle. On the other hand, rounded panels and oblique angles can be used to achieve better space utilization which, in the end, will make the boat so much better that the increased building costs can be justified. Another way of increasing usable space is to let areas and compartments overlap one another. It is not always necessary to have the full cabin height over the full length of the boat. For example, a toilet can be under a cockpit seat with the rest of the head area under the superstructure. Instead of thinking of the accommodation as a two-dimensional jigsaw puzzle, it might be fruitful to think of it as a three-dimensional puzzle to utilize the space available in the best way. A word of warning though: complicating things too much might raise the cost out of all proportion, so a better way might be to make the whole boat bigger and simpler to fulfil the requirements.

The amount of standard equipment also plays an important role in the overall cost of the boat, regardless of whether she is light or heavy. By this we mean whether to have an air-conditioner/heater, running hot and cold water, a water maker, a freezer/refrigerator, electric winches, full electronics with radar, a chart plotter and auto pilot, self-furling sails and so on. All these items can almost equal the cost of the rest of the boat.

Fig 2.3 Preliminary layout for the YD–41



Checklist of considerations

To summarize the above considerations the following list can be applied:

1. Define the intended use and limits.
2. Collect information about similar boats.
3. Decide on the main dimensions and ratios.
4. Decide on the preliminary layout and exterior.
5. Make a first approximation of weights and form parameters.
6. Check against 3 and correct if necessary.
7. Produce a preliminary design to work from.

Checklist for the YD–41

Having considered these points we are now ready to lay down a preliminary design. To make that meaningful we must decide on a specific one, and in this book we will use the YD–41. The design brief for this yacht is as follows:

1. A fast ocean-going yacht, with accommodation for four, to be capable of being easily handled by a crew of two. The performance, comfort and safety shall allow for fast ocean crossings with average speeds above 10 knots in favourable conditions.
2. See Fig 2.2 for comparison with a similar yacht.
3. The main dimensions and ratios are also derived from the comparison in Fig 2.2.
4. Fig 2.3 (page 21) is a first sketch of the yacht showing the principal areas of accommodation. Basically, they are designed around the assumption that they will be functional under way with a crew of four. This means four good sea-berths, two in the aft cabin and two in the saloon, a galley, head and navigation area in the pitch centre of the boat. The saloon shall be big enough to accommodate the occasional racing crew, and other social entertaining in harbours, and the forward cabin shall be used as an in-harbour master cabin. The accommodation shall not be pressed into the ends of the boat to enhance performance and judged on a length-only basis, as this will reduce the building costs.

Having established the main dimensions, type of boat and area of use we can proceed with the more precise design work. Comparing with Fig 2.2 we can see that the design brief is met quite well, with the main dimensions and their connected ratios chosen.

3 HULL GEOMETRY

The hull of a yacht is a complex three-dimensional shape, which cannot be defined by any simple mathematical expression. Gross features of the hull can be described by dimensional quantities such as length, beam and draft, or non-dimensional ones like prismatic coefficient or slenderness (length/displacement) ratio. For an accurate definition of the hull the traditional line drawing is still in use, although most yacht designers now take advantage of the rapid developments in CAD introduced in Chapter 1.

In this chapter we start by defining a number of quantities, frequently referred to in yachting literature, describing the general features of the yacht. Thereafter, we will explain the principles of the traditional drawing and the tools required to produce it. We recommend a certain work plan for the accurate production of the drawings and, finally, we show briefly how the hull lines are generated in a modern CAD program.

DEFINITIONS

The list of definitions below includes the basic geometrical quantities used in defining a yacht hull. Many more quantities are used in general ship hydrodynamics, but they are not usually referred to in the yachting field. A complete list may be found in *Dictionary of Ship Hydrodynamics*, International Towing Tank Conference (ITTC, 2017).

◆ Length overall (L_{OA})

The maximum length of the hull from the forwardmost point on the stem to the extreme after end (see Fig 3.1). According to common practice, spars or fittings, like bowsprits, pulpits, etc. are not included and neither is the rudder.

◆ Length of waterline (L_{WL})

The length of the designed waterline (often referred to as the DWL).

