Chapter 2
Sailing Yacht Geometry and Mass Properties

2.1 Introduction

The mechanics of sailing are almost entirely determined by the geometrical characteristics and mass properties of the sailing vessel. It is therefore useful to summarize how the geometry and mass properties of a sailing yacht are, commonly, described and to take notice of the nomenclature that is used for this purpose.

One problem in this respect is that there are many different types of sailing yacht. It is an almost impossible job to address all of these. As already mentioned in Chap. 1 we will limit ourselves to the most common type of sailing yacht: single-masted mono-hulls with 'fore-and-aft', Bermuda-rigged sails. As a consequence the list of characteristic parameters and notions to be discussed hereafter is not exhaustive in the sense that it does not (fully) cover other types of sailing yacht such as multi-hulls and multi-masted yachts.

When describing the geometry and mass properties of a sailing yacht it is useful to distinguish three categories of quantities. For the hydro-mechanic forces acting on a sailing yacht the geometrical characteristics of the under-water part of the hull and the appendages are the most important. For the aerodynamic forces these are the geometrical characteristics of the sailing rig and the above-the-water part of the hull. The general mechanics and stability properties of a yacht are also determined by the mass properties.

The three categories just mentioned are described in the following sections.

2.2 Hull Geometry

The geometry of the hull of a sailing yacht is usually described by means of traditional lines drawings and/or by computer aided mathematical descriptions (Larsson and Eliasson 1996; Claughton et al. 1999). The latter are sometimes known as Lines Processing Programs (LPP). An example of a lines drawing is reproduced in

J. W. Slooff, *The Aero- and Hydromechanics of Keel Yachts,*
DOI 10.1007/978-3-319-13275-4_2

Fig. 2.2.1. A brief treatise of computer aided mathematical representations can be found in Claughton et al. (1999).

Although every detail of the geometry has, in principle, some influence on the hydro- or aerodynamics, there is a limited set of parameters or quantities that is commonly used to describe the most important characteristics. Here, we will largely follow the description given in Larsson and Eliasson (1996).

The two most important dimensions of a sailing yacht are the length and the displacement. Two different measures of the length of the hull are usually distinguished (see Fig. 2.2.1):

- The *length overall* (L_{OA})
- The *length of the waterline* (L_{WL})

L_{OA} is the distance between the most forward and the most rearward points on the hull. L_{WL} is the distance between the most forward and the most rearward points on the *design waterline* (DWL). The latter is the intersection of the plane, undisturbed water surface with the external surface of the hull under design weight, floating conditions and zero heel.

Measures of the displacement are:

- The volume *displacement* (∇) of the complete underwater part of the yacht. The corresponding weight displacement is denoted as ∇
- The volume displacement of the underwater part of the hull only (∇_h), without appendages[1]
- The *displacement/length ratio*. This is usually defined as

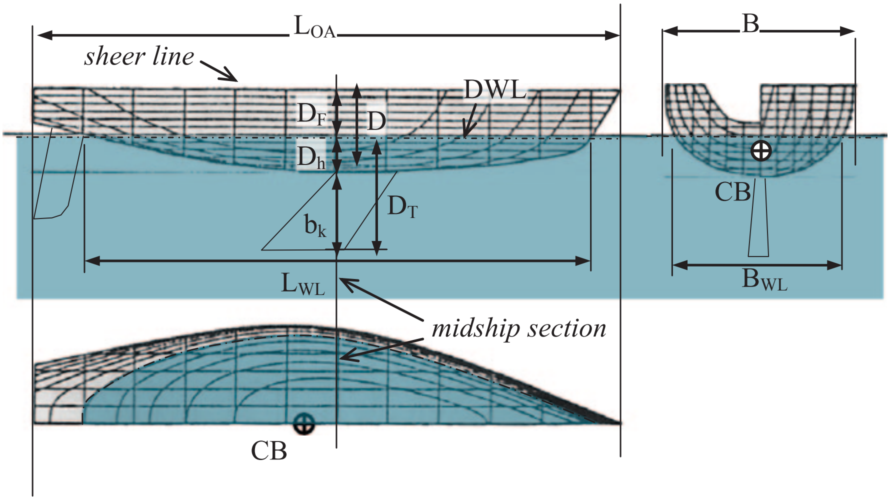

Fig. 2.2.1 *Example of traditional, three-view lines drawing of a sailing yacht. (From http://dsyhs.tudelft.nl, adapted)*

