An automated computational method for planing hull form definition in concept design

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Dedicated to the memory of Dale

Abstract

   This paper describes the development of a computer-based method for producing chined planing boat hull forms adequate to be applied in concept design. The method is based on a

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ⱷ Professor Dale Eugene Calkins died suddenly, on June 29th 1999, in Ann Arbor, close to his birthplace of Detroit. The marine community certainly lost a very creative and versatile mind.

   Professor Calkins graduated in Aeronautical Engineering in 1961 at the University of Detroit, took his M.Sc. degree in Aerospace Engineering at the San Diego State University, in 1969, after working in Seattle for many years for Boeing. He took his Doctorate degree in Naval Architecture at the University of California, Berkeley in 1976. He started his academic life at the Federal University of Rio de Janeiro as a visiting professor in 1976, contributing greatly in Advanced Marine Vehicles Design. Professor Calkins' professional engineering carrier included experience in the industrial, government, academic and consulting sectors of research and development in engineering design. His technical specialties included knowledge-based engineering (KBE) and computer-aided design engineering (CAD/CAE) in the aeronautical, marine and automotive fields. He spent the last 20 years of his life teaching and researching at the University of Washington and created several courses in Engineering, one of which was the very successful Formula SAE car program. At the time of his death he was applying for full Professorship and was also working in a research sponsored by Ford, contributing with his experience and creativity in the development of an automobile design system.

   Dale was a happy and joyful man who knew how to maintain solid friendships. He was a true designer, with a passion for vehicles. Perhaps one his greatest abilities was the way he combined the use of knowledge and creativity, that he believed should never be dissociated.

   He is survived by Beth, his wife, their son and daughter Jeremy and Kirstie and his son Scott, from his first marriage.

Richard Schachter

principle where the designer specifies a small set of critical parameters he/she wishes obtain or keep preserved and generates a complete hull form, without the traditional skilled recourse of giving stations point by point. From this set of parameters a detailed and faired drawing with offsets is generated very quickly. The method allows, in its execution mode, the flexibility to modify, adjust and enlarge the input set of parameters. The method was created to allow both (1) automated hull form definitions when integrated to an existing computer system and (2) quick but detailed preliminary calculations of stability, lift and drag, volumes and internal space allocations, sea-keeping estimates, etc., all with very reasonable precision. As application examples some planing boat hull forms are generated. Some are typical and others less usual. The later ones are defined to show the method's limits, in order to validate it. © 2000 Elsevier Science Ltd. All rights reserved.

1. Introduction

The maritime community has produced excellent specialized computer systems for hull form definitions, such as Autodesk Inc.'s Autoship, Blue Peter Marine Systems Pty Ltd's Hullform, New Wave Systems Inc.'s Nautilus, Design Systems and Services, Inc.'s Fast Ship, Maxsurf's Maxsurf and Herbert Engineering Corp.'s Hecsalv, among many others. It was not the intent of the authors to develop software to this level, because this is not our area of work. Nonetheless, there were two essential needs that prompted the authors to develop a hull form geometry tool that allows rapid hull form definition. From two existing systems, one created by each author, a tool was developed. The tool, which is structured to perform automated hull form definition using only hull form feature values, may also be used manually by experienced designers during the conceptual design process.

2. Design process stages

The process of design usually proceeds through three stages including *Concept Design*, *Preliminary Design* and *Detail Design*. Concept design deals with development of a system at its highest level, usually with a very coarse representation limited to the major sub-systems. Preliminary design proceeds to the next level of representation and is also known as embodiment design. Detail design includes analysis and results in a part or component design at a level suitable for manufacture. The development of complex systems requires a sequence of engineering and management decisions, which must satisfy many competing requirements. Design is recognized as the primary contributor to the final product form, cost, reliability and market acceptance. The high-level engineering design and analysis process (conceptual design phase) is particularly important since the life-cycle costs and overall quality of the system are determined during this phase. The major opportunities for cost savings occur in the earliest phases of a product design. Approximately 70% of the

life-cycle costs are frozen by the end of the conceptual design phase. The key to shortening the design cycle is to shorten the conceptual design phase, which will also reduce the amount of engineering in the redesign stage. The design tool should allow the designer to examine more configurations at greater levels of detail. The problem then is to develop an architecture for a design tool that meets all these requirements.

3. Design domain

Marine small craft have been selected as the design domain. Small craft are usually defined as vessels under 60 m in length. Included are recreational craft, fishing trawlers, pleasure yachts and patrol boats. The small craft studied have been segregated into categories, Fig. 1, according to their hull configuration type (Calkins, 1985). These small craft types can then be simplified by their cross-section geometry showing that, in the small craft domain, the hull geometry is primarily characterized by the shape of the *Keel*, *Chine* and *Sheer* curves, Fig. 2. Small craft categories include:

Runabout	Boats designed with either forward bow rider cockpit without sleeping accommodations, or conventional control station location
Sportboats	Generally large runabouts of mono-hull deep-vee configuration
Cruiser	Boats with cabins and sleeping accommodations, cruisers are commonly referred to as recreational powerboats
Motor cruiser	Double-cabin boats with raised trunk cabin and dual helm (>35 ft)
Motor yacht	Lengths from 40 to 100 ft.

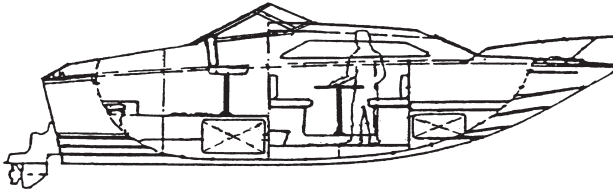## 4. Feature-based parametric geometry

Vehicle system geometry can be modeled by decomposing the surface geometry into *Control Curves* which are defined by design *Features*. Geometry features include information on position, slope and curvature (length, angle, radii of curvature) of each control curve. The extraction of features establishes a database of characteristic curves which represent each individual vehicle design. The value of these "features" establishes a design state for the surface geometry. These control curve features are combined with basis functions, usually polynomials, to create a surface geometry model. The designer must simply specify numerical values of the features to generate an instance of a system geometry. The surface geometry of the small craft hull form makes it an ideal design domain in which to develop the *Feature Extraction* technique. A large and varied database is available in the open literature, which will ensure a large range, or matrix, of features.
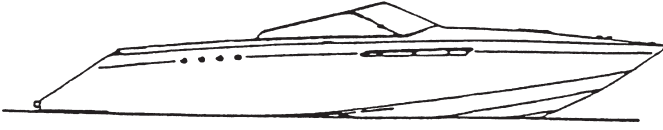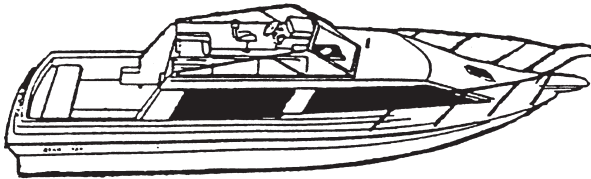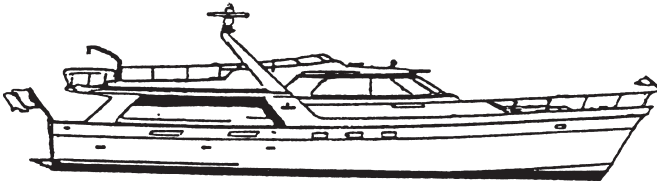
Runabout