◆ Length between perpendiculars (L_{PP})

This length is not much used in yachting but is quite important for ships. The forward perpendicular (FP) is the forward end of the designed waterline, while the aft perpendicular (AP) is the centre of the rudder stock.

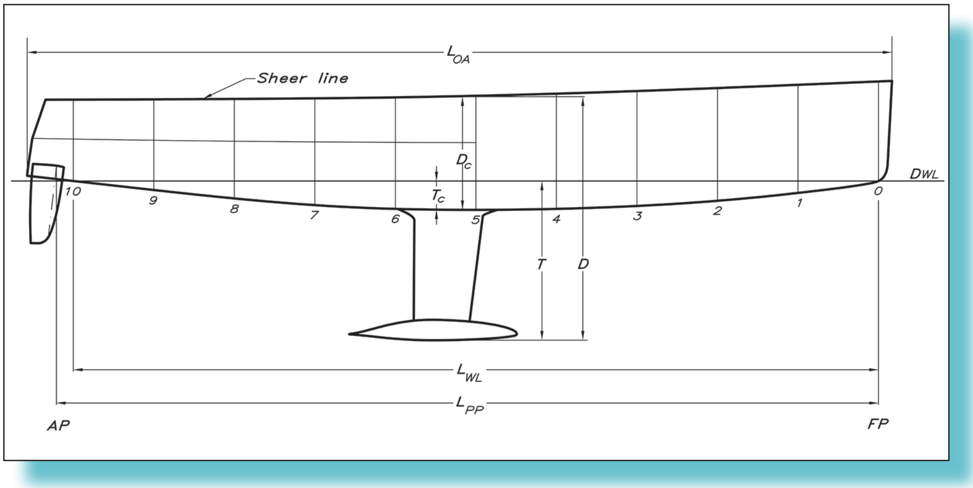


Fig 3.1 Definitions of the main dimensions

Rated length

A very important parameter in traditional rating rules. Usually L is obtained by considering the fullness of the bow and stern sections.

Beam (B or B_{MAX})

The maximum beam of the hull excluding fittings, like rubbing strakes.

Beam of waterline (B_{WL})

The maximum beam at the designed waterline.

Draft (T)

The maximum draft of the yacht when floating on the designed waterline. T_c is the draft of the hull without the keel (the 'canoe' body).

Depth (D)

The vertical distance from the deepest point of the keel to the sheer line (see below). D_c is without the keel.

Displacement

This could either be mass displacement (m), i.e. the mass of the yacht, or volume displacement (V or ∇), the volume of the immersed part of the yacht. m_c, V_c and ∇_c are the corresponding notations without the keel.

Midship section

For ships, this section is located midway between the fore and aft perpendiculars. For yachts it is more common to put it midway between the fore and aft ends of the waterline. The area of the midship section (submerged part) is denoted A_M, with an index 'c' indicating that the keel is not included. C_{Mc} is the midship sectional area coefficient defined for the canoe body as $C_{Mc}=A_{Mc}/(B_{WL}\cdot T_c)$.

◆ Maximum area section

For yachts the maximum area section is usually located behind the midship section. Its area is denoted A_X (A_{Xc}).

◆ Prismatic coefficient (C_P)

This is the ratio of the volume displacement and the maximum section area multiplied by the waterline length, i.e. $C_P = \nabla/(A_X \cdot L_{WL})$. This value is very much influenced by the keel and in most yacht applications only the canoe body is considered: $C_{Pc} = \nabla_c/(A_{Xc} \cdot L_{WL})$. See Fig 3.2. The prismatic coefficient is representative of the fullness of the yacht. The fuller the ends, the larger the C_{Pc}. Its optimum value depends on the speed, as explained in Chapter 5. Note that the index c is often dropped, even if the coefficient refers to the canoe body.