[1] In naval architecture it is common practice to indicate the hull by the subscript c (from canoe body). In this book we will use the subscript h because we have other use for the subscript c.

$$\nabla_h^{1/3}/L_{WL} \tag{2.2.1}$$

It is a dimensionless measure of the slenderness of the hull.

The most important lateral dimensions are

- The (maximum) *beam* (B) of the yacht, the maximum width of the hull
- The (maximum) *beam of the waterline* (B_{WL}), the maximum width of the design waterline (DWL)

The most important vertical dimensions are

- The *depth* D of the hull, the vertical distance between the deepest point of the hull and the sheer line (see Fig. 2.2.1)
- The *draft* D_h of the underwater part of the hull
- The f*reeboard* D_F, the vertical distance between the sheer line and the waterline
- The *span* b_k of the keel and b_r of the rudder
- The total draft[2] $D_T = D_h + b_k$

Other quantities of importance are

- The *centre of buoyancy* CB, characterized by its longitudinal position LCB and its vertical position VCB
- The *midship section* is the cross-section at 50 % of the length of the waterline.

LCB is usually measured from the midship section (positive forward) and expressed in fractions of L_{WL}. For example, LCB = −0.05 means that the centre of buoyancy is positioned 5 % ***aft*** of the midship section.

- The *maximum area section* is the cross-section with the maximum submerged area. For sailing yachts it is usually positioned aft of amidships. The maximum section area is denoted as S_{Xmax} (see Fig. 2.2.2)
- The *section coefficient* C_m is the ratio between the maximum section area and the rectangle circumscribing the maximum area section:

$$C_m = S_{Xmax}/(B_{WL} * D_h) \tag{2.2.2}$$

- The *block coefficient* C_B. This is the ratio between the displacement volume ∇_h of the hull and the volume of the rectangular box circumscribing the underwater part of the hull:

$$C_B = \nabla_h/(L_{WL} * B_{WL} * D_h) \tag{2.2.3}$$

- The *prismatic coefficient* C_P. This is the ratio between the displacement volume and the volume of a cylinder with the length of the waterline circumscribing the submerged part of the maximum area section at zero heel:

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[2] In naval architecture the total draft of a yacht is usually denoted as T. In this book we use D_T because we have other use for the letter T.