Sportboat

Cruiser

Motor Cruiser

Motor Yacht
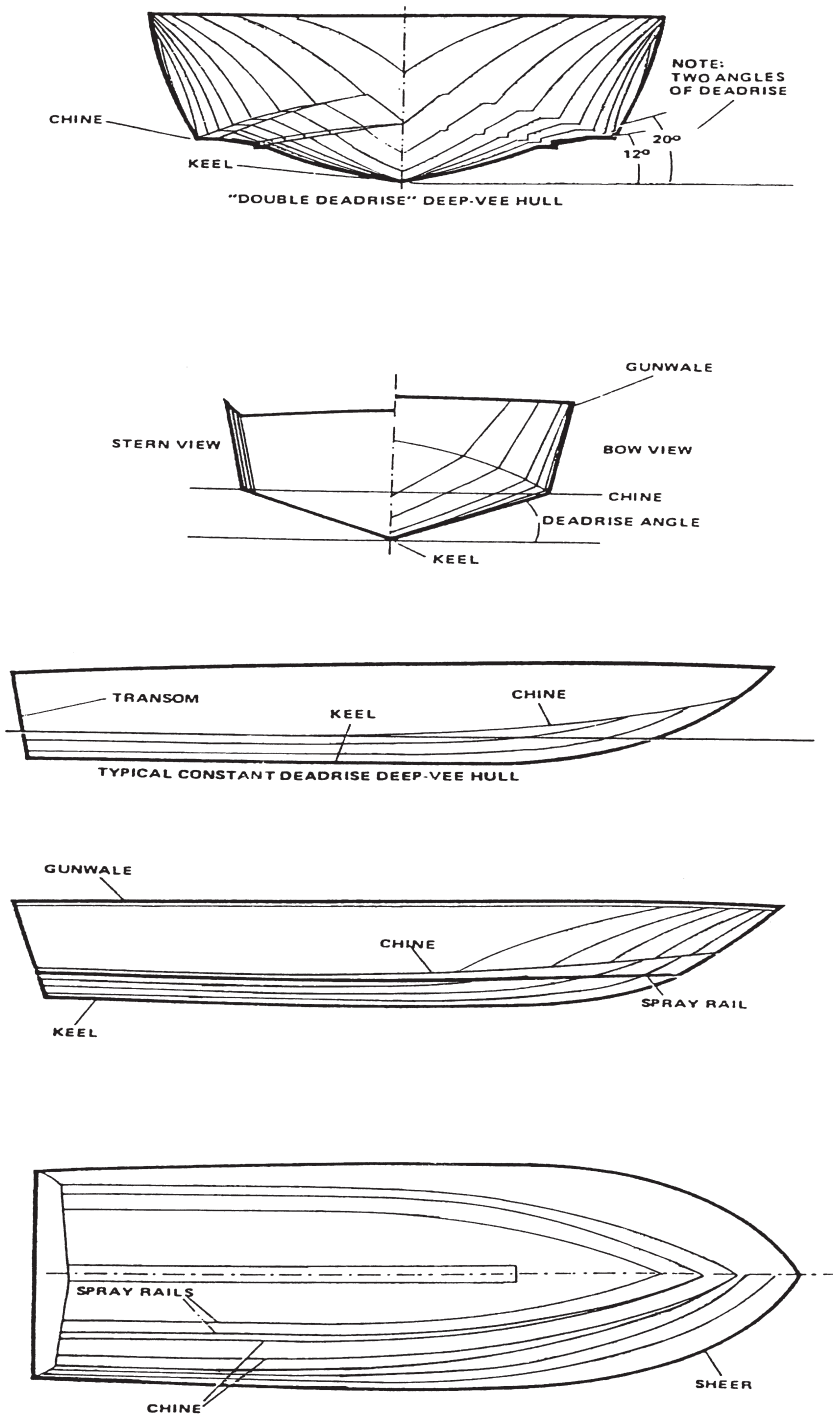
Fig. 1.   Hull configuration types.

Fig. 2.   Planing hull form geometry.

5. Feature-based parametric geometry modeler system components

The work reported is the result of a joint program between the University of Washington and the Federal University of Rio de Janeiro. The intent of this work is to combine two independently developed hull form definition programs into a unified approach that allows the designer to rapidly develop hull form geometry to meet the above objectives in the hull form conceptual design process. The method of this work, dealing with the geometry of chined planing hulls, is the first routine that works in both systems and the first one of the merger that is being developed.

5.1. Hull form tool: Federal University of Rio de Janeiro

Since it is initialized by parameters, the first method, which was developed at the Federal University of Rio de Janeiro, can be used as a single program or integrated into the above-mentioned existing automated design computer systems (Keane et al., 1991; Calkins and McCaffree, 1991), the authors of which have been cooperating to merge into one new Vehicle Design System, combining features of both tools. Both systems emulate the design process, try to bring design features to early stages of design and use databases.

The method presented in this paper was created to deal with chined mono- or multi-hull forms, not applicable in the former method (Keane et al., 1991). The differences are fundamental, because the former method deals with 'volumetric' hulls, rather than 'linear' ones. This leads to completely different sets of initial parameters of interest, as can be seen. In the method for round hull forms, the set of parameters include: main characteristics, form coefficients, angles (half — of waterplane and upper deck entrances, rise of floor, flare, stem and stern rakes), lengths (keel and parallel middle body), position of maximum beam, beams (of waterline at transom, of the deck and the deck aft), etc.

In this paper, specific to planing boats hull forms, the parameters of interest adopted are: main characteristics, deadrise, flare, beams along the length, parallel middle body, stem rake and rocker, and keel variation, number, position and longitudinal variation (warp) of chines, deck line, etc. In order to make feasible the former method, Lewis sections were used (Keane, 1988). This was useful because once bounded by a given beam, flare angle and rise of floor angle, the Lewis method would guarantee a middle section area and, thus, the volume, block coefficient, etc. For planing boats, the parameters the designer has in mind are clearly different: the worries are with deadrise, chine development and parameters to be used by routines designed for planing boats, such as dynamic equilibrium, ride comfort analysis, etc.

This first computer system is run in cycles where the hull form is modified manually or automatically, in the last case freeing the user to merely monitor each cycle. This is done by using a default database to start the process and there is a special language of the system which allows for the 'dynamic' modification of the parameters in the database as each program (of as many as available are attached) is run. This system allows for sequencing, adding and removing routines or design theory modules (e.g., hull form definition, dynamic equilibrium, hydrostatics, stab-

ility, etc.) and provides function mappings of almost any combination of parameters of the database. In this system the algorithms are generic and absurd results of a module tend to be modified in the cyclic process by the overall results analysis.

When the method is used as a single program, it allows the designer to visualize the hull form obtained and, in an interactive process, adjust parameters in order to suit his/her objectives in mind. The output (offsets) can be used as input for other routines or for drafting of the lines plan. When used integrated to the systems, the given parameters are modified in the design cyclic process (manually or automatically) as a function of calculations-and-result analyses of equilibrium, stability, resistance, etc.

The principle that generated this method is similar to one developed for round hull forms (Keane, 1988) and successfully applied to the computer system mentioned above. The intent was to allow the quick creation of new hull forms in a process that was simple, but would produce quite detailed hull forms, in order to allow parametric surveys in the concept design phase. Later this method was incorporated as a routine in the integrated computer system (Keane et al., 1991), the intent of which was to try to deal with the contradiction that exists in concept design, where information is sparse but it is desirable to have more precise calculations or estimates. It is desirable to have a system that would deal with detailed calculations in early stages of design. In this system, default complete hull forms are generated to start the process and the analysis of detailed calculations (by the user or by optimization methods) interacts, deforming or altering the hull form in a convergence process.

5.2. Hull form tool: University of Washington

The second existing system is structured as a module of a synthesis computer model (Calkins 1983, 1988) including synthesis (geometry definition) and engineering design modules (performance evaluation). In this system there are database research values to calibrate the formulation with coefficients and a design database, like the former, of which each database file is a set of parameters that represents one design. This last mentioned similarity of both systems leads to the possibility of merging the systems and taking the best out of each. The hull form geometry definition developed at the University of Washington was based on the use of hull longitudinal control curves that are developed using the concept of features.

5.2.1. Master control curves

To evaluate different features based on individual hull forms, the master control curves are digitized for quantitative comparison. The two-dimensional (2D) orthogonal projections include the keel, chine and sheer control curves. Small craft design orthographic projections are scanned to digitize their master control curves which define the hull form geometry. In the small craft design domain, the master control curves are known as the keel, chine and sheer curves. The feature identification scheme is based on curve fitting these digitized master control curves, Fig. 3. The master control curves may then be used to define the hull form surface using either a B-spline or a developable surface modeler (Calkins et al., 1989).
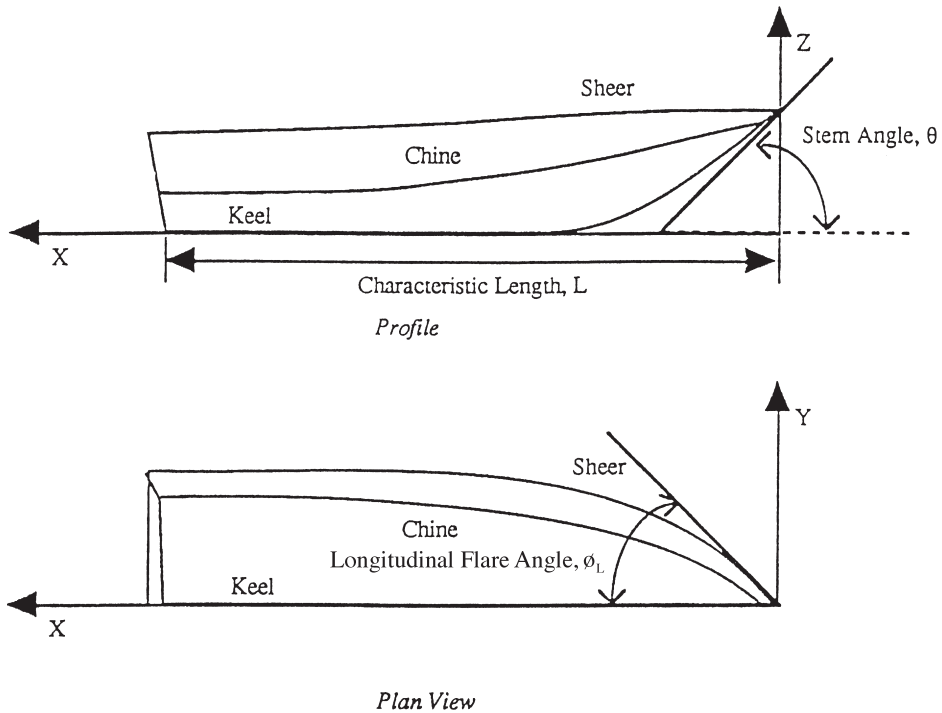
Fig. 3.   Geometry identification.