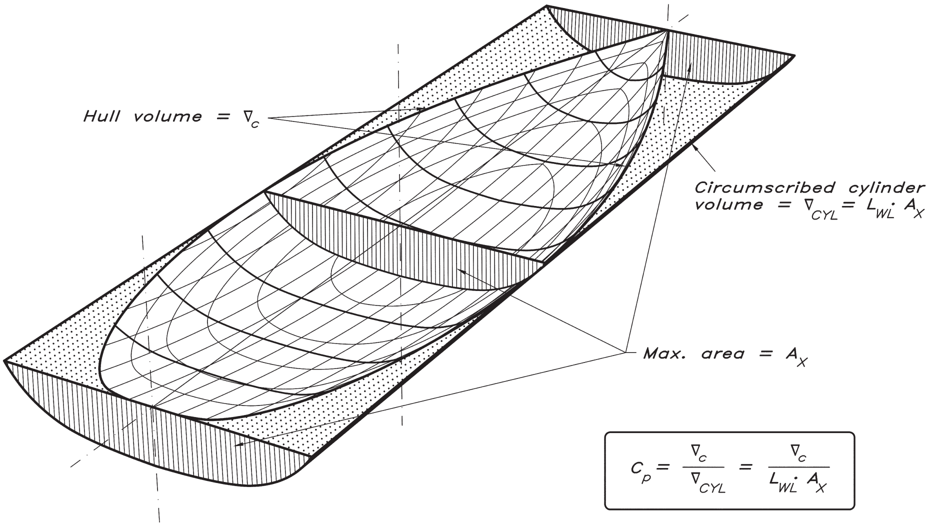


Fig 3.2 The prismatic coefficient

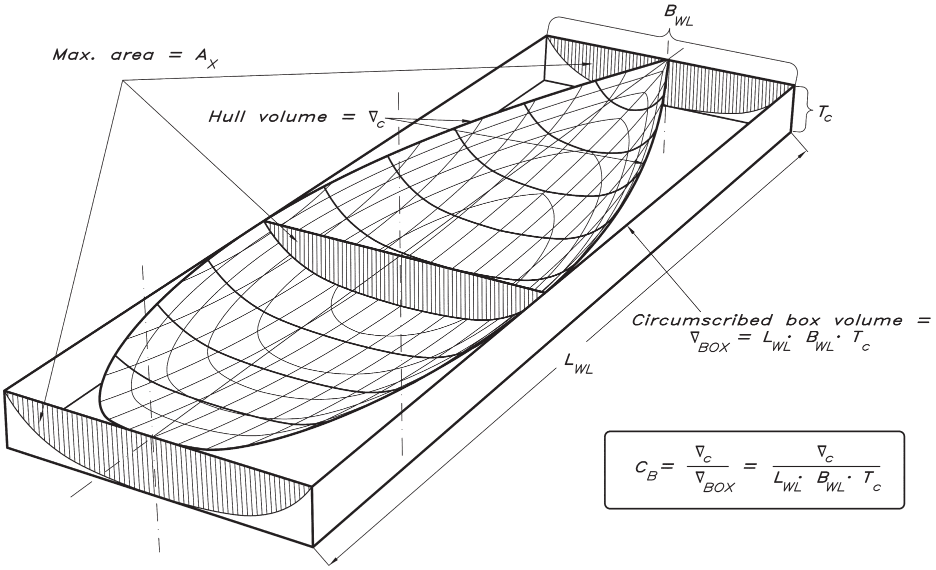


Fig 3.3 The block coefficient

Block coefficient (C_B)

Although quite important in general ship hydrodynamics this coefficient is not so commonly used in yacht design. The volume displacement is now divided by the volume of a circumscribed block (only the canoe body value is of any relevance) $C_{Bc} = \nabla_c /(L_{WL} \cdot B_{WL} \cdot T_c)$. See Fig 3.3.

Centre of buoyancy (B)

The centre of gravity of the displaced volume of water. Its longitudinal and vertical positions are denoted by LCB and VCB, respectively.

Centre of gravity (G)

The centre of gravity of the yacht must be on the same vertical line as the centre of buoyancy. In drawings, G is often marked with a special symbol created by a circle and a cross. This is used also for marking geometric centres of gravity. See, for instance, Fig 9.2.

Sheer line

The intersection between the deck and the topside. Traditionally, the projection of this line on the symmetry plane is concave, the 'sheer' is positive. Zero and negative sheer may be found on some extreme racing yachts and powerboats.

Freeboard

The vertical distance between the sheer line and the waterline.