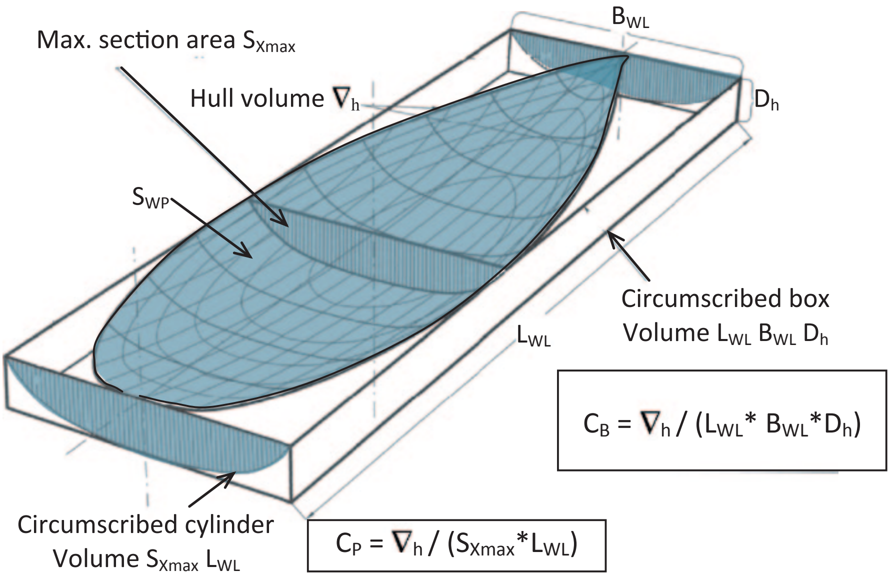

Fig. 2.2.2 Defining hull areas and volumes

$$C_P = \nabla_h/(S_{Xmax} * L_{WL}) = C_B/C_m \tag{2.2.4}$$

The prismatic coefficient is a measure of the fullness of the bow and stern parts of a yacht. The fuller the bow and stern the larger the prismatic coefficient.

The ratio S_{Xmax}/L_{WL}^2 is another measure of the slenderness of the hull. From the expression (2.2.1) and Eq. (2.2.4) it follows that

$$S_{Xmax}/L_{WL}^2 = (\nabla_h/L_{WL}^3)/C_P \tag{2.2.5}$$

- The *waterplane area* (S_{WP}) is the area enclosed by the design waterline
- The *waterplane coefficient* (C_{WP}) is the ratio between the waterplane area and the rectangle circumscribing the waterline:

$$C_{WP} = S_{WP}/(L_{WL} * B_{WL}) \tag{2.2.6}$$

2.3 Appendages

The most important dimensions of the appendages (Fig. 2.3.1) are the span b_k, b_r and area S_k, S_r of the keel and rudder, respectively. The length of the intersection of the keel with the hull is called the root chord (c_R). The length of the keel at the tip is called the tip chord c_T. It follows that the area of a trapezoidal keel is given by

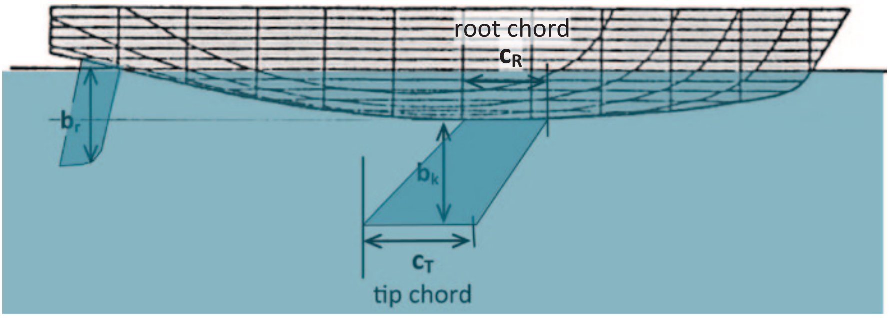

Fig. 2.3.1 *Definition of dimensions of keel and rudder*

$$S_k = b_k (c_R + c_T)/2 \tag{2.3.1}$$

A similar expression holds, of course, for the rudder area.

Other quantities of importance are the aspect ratios A_k and A_r of keel and rudder. These are defined by

$$A_k = b_k{}^2 / S_k \tag{2.3.2}$$

and

$$A_r = b_r{}^2 / S_r \tag{2.3.3}$$

2.4 Rig and Sails

For a Bermuda-rigged yacht the dimensions of the rig and sails are usually described by the quantities indicated in Fig. 2.4.1. These follow the so-called IOR convention (International Measurement System 2011) of the Offshore Racing Council of the International Yacht Racing Union.