5.2.2. Master control curve features

Every type of hull has a characteristic look, a recognizable combination of curves and contours that may be defined by features to reduce the information necessary to define the geometry. In this research, features include: (1) point positions, [x^*, y^*, z^*] and (2) slope information, Fig. 3. The keel features are defined for the profile projection only, since the keel is a planar curve. The profile of the keel between positions 3 and 4 of Fig. 4 is defined to be a line. The selection of position 3 should be based on the slope of the keel going to zero. The slope feature is calculated as the tangent to the curve at the feature position. The same X position is used for positions 1, 2 and 3 in the profile and plan views for a given control curve. The features identified on the master control curves for different commercial designs are not necessarily located at the same X position from the bow.

Figs. 4–6 illustrate the selection points necessary for the "feature extraction" technique. A major objective of this research was to extract features from the small craft hull form database of commercial designs. These features will comprise a range of features appropriate to the geometry of commercially successful small craft hulls. The "feature extraction" technique is based on the use of a scanner and appropriate software in the Macintosh computer environment. The geometry hull form database is in the form of orthogonal 2D projections which include the profile and plan views.
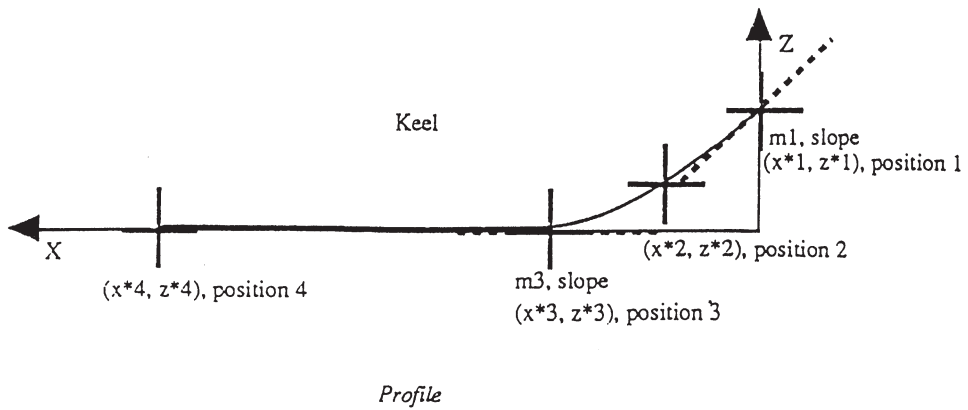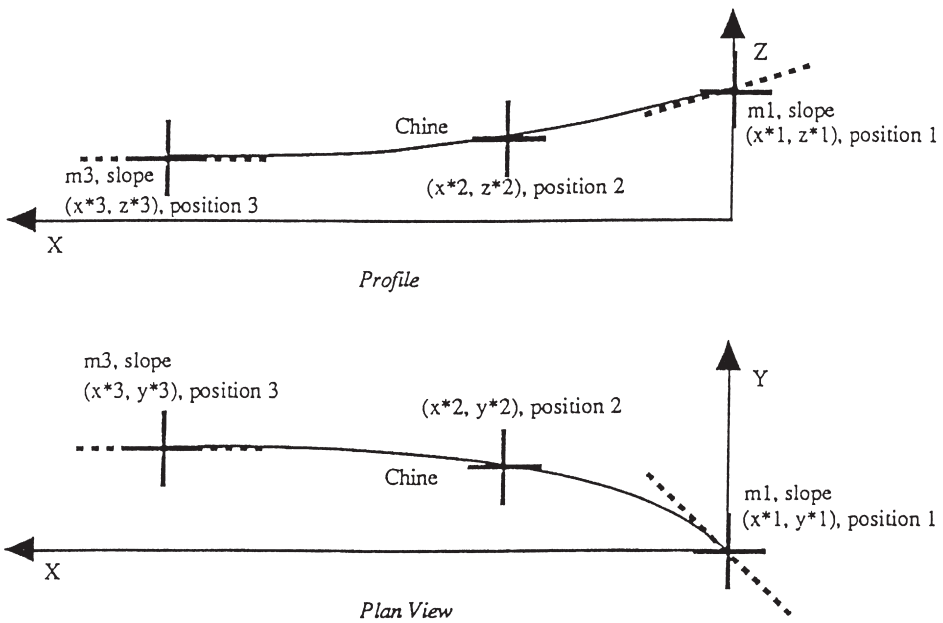
Fig. 4.   Keel feature definition.

Fig. 5.   Chine feature definition.

6. Combined planing hull form method

The proposed method uses a combination of longitudinal and transverse consider-
ations of the hull form. The designer may develop a new design or consult and/or
alter an existing one. In the 'New' mode the designer inputs the main characteristics,
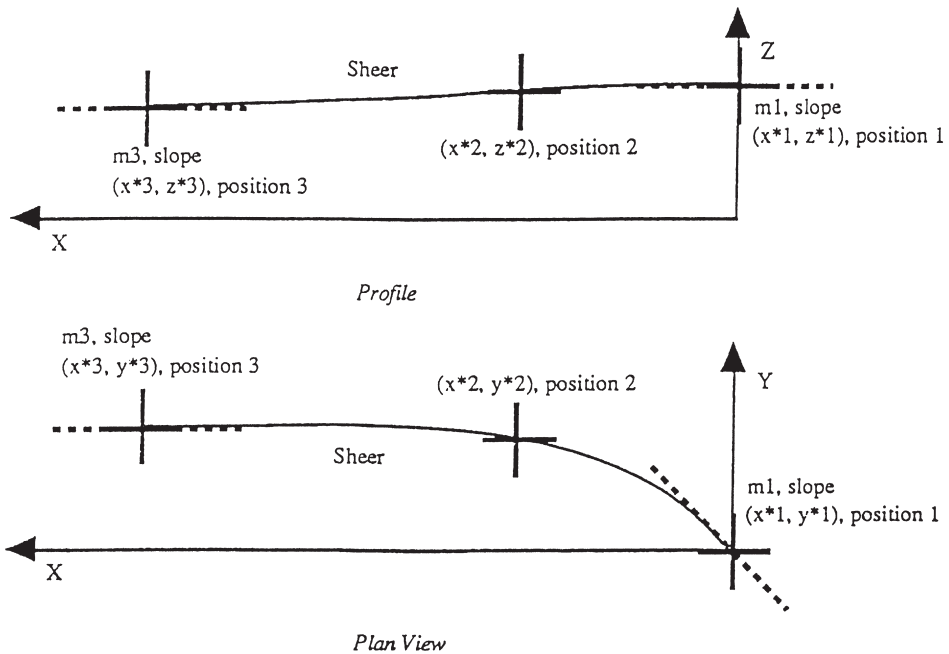decides whether to use flare angles or the coordinates of the last chine, enters the

Fig. 6.   Sheer feature definition.

number of chines and the length of the parallel mid-body. To finalize the initial data entry, the number of stations and their longitudinal positions are requested.

6.1. Main characteristics

The parallel mid-body is defined by the designer in terms of the number of stations, from amidships, represented by Station 10 (the stern is defined as Station 0), spread equally forward and aft, with preference to aft if the number given is even. For a parallel mid-body of four stations, the identical stations will be Stations 8, 9, 10 and 11. The parameters required to run the program are requested when the manual mode is run. In the automatic mode, as structured, these parameters are given in the general design database. In the manual mode there are the general initial data input and the input station by station. The general initial data are:

1. overall length (*LOA*);
2. overall breadth (*B*);
3. depth (*D*);
4. draught (*T*);
5. keel height at Station 20 (*K20*);
6. forward rake angle (R_{fwd});
7. height of rake end above base line (*Hr*);
8. number of chines (*NCh*);

9. flare angle or chine breadth;
10. parallel body length in number of stations (*Pb*);
11. number of stations additional to the default ones (*NSta*); and
12. position of additional stations in station numbers.