Tumble home

When the maximum beam is below the sheer line the upper part of the topsides will bend inwards (see Fig 3.4). To some extent this reduces the weight at deck level, but it also reduces the righting moment of the crew on the windward rail. Further, the hull becomes more vulnerable to outer skin damage in harbours.

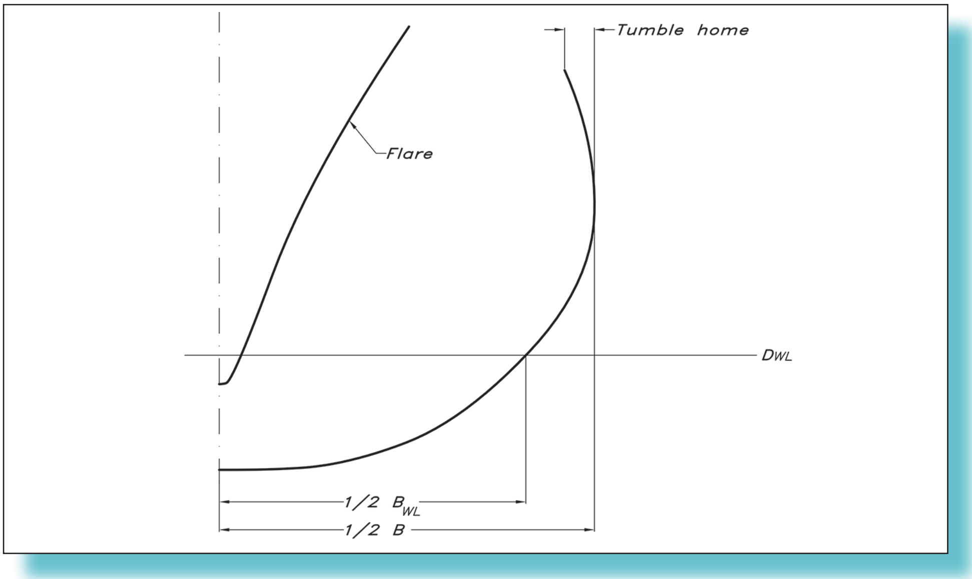


Fig 3.4 Definition of tumble home and flare

◆ Flare

The opposite of tumble home. On the forebody in particular, the sections may bend outwards to reduce excessive pitching of the yacht and to keep it drier when beating to windward.

◆ Scale factor (α)

This is not a geometrical parameter of the hull, but it is very important when designing a yacht. The scale factor is simply the ratio of a length (for instance the L_{WL}) at full scale to the corresponding length at model scale. Note that the ratio of corresponding areas (like the wetted area) is α^2 and of corresponding volumes (like displacement) α^3.

LINE DRAWING

A complete line drawing of the YD–41 is presented in Fig 3.5 (overleaf). The hull is shown in three views: the profile plan (top left), the body plan (top right) and half breadth plan (bottom). Note that the bow is to the right.

In principle, the hull can be defined by its intersection with two different families of planes, and these are usually taken as horizontal ones (waterlines) and vertical ones at right angles to the longitudinal axis of the hull (sections). While the number of waterlines is chosen rather arbitrarily, there are standard rules for the positioning of the sections. In yacht architecture the designed waterline is usually divided into ten equal parts and the corresponding sections are numbered from the forward perpendicular (section 0) backwards. At the ends, other equidistant sections, like # 11 and # −1 may be added, and to define rapid changes in the geometry, half or quarter sections may be introduced as well. In Fig 3.5 half sections are used throughout.

The profile is very important for the appearance of the yacht, showing the shapes of the bow and stern and the sheer line. When drawing the waterlines, displayed in the half breadth plan, it is most helpful if the lines end in a geometrically well-defined way. Therefore a 'ghost' stem and a 'ghost' transom may be added. The ghost stem is the imagined sharp leading edge of the hull, which in practice often has a rounded stem, and the ghost transom is introduced because the real transom is often curved and inclined. If an imagined vertical transom is put near the real one at some convenient station, it will facilitate the fairing of the lines. The drawing of Fig 3.5 has been produced on a CAD system and no ghost stem is shown. However, a ghost transom is included.

In the body plan, the cross-sections of the hull are displayed. Since the hull is usually symmetrical port and starboard, only one half needs to be shown, and this makes it possible to present the forebody to the right and the afterbody to the left. In this way mixing of the lines is avoided and the picture is clearer. Note that in the figure the half stations are drawn with a different line type.