- 'I' is the height of the fore triangle
- J is the base of the fore triangle
- LP is the luff perpendicular
- P is the height of the mainsail
- E is the base of the mainsail
- BAD stands for Boom-Above-Deck (sometimes called BAS, Boom-Above-Sheerline), that is the distance between the sheer line and attachment point of the boom on the mast

With these definitions the area $S_{f\Delta}$ of the fore triangle is

$$S_{f\Delta} = 0.5\, I * J \tag{2.4.1}$$

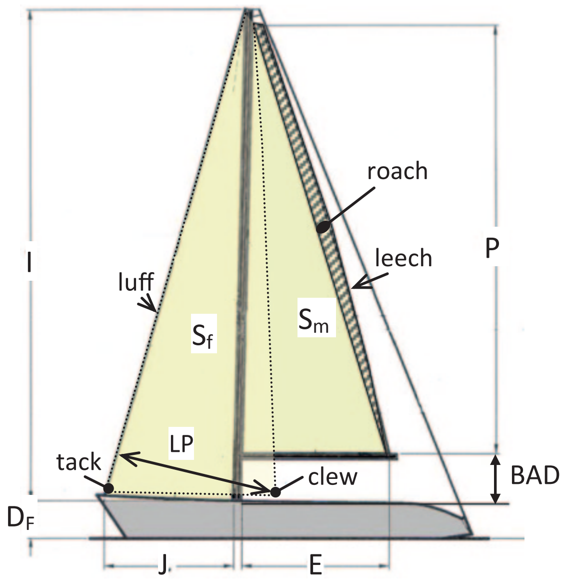

Fig. 2.4.1 *Characteristic dimensions of the rig and sails of a sailing yacht*

and the area $S_{M\Delta}$ of the mainsail triangle is

$$S_{m\Delta} = 0.5\ E * P \tag{2.4.2}$$

The total reference sail area is then given by

$$S_{S\Delta} = S_{m\Delta} + S_{f\Delta} \tag{2.4.3}$$

Note that this implies that any overlap between fore- and mainsail, defined as LP/J (%), is not accounted for in the definition of the reference sail area. This applies also to the 'roach' of the mainsail, that is the area between the triangle and the actual leech of the mainsail.

Note also that the mast height is about equal to or slightly larger than P+BAD and that the total height h_m of the sail top above the water surface is about

$$h_m \cong P + BAD + D_F \tag{2.4.4}$$

While for a masthead rig there holds $I \cong P + BAD$, one has $I < P + BAD$ for a fractional rig.

The dimensions of spinnaker type foresails (or head sails) are measured in a different way (See Fig. 2.4.2):

- SPL is the length of the spinnaker pole
- SF is the length of the spinnaker foot
- SLU is the length of the luff

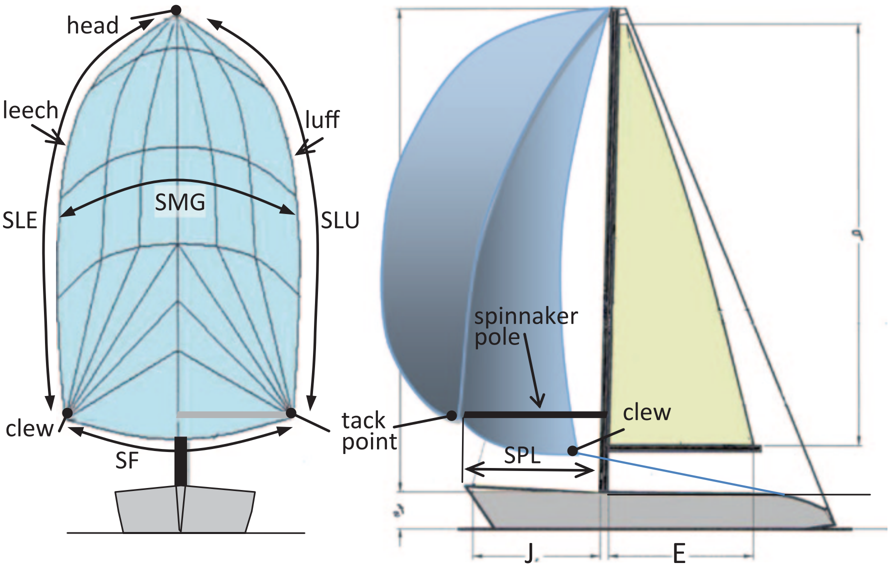

Fig. 2.4.2 Describing the dimensions of spinnaker type foresails

- SLE is the length of the leech
- SMG is the spinnaker mid-girth length (measured between the points at 50 % of the luff and leech)