6.2. Stations definition

The transverse definition was based on deadrise angle, keel height, chine coordinates at a section, deck coordinates and flare, using straight lines, unlike the longitudinal definition. This was used to ensure the proper angles and discontinuities of a section of a planing boat. The trade-off of this decision is that when a curved section is required, such as concavities and convexities, the user must give more 'chine' points to obtain the desired effect. This was found to be a reasonable procedure, since some renowned professional software also adopts it.

The method requires a minimum of three stations, one at the stern, one at amidships and one at the bow. These are given as default ones, respectively at Stations 0, 10 and 20. Station 20 is where the fore perpendicular is defined. The user may specify how many and which stations besides these three are to be defined for the design. The waterline length (*LWL*) is defined as the interception of the stem — the fore rake line — with the keel height of Station 20. The hull form is divided into 21 stations, spaced by *LWL*/20. The station location is to be given as station numbers, with decimals allowed (e.g., station 17.26). The hull form drawing provides that station definition and gives the longitudinal position of it in meters, for design-interactive action. A station should be given at lengths where deflections of the deck, the profile (form variation) are required, or where there is a need to control keel or chine longitudinal developments or deadrise variations that are not continuous, or to mark a deadrise angle at a particular position.

The program provides a device that allows the definition of stems forward and higher of the interception of the waterline with the wetted part of the bow. This is the case when a catamaran, a trimaran or a mono-hull with a blunt front edge is defined. In the traditional hull form definition software, where these are defined station by station, point by point, this is trivial and straightforward. In the case of the automatic parametric and simplified definition of this work, it is a cumbersome problem and maybe the reason why general automatic hull form definitions have never succeeded before. A parameter keel height at Station 20 (*K20*) is provided for definition. If the hull form ends in a simple sharp edge, it should be given as the same value as the draught (*T*). If a blunt flat bow is to be defined, the user should define the extra extreme station, by typing 21. This will allow the definition of this extreme station, being no longer an edge point. Furthermore, if the designer wishes to define a more elaborated bow (out of the water) as in the case of catamarans and trimarans or bows designed for sea-keeping, a value greater than *T* should be given for *K20*.

As many stations as necessary can be defined at fraction positions between stations 19 and 20. This will make the program draw the waterline length (*LWL*) position at a different station, at the interception of the waterline with the immersed part of the

hull. The subsequent input data, only for the default and special stations selected, and the (*i*) chines to be given are:

1. half beam (*Yd*);
2. keel height (*Zk*);
3. deck height (*Zd*);
4. deadrise angle (*β*); and
5. coordinates of each chine (*Yci*, *Zci*), with an option of flare angle (*ϕ*).

The number of chines the program deals with are unlimited, but the use of too many may cause the input process to be slow, since instant graphical visualization of the input is still not available. The chines are treated, in the program, as inflection points between the base line and the deck line at the side. Depending on the type of hull form desired, it may be found that the use of five in most cases or about 12 in special ones are reasonable settings, but it is suggested that the user makes a previous sketch of the stations in scale or on squared paper. This also means that if the designer wishes to anticipate a preliminary positioning of, say, spray rails in the concept design, it can be done.

7. Longitudinal control curve development

From the basic stations given, the program proceeds with the definition of the intermediate ones using the analytical methods shown ahead. The remaining stations are interpolated and the longitudinal development of the keel, chines and sheer are defined as follows.

7.1. Polynomial representation of master control curves

The mathematical representation of the control curves involves finding a suitable mathematical expression for depicting the contours. Polynomial expressions were found to be satisfactory. B-spline curves were also considered, but were rejected because of their non-intuitive nature. Since the slopes of the boundary conditions (endpoints) are well defined for commercial hulls as described by their stem angle, the control curve definition uses polynomial curves. It is necessary to define the control curves with a cubic polynomial to ensure accurate geometry representation for all designs. The keel, chine and sheer control curves can be represented with a cubic polynomial as:

$$z^* = c_1(x^*)^3 + c_2(x^*)^2 + c_3(x^*) + c_4, \tag{1}$$

where x^* and z^* are the non-dimensional coordinates (*x/LOA*, *z/LOA*).

Quartic polynomials were initially considered to represent the control curves. This was found to be reasonable because the position and slope are features that can define a control curve. Choosing fourth-order polynomial equations requires that five coefficients be determined from curve data regarding the coordinates of the two

endpoints and their respective slopes. The coordinates were from the three stations given and the slopes, at bow and stern.

Nonetheless, it was found from tests that if the endpoint angles were prescribed with exact values, undesired inflections would occur in the point adjustments and, once this was sorted out, either these angle values or coordinates would have been modified. It was also noted that, although angles such as half-water-plane entrance and forward rake were intuitive for a designer to make quick estimates, the same was not true for (multiple) chine inclinations at the bow or upper deck angles. Therefore, for the sake of the designer's practical intuition and automation ease, the endpoints represented by angles were made to be automatically defined by the program, from the given parameters. For such, slope definition relations were defined by trial and error (and coded) to generate the endpoint angles within the desired ranges, from the stations' coordinates in the interactive hull design process. This worked well for the stern, where the control curves are 'better behaved', but not at the stem. This led to abandoning the stem slope, which would be defined by the forward coordinates, and to use cubic polynomials. The relations mentioned above for the stern were defined as "stern slopes".

The individual control curves are, therefore, represented as cubic polynomials where the position and stern slope are features used to define the control curve. Choosing third-order polynomial equations requires that four coefficients be determined from curve data regarding the coordinates of the stern endpoints and its respective slope.

The "stern slopes" used in the control curves are defined as the relation between the coordinates of the stern extremity and the next station given. This relation is given as $-[(z_{n-1}-z_n)/2]/(x_{n-1}-x_n)$, i.e., an inclination formed by the connection of the stern height to half the height of the next station. Since rake angles must be represented as given, these are drawn as straight lines, from the bow tip to the height of rake end, and the keel's control curves are drawn from the rake end to the stern. For the chines (which may be multiple and which in multi-hulls may be conveniently defined to be keels) the program uses the "stern slope", as defined above. The forward slope is defined at the last station given, and prolonged to its interception with the rake. For the sheer it is the same as the chines, closing it up by joining beams at deck coordinates until the tip is reached.

Using the features, the coefficients of the third-order polynomial for the keel, chines and sheer are solved for. The feature positions identified by the stations and in Figs. 4–6 are used to define the control curves, and can be written as a system of non-linear equations:

$$(z^*)_1 = c_1(x^*)_1^3 + c_2(x^*)_1^2 + c_3(x^*)_1 + c_4,$$

$$(z^*)_2 = c_1(x^*)_2^3 + c_2(x^*)_2^2 + c_3(x^*)_2 + c_4,$$

$$(z^*)_3 = c_1(x^*)_3^3 + c_2(x^*)_3^2 + c_3(x^*)_3 + c_4,$$

$$(z^*)_3' = 3c_1(x^*)_3^3 + 2c_2(x^*)_3^2 + c_3, \tag{2}$$

where:

$(z^*)_i$	height at position i
$(z^*)_i'$	slope at position i
$(x^*)_i$	length at position i
$i(1, n)$	number of stations, from forward to stern

Matrix notation can be used to simplify these computations. These non-linear equations in terms of coefficients can be expressed in matrix form as $AX=B$. The solution of $AX=B$ is $X=A^{-1}B$, where A^{-1} is the inverse matrix of A. The coefficients of the cubic polynomial are the elements of the solution vector X:

$$X=[c_1, c_2, c_3, c_4]. \tag{3}$$

Note that the nth station is always the Stern Station 0 and its derivative (slope) is always for the "stern slope", as defined above. The number n of stations varies according to the user's request. If the user prescribes the minimum default number of stations (three), position 1 will be Station 20 (stem), position 2 will be Station 10 (mid-body) and position 3 will be Station 0 (stern). When more than three stations are requested for the hull form definition, the method adjusts the cubic curves using sets of 3 consecutive points, moving ahead. The nth slope ("stern slope") and three points; then two of the last points will be re-utilized by the next set of three points, which selects the next point and so on, until the height of the rake end or the last station is used. The overlapping of the common points will produce different curves connecting the two same points. These curves are averaged to a mean curve.