The above cuts through the hull are sufficient for defining the shape, but another two families of cuts are usually added, to aid in the visual perception of the body. Buttocks are introduced in the profile plan, showing vertical, longitudinal cuts through the hull at positions indicated in the half breadth plan. The diagonals in the lower part of the half breadth plan are also quite important. They are obtained by cutting the hull longitudinally

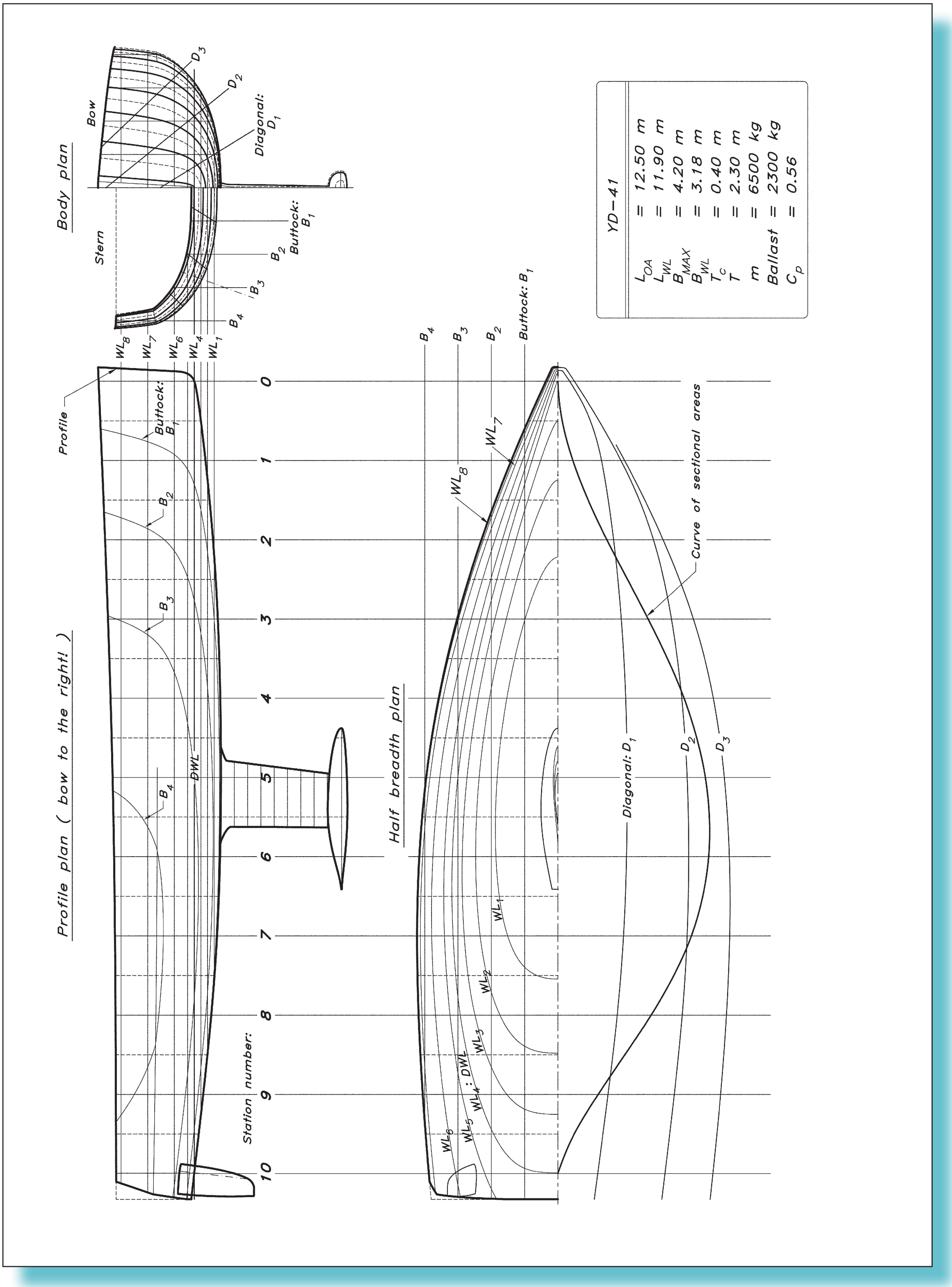


Fig 3.5 The line drawing

in different inclined planes, as indicated in the body plan. The planes should be, as much as possible, at right angles to the surface of the hull, thus representing its longitudinal smoothness. In practice, the flow tends to follow the diagonals, at least approximately, so that they are representative of the hull shape as 'seen' by the water. Special attention should be paid to the after end of the diagonals, where knuckles, not noticed in the other cuts, may be found, particularly on yachts designed under the International Offshore Rule (IOR) in the 1970s and 1980s. Almost certainly, such unevenness increases the resistance and reduces the speed of the yacht.