With these definitions the area S_{SS} of the spinnaker is calculated as (ORC Rating Systems 2011)

$$S_{SS} = \{(SLU + SLE)/2\} * (SF + 4SMG)/6 \tag{2.4.5}$$

It is further noted that for a symmetric spinnaker there holds $SLU = SLE$.

2.5 Mass Properties

In addition to the dimensions, the mass properties of a sailing yacht are also very important for the sailing performance as well as for other characteristics such as stability. The main mass properties are the following:

- The total mass m is given by

$$m = \rho\nabla \tag{2.5.1}$$

where ρ is the density of (sea)water and ∇ is the displacement volume

- The total weight $\boldsymbol{\nabla}$ (a force) is then given by

$$\boldsymbol{\nabla} = \boldsymbol{g}\,\mathrm{m} = \rho \boldsymbol{g} \nabla \tag{2.5.2}$$

  where $\boldsymbol{g}$ is the gravitational acceleration (9.82 m/s^2)

- The *centre of gravity* (CG) is the point where the total mass can be considered to be concentrated. That is, the action of gravity on the actual yacht is the same as if all its mass were concentrated in the centre of gravity.
  For a sailing yacht the centre of gravity is usually positioned somewhat aft of amidships. Under floating conditions the centre of gravity and the center of buoyancy are on the same vertical line.
  Depending on the type of yacht the vertical position of the CG can be above or below the water surface. For shallow draft, modern cruising yachts the CG is usually close to the water surface. For a racing yacht it can be a significant fraction of the total draft below the surface.

Measures of the distribution of mass are the so-called *mass moments of inertia*. They play an important role in the rotational motions of a ship in a seaway and in manoeuvering. Their definition requires the adoption of a coordinate system.The so-called ship-coordinate system of a sailing yacht is indicated in Fig. 2.5.1. The origin is usually taken in the centre of gravity (CG) or amidships in the intersection of the plane of symmetry with the waterplane. The longitudinal or ξ-axis is horizontal and in the plane of symmetry. The lateral or η-axis is perpendicular to the plane of symmetry. The vertical or ζ-axis is in the plane of symmetry. Note that this system is fixed to the yacht. It tilts with the yacht when the yacht heels.

The moment of inertia with respect to a certain, for example the ξ-, axis of a mass element (δm in Fig. 2.5.1) is given by

$$\delta I_{\xi\xi} = \delta m(d_\eta{}^2 + d_\zeta{}^2), \tag{2.5.3}$$

where the position of the mass element is given by the distances d_η, d_ζ as indicated in Fig. 2.5.1. Note that the factor $(d_\eta{}^2 + d_\zeta{}^2)$ is nothing else but the square of the radial distance r_ξ between the mass element δm and the ξ-axis. According to Pythagoras' law:

$$r_\xi^2 = (d_\eta{}^2 + d_\zeta{}^2) \tag{2.5.4}$$

The total mass moment of inertia around the ξ-axis is obtained by adding all mass elements that are part of the ship. This is expressed as

$$I_{\xi\xi} = \Sigma \delta m\,(d_\eta{}^2 + d_\zeta{}^2) \tag{2.5.5}$$

where the symbol Σ stands for the summing operation over all mass elements.