Practical example tests led to a few exceptions in the programming, one of them being that if two points on different stations are to be connected, if they are identical, the interpolation will be a straight line, not cubic. It was noted that users incorporated this simple 'rule' into their practice very easily, prescribing decimal differences to, say, beams when a deck curvature was to be shown between given points to find out where a maximum beam should be given.

7.2. Feature extraction procedure

The feature extraction technique is based on the use of a scanner and appropriate software. The database of hull form geometry is in the form of orthogonal 2D projections including the profile, plan and body views. These views or drawings are scanned to record the master control curves, which define the geometry envelope. The 2D orthogonal projections must be edited (cleaned up) in order to extract the curve of interest: keel, chine or sheer line. Each drawing, view, is oriented in a Cartesian coordinate system with the keel line in the x direction with the bow as the origin.

In evaluating features each drawing is non-dimensionalized using a characteristic length, L, which is defined as the distance in the x direction from the bow to the intersection of the transom and keel, Fig. 3. By non-dimensionalizing each drawing,

a direct comparison can be made between the curves of interest for different hull designs. The "feature extraction" procedure can be divided into two phases. Phase I provides the information necessary to define the master control curves by digitization of the 2D orthogonal drawings. Phase II is used to compute features which mathematically represent the master control curves. Each phase is organized in steps.

7.2.1. Phase I — hull digitization

Phase I defines the hull geometry by the digitization of the orthogonal drawings. In order to obtain an accurate numerical representation of the commercial small craft designs it is necessary to compare the "feature extraction" results to the original digitized projections. The following steps must be performed to digitize the master control curves for all of the hull designs in the hull form database:

1. scanning procedure;
2. endpoint matching;
3. interpolation;
4. non-dimensionalize data; and
5. graphic comparison.

7.2.2. Phase II — feature computations

Phase II is the procedure to generate features that can be used to define a new set of control curves which match the original master control curves digitized from the hull form database. The new control curves require a limited number of point positions and slope information, accomplishing the same task as digitizing a large number of points. The limited number of point positions and slopes are the desired features. The following steps must be performed to identify the features of each commercial small craft design:

1. calculate coefficients;
2. generate control curves; and
3. graphic comparison.

7.3. Geometry feature database

The hull geometry is important to every economically successful design. Figs. 7–9 show the general trends of the master control curve for the keel, chine and sheer in both profile and plan views. These figures illustrate the ranges of the design features. The stem angles, θ, vary between:

$30° \leq \theta \leq 69°$ cruiser
$14° \leq \theta \leq 29°$ sportboat

The range illustrates that there is a distinct difference between the geometry of the cruiser and the sportboat in the keel control curve. For large stem angles, the keel has a smaller radius of curvature at the forefoot. The deadrise angles, β, vary between:
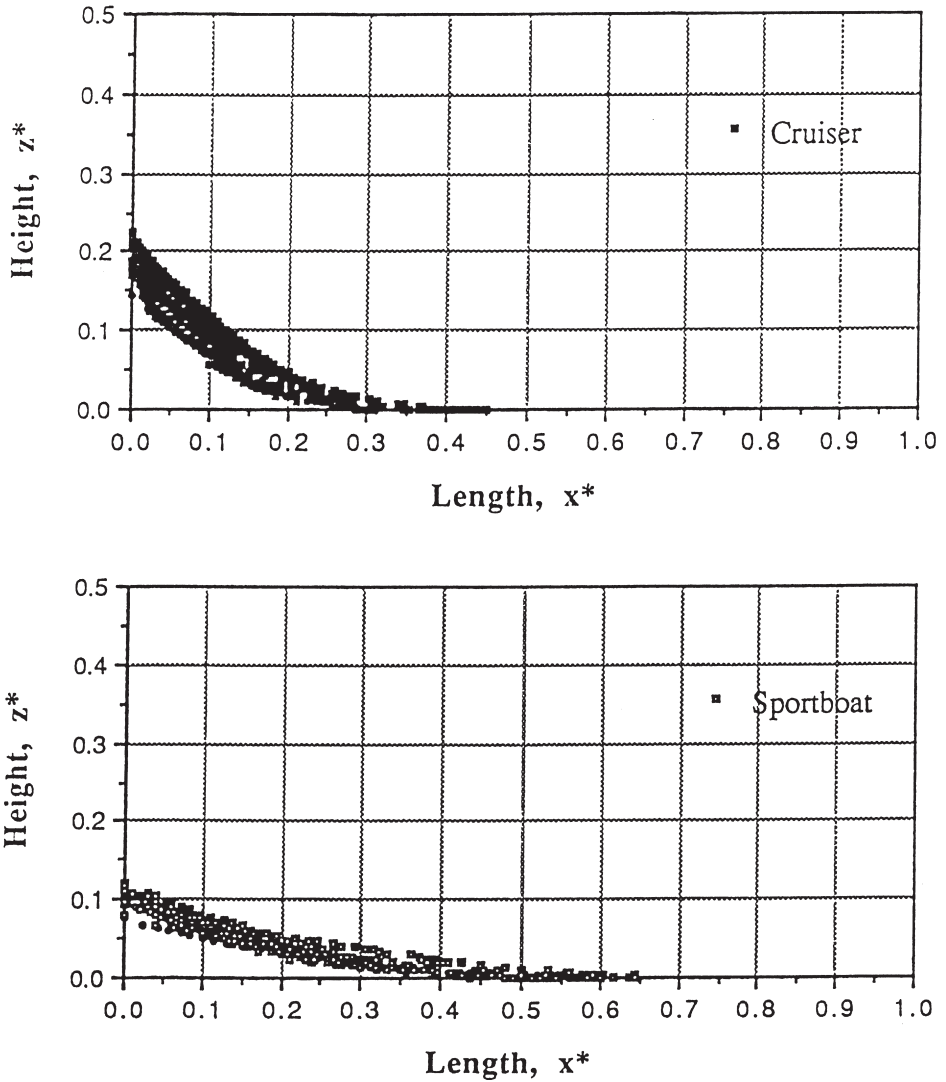
Fig. 7.   Keel features.

20°≤β≤30°   cruiser
12°≤β≤25°   sportboat

7.4. Feature extraction results

Table 1 illustrates the ranges of the keel features for the hull form database. The keel comparison in Fig. 7 illustrates the difference in the hull types between the
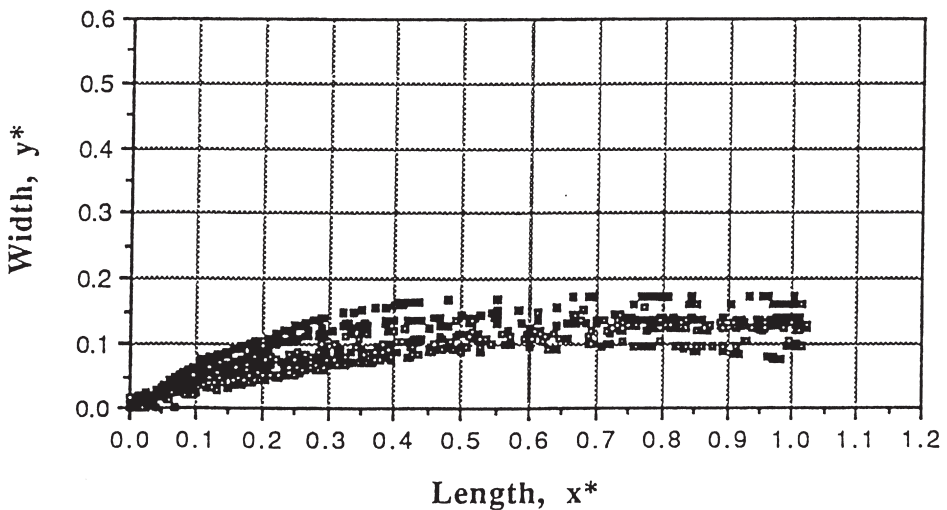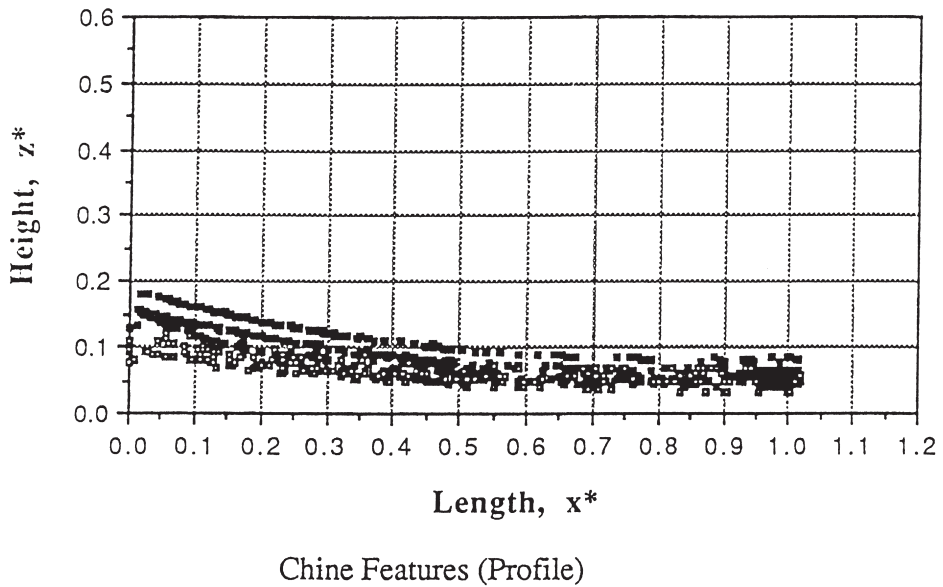
Chine Features (Profile)

Fig. 8.   Chine features.

sportboat and cruiser. The sportboat is flat and has much less curvature than the cruiser at the forefoot, as shown in Fig. 7.