The other line in the lower part of the half breadth plan is the curve of sectional areas, representing the longitudinal distribution of the submerged volume of the yacht. The value at each section is proportional to the submerged area of that section, while the total area under the curve represents the displacement (volume). A more detailed description of the construction of the curve of sectional areas will be given in Chapter 4.

If the drawing is produced manually, a table of offsets is usually provided by the designer. This is to enable the builder to lay out the lines at full size and produce his templates. Offsets are always provided for the waterlines, but the same information may be given for diagonals and/or buttocks, too. Note that all measurements are to the outside of the shell. For drawings produced by a CAD system the geometry information can be transferred directly to a numerically controlled cutting machine. Usually the international Initial Graphics Exchange Specification (IGES) standard is then used as the file format.

TOOLS

A manual drawing should be made on a special plastic film, available in different thicknesses. The film is robust and will not be damaged by erasing. Furthermore, it is unaffected by the humidity of the air, which may shrink ordinary paper.

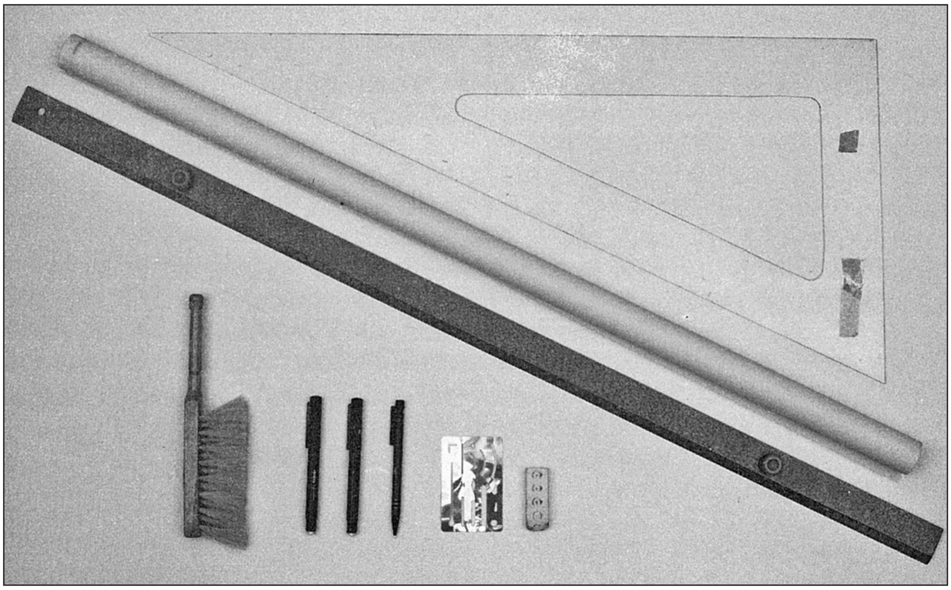


Fig 3.6 Tools (set square, plastic film, straight edge, brush, pens, pencil, erasing shield and eraser)