The moments of inertia about the other axes are given by

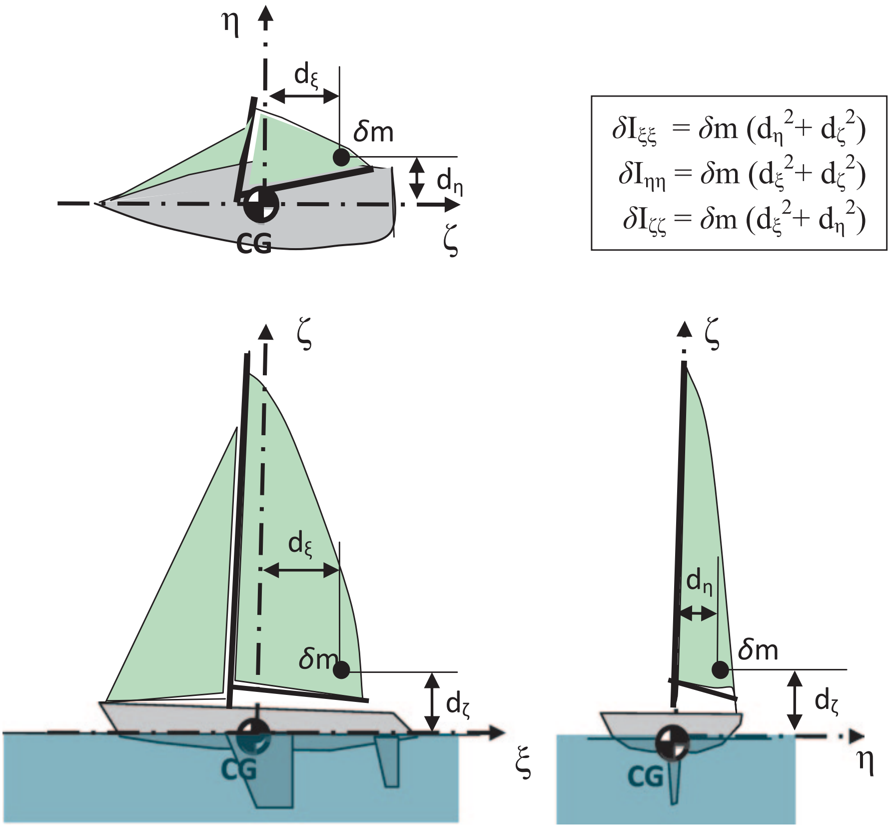

Fig. 2.5.1 *Yacht coordinate system and mass moments of inertia*

$$I_{\eta\eta} = \Sigma\delta m \, (d_\xi{}^2 + d_\zeta{}^2) \tag{2.5.6}$$

$$I_{\zeta\zeta} = \Sigma\delta m \, (d_\xi{}^2 + d_\eta{}^2) \tag{2.5.7}$$

It is further customary to express a mass moment of inertia of a sailing yacht in terms of a so-called *radius of gyration* or *gyradius*. For the ξ-axis this is defined by

$$I_{\xi\xi} = m k_\xi{}^2 = \rho \nabla k_\xi{}^2 \tag{2.5.8}$$

or

$$k_\xi = \sqrt{\{I_{\xi\xi} / (\rho\nabla)\}} \tag{2.5.9}$$

with corresponding definitions for the other axes. The gyradius is the distance from the axis of rotation at which a mass equal to the total mass must be positioned in order to give the same moment of inertia.

The gyradius is sometimes expressed in terms of the length of the waterline of the yacht:

$$C_{k\xi} = k_{\xi}/L_{WL} \quad (2.5.10),$$

etc. A typical value for the gyradius about the η-axis of a sailing yacht is $C_{k\eta} = 0.25$.

It will be clear from the definitions given above that the gyradius is a measure of the eccentricity in the distribution of mass. The gyradius is small when the mass is concentrated around the centre of gravity. Heavy loads in the bow and stern, a heavy mast and a deep keel with a heavy bulb lead to relatively large values of the gyradius.

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