The chine of both sportboats and cruisers is the same characteristic shape in the profile and plan view. The general curvature of these control curves is parabolic as shown in Fig. 8. Table 2 lists the ranges of the chine features.

The sheer is more a design factor in evaluating deck wetness. The bow sheer is
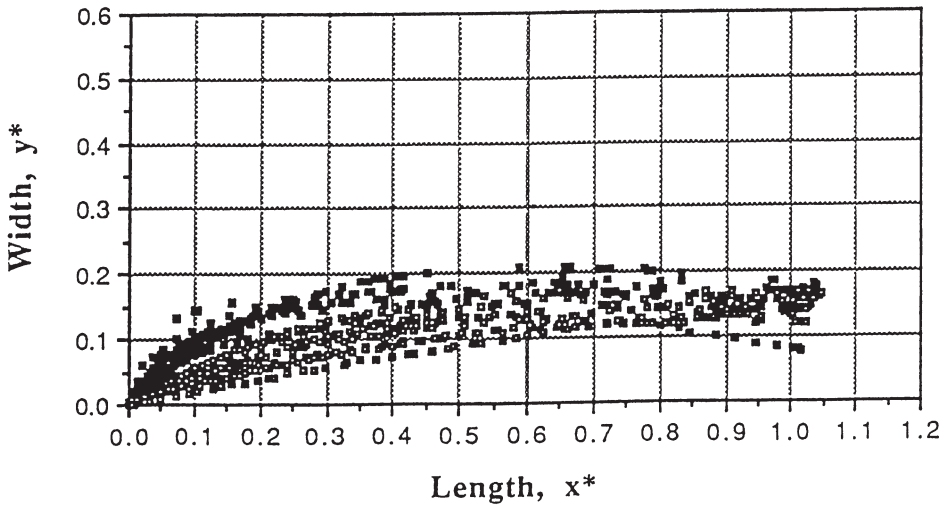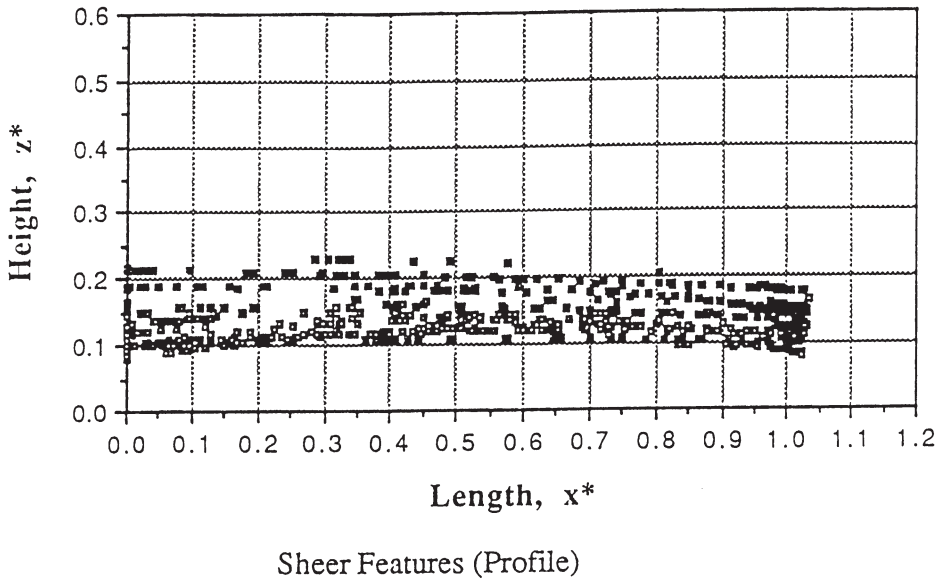
Fig. 9.   Sheer features.

lower in sportboats for aerodynamic reasons. The overall shape of the sheer for sportboats and cruisers is the same as illustrated in Fig. 9. Table 3 lists the design ranges of the sheer features. Tables 1–3 represent design ranges for small craft hull features, which can be used to simplify hull design.

The "feature extraction" technique still involves digitizing the master control curves to guarantee that the cubic polynomial accurately defines the geometry. The

Table 1
Keel features

	Sportboat		Cruiser	
	Minimum	Maximum	Minimum	Maximum
Stem angle, θ (°)	14.94	28.93	37.08	68.90
Length, x^* (position 1)	0	0	0	0
Length, x^* (position 2)	0.25	0.32	0.15	0.22
Length, x^* (position 3)	0.51	0.64	0.31	0.45
Length, x^* (position 4)	1	1	1	1
Height, z^* (position 1)	0.078	0.12	0.14	0.22
Height, z^* (position 2)	0.013	0.036	0.022	0.052
Height, z^* (position 3)	0	0	0	0
Height, z^* (position 4)	0	0	0	0

Table 2
Chine features

	Sportboat		Cruiser	
	Minimum	Maximum	Minimum	Maximum
Chine (plan view)				
Longitudinal Flare angle, ϕ_L (°)	9.03	21.80	26.57	50.19
Chine (profile)				
Stem angle, θ (°)	5.70	11.31	10.15	18.57
Length, x^* (position 1)	0	0.058	0.0138	0.0385
Length, x^* (position 2)	0.2174	0.4946	0.3015	0.4200
Length, x^* (position 3)	0.9430	1.0160	0.9783	1.0140
Width, y^* (position 1)	0	0	0	0
Width, y^* (position 2)	0.0580	0.1289	0.1048	0.1420
Width, y^* (position 3)	0.0890	0.1299	0.1240	0.1725
Height, z^* (position 1)	0.0816	0.1292	0.1079	0.1830
Height, z^* (position 2)	0.0541	0.0906	0.0800	0.1200
Height, z^* (position 3)	0.0294	0.0670	0.0457	0.0800

simplification of the master control curve to a few selected features defines each hull design using a minimum amount of initial information. The use of feature control curves for small craft hull design allows for real-time three-dimensional visualization. The ranges of features provide commercially realistic parameters for new hull designs. The feature-based control curve technique was developed to generate the coefficients of the cubic polynomials, which represent the synthesized control curves of the hull design. The input to this program is the hull design features. The hull feature tool generates a list of control curve points in the same manner as digitizing the 2D orthogonal drawings by hand.