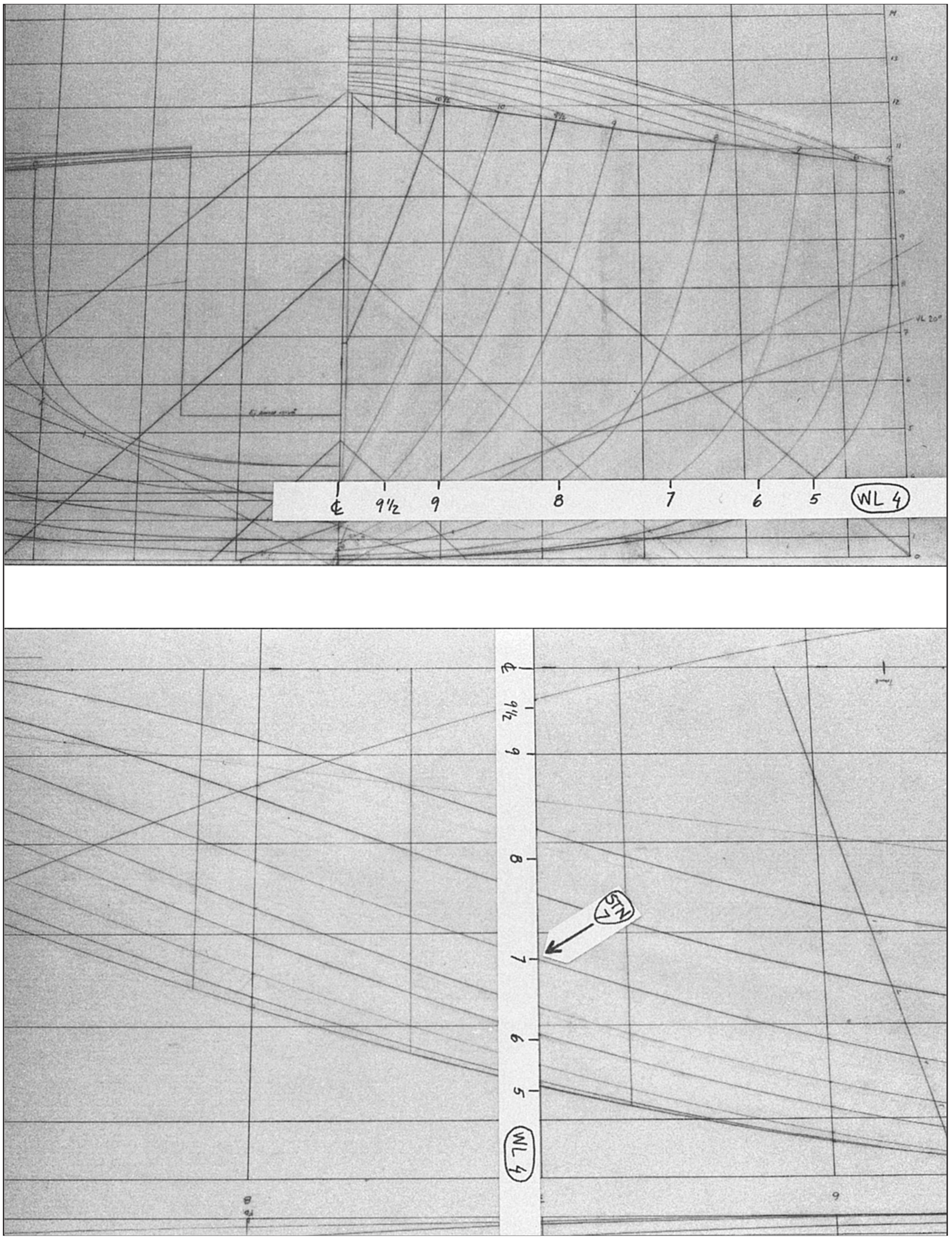


Fig 3.7 Transfer of measures from body plan (TOP) to half breadth plan (BOTTOM) using a paper ribbon

Since the film is transparent the grid for the line drawing is drawn on the back so that it will remain, even after erasing the hull lines on the front many times. Great care must be exercised when drawing the grid, making sure that the alignment and spacing are correct and that all angles are exactly 90°. In Fig 3.5 the grid is shown as thin horizontal and vertical lines, representing waterlines, buttocks and stations.

Black ink should be used when drawing the grid and preferably when finishing the hull lines too. However, when working on the lines a pencil and an eraser are needed. There are, in fact, special pencils and erasers for this type of work on plastic film. An erasing shield and a brush are also most useful (see Fig 3.6).