Table 3
Sheer features

	Sportboat		Cruiser	
	Minimum	Maximum	Minimum	Maximum
Sheer (plan view)				
Longitudinal Flare angle, ϕ_L (°)	14.57	28.81	38.31	54.85
Sheer (profile)				
Stem angle, θ (°)	−5.09	5.94	−3.15	1.63
Length, x^* (position 1)	0	0	0	0
Length, x^* (position 2)	0.2174	0.5200	0.2965	0.3510
Length, x^* (position 3)	0.8810	1.0350	0.9897	1.0380
Width, y^* (position 1)	0	0	0	0
Width, y^* (position 2)	0.0927	0.1584	0.1433	0.1935
Width, y^* (position 3)	0.1230	0.1698	0.1290	0.2103
Height, z^* (position 1)	0.0816	0.1292	0.1440	0.2180
Height, z^* (position 2)	0.1099	0.1920	0.1518	0.2290
Height, z^* (position 3)	0.0820	0.1634	0.1413	0.1780
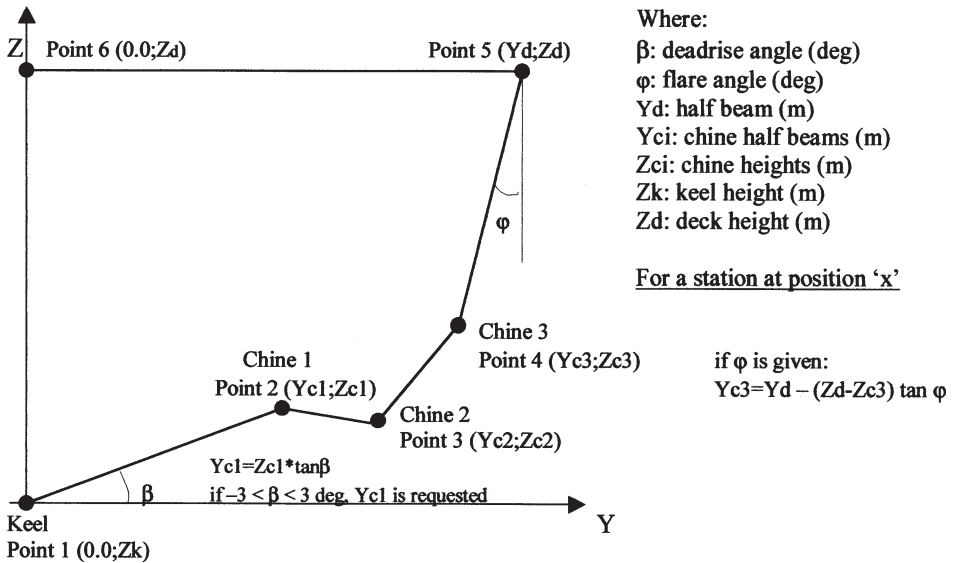
Fig. 10.   Station coordinate system — three-chine example.

8. Hull form definition process

The keel points of the extreme bow stations are obtained over the rake angle line, an inclined line starting from Station 21 and ending at a certain point above the base

line (height of the rake line end). Station 20 is defined within this range and is positioned longitudinally according to its given keel height. The longitudinal division of stations is made and the intermediate stations that fall into this range have their keel heights defined by this line. For the keels of the other intermediate stations, interpolations are made from the height of the rake line end to the keel height of the next most forward given station, then from this to the next given one, and so on, moving astern.

The chines definition uses the deck definition and the keels' definition at each station, given or interpolated. The chines of each station are defined using the given coordinates (Yci, Zci), half beam and height as shown in Fig. 10, which is an example case for three chines (six points and three pairs of coordinates). For the first chine (Point 2) the deadrise angle is used to compute one of the ordinates, and for the last chine (Point 5) the user may either prescribe the coordinates or give instead the flare angle and the chine's half beam. In the case of a single-chined form, the user may choose to prescribe solely the deadrise and flare angles. The first point is the keel height with half beam nil. The second point — Chine 1 — is determined by the deadrise angle and the chine height. If the deadrise angle is small ($-3.0° < \beta < 3.0°$), the height of the chine loses practical meaning and the program requires, instead, the chine's half beam. For the next chines the coordinates (y, z) are used. For the last chine there is the user's option to either use coordinates like the other chines
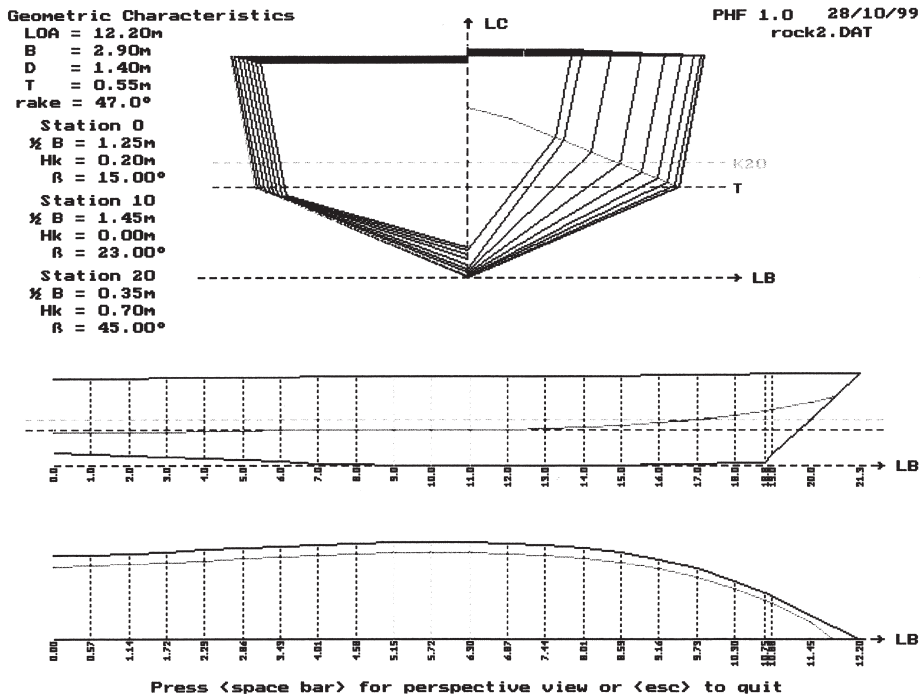

Fig. 11.   Single-chined 'rocker'-type hull form.

Table 4
Offsets — single-chined 'rocker'-type hull form[a]

No.	LWL/20	Xsta	Yk	Zk	YC1	ZC1	Yd	Zd	YLC	ZLC
0	0.00	0.000	0.000	0.200	1.093	0.493	1.250	1.300	0.000	1.300
1	1.00	0.572	0.000	0.184	1.109	0.497	1.266	1.304	0.000	1.304
2	2.00	1.145	0.000	0.163	1.131	0.503	1.287	1.309	0.000	1.309
3	3.00	1.717	0.000	0.137	1.156	0.511	1.313	1.316	0.000	1.316
4	4.00	2.290	0.000	0.110	1.184	0.518	1.340	1.323	0.000	1.323
5	5.00	2.862	0.000	0.082	1.212	0.526	1.368	1.329	0.000	1.329
6	6.00	3.435	0.000	0.055	1.239	0.534	1.395	1.336	0.000	1.336
7	7.00	4.007	0.000	0.032	1.262	0.540	1.418	1.342	0.000	1.342
8	8.00	4.580	0.000	0.013	1.282	0.546	1.437	1.347	0.000	1.347
9	9.00	5.152	0.000	−0.000	1.294	0.549	1.450	1.350	0.000	1.350
10	10.00	5.725	0.000	0.000	1.294	0.549	1.450	1.350	0.000	1.350
11	11.00	6.297	0.000	0.000	1.294	0.549	1.450	1.350	0.000	1.350
12	12.00	6.870	0.000	0.000	1.286	0.553	1.441	1.350	0.000	1.350
13	13.00	7.442	0.000	0.000	1.264	0.562	1.418	1.351	0.000	1.351
14	14.00	8.015	0.000	0.000	1.224	0.578	1.374	1.353	0.000	1.353
15	15.00	8.587	0.000	0.000	1.158	0.604	1.305	1.357	0.000	1.357
16	16.00	9.159	0.000	0.000	1.063	0.643	1.203	1.361	0.000	1.361
17	17.00	9.732	0.000	0.000	0.932	0.696	1.062	1.368	0.000	1.368
18	18.00	10.304	0.000	0.000	0.759	0.766	0.877	1.376	0.000	1.376
19	18.69	10.699	0.000	0.000	0.613	0.825	0.721	1.383	0.000	1.383
20	19.00	10.877	0.000	0.166	0.539	0.855	0.642	1.387	0.000	1.387
21	20.00	11.449	0.000	0.700	0.266	0.966	0.350	1.400	0.000	1.400
22	21.31	12.200	0.000	1.400	0.000	1.400	0.000	1.400	0.000	1.400

[a] Where: sta=station; k=keel; C=chine; d=deck; LC=centerline; Hull File: ROCK2.DAT. Units: m; *LOA*=12.200; *LWL*=11.449; Breadth=2.900; Depth=1.400; Draught=0.550; *K20*=0.700; Parallel body=3 station(s); Number of stations=4; Number of chines=1; Rake angle of bow=47.00°; Height of rake end=0.000

or give the flare angle and the chine's height. The point $n-1$ is defined by the deck line, being the height equal to the depth given for that station. The last point (n) closes the station, using a nil half beam and the same depth.

This procedure, although having some limitations (see Section 10, ahead) allows, as a trade-off, the hull form definition of the vast majority of shapes with a minimum number of parameters and stations. Given the main characteristics, rake and mid-body size, all that is required for the stations are their half beams, keel heights, deadrise angles and the chine coordinates. Having been given all the required parameters, the program generates the hull offsets and draws the plan of stations including the special given ones; the profile with the keel line, Fig. 11, all chines, the given draught and the projection of the keel height of Station 20 (for definition purposes to determine the interaction of extra stations), including the stations' positions (in meters) and station number; the half waterplane with the chines' developments. The relevant input data are also tabulated to ease interaction or correction of lines. An isometric perspective of the defined hull form is also shown, Fig. 12. In the manual
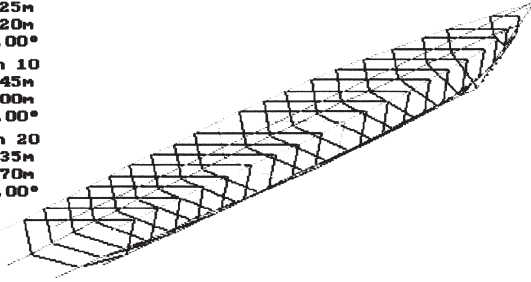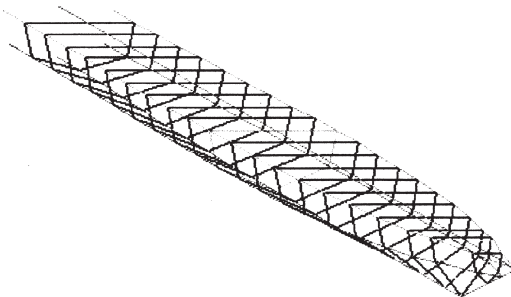
Fig. 12.   Isometric — single-chined 'rocker'-type hull form.

mode, three offset files are generated: one for the input data, one for drafting the lines plan (Table 4) and another in a professional software format for running that system.

9. Case studies

The prescribing process of parameters was made to be consistent with design practice values, to help in the intuition for form definitions. To demonstrate the method, the hull forms of seven types of planing craft were defined using the program, exercising different features. All of these hull forms were defined very quickly (in minutes) with at the most, for the more complex forms, the use of squared paper for the sections. To give an idea of how quick the input is, Table 5 shows how many parameters needed to be input for each of the examples shown below.

If the user wishes to define a variable deadrise hull, a smaller angle is prescribed for the stern and all keels are at the base line, and a 'falling chine' hull results, Fig. 13. It should be noticed in this figure that a few more stations were prescribed in order to obtain a better chine development at the bow (with the reminder that the station defined at the point where the rake ends is generated automatically, without input). The possibility of giving as many stations as necessary at any position helps the user to work in the inverse direction. Data can be taken from an existing body
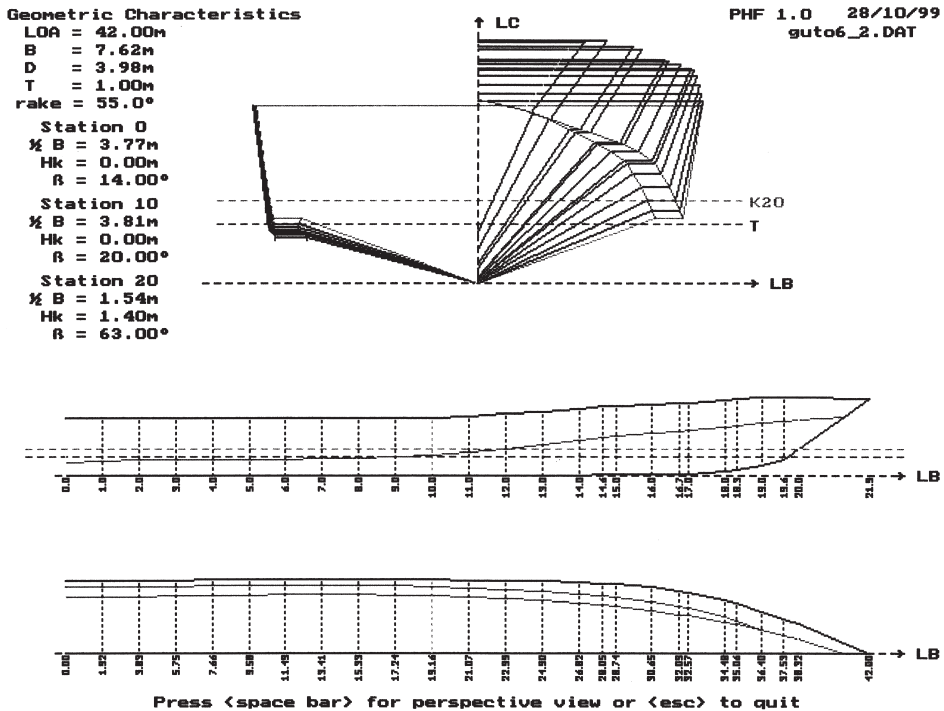

Fig. 13.   Hull form with horizontal keel and 'falling chines'.

Table 5
Number of parameters required for defining a hull form in the program

Figure no.	No. of stations given	No. of chines given	Total no. of parameters[a]
11, 12	3[b]	1[b]	25[b]
13	6	2	55
14	4	2	40
15	4	2	40
16	3[b]	1[b]	25[b]
17	4	5	60
18	3[b]	6	55

[a] Including *LOA*, *B*, *D*, *T*, *K20*, R_{fwd}, *Hr*, *NCh*, etc., as the 11 initial parameters (the chine coordinates — *Yc* and *Zc* — count as two parameters).
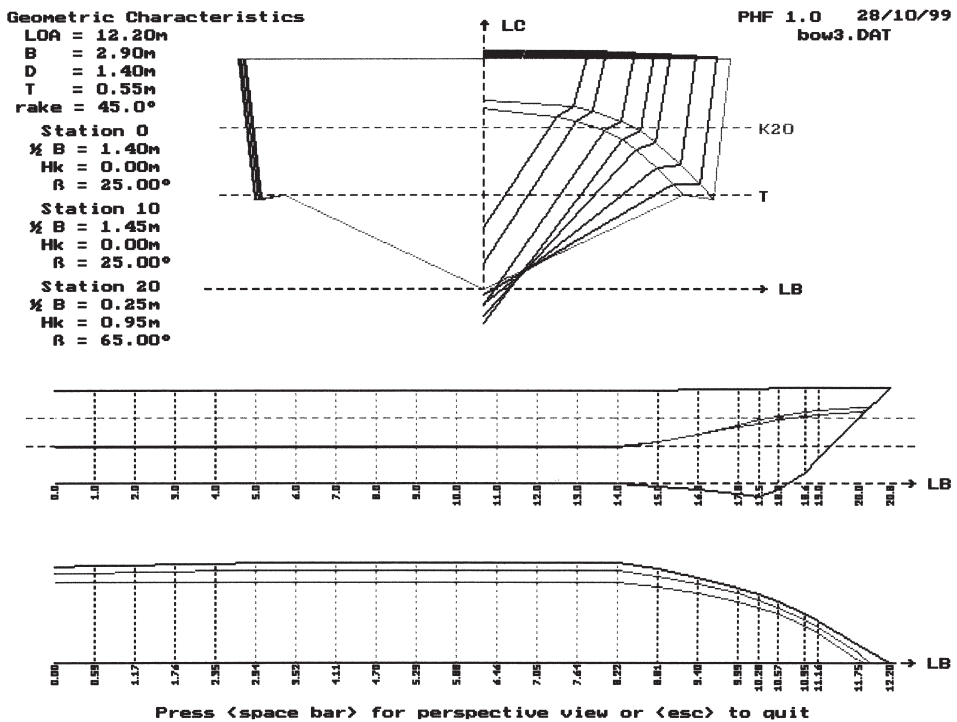
[b] Minimum required.

Fig. 14.   Anti-slam double-chined deep-vee constant deadrise hull.

plan in order to input the hull form into the computer system, as long as Stations 0, 10 and 20 are also known.

If the deadrise is variable and the chines are to be kept within the same height, the user will feel the need to define higher keels at smaller angles, resulting in a 'rocker' hull form, Figs. 11 and 12. If 'delta' hulls are needed, obviously the beam at stern should be given greater. For sea-keeping anti-slam bows, extra stations can be prescribed, Figs. 13 and 14. It can be noticed in Fig. 14 that a deep 'vee' constant deadrise and a 'negative keel' for the bow were exemplified. The parallel mid-body given in number of stations can be used interactively to help deform conveniently the chines forward.

Another negative keel height was prescribed in the example of Fig. 15, creating a 'falling keel' hull. Negative or 'zero' deadrise angles can be prescribed to allow inverted 'vees', Fig. 16, or slopes of multi-hulls forms Fig. 17 (see offsets in Table 6). In these two examples the mentioned 'Station 21' blunt bow was exercised. It can be noted that, for the inverted 'vee' hull form, the forward rake was given nearly vertical. This hull form also shows an example of a negative flare angle, making the deck side less wide than the bottom.

It should be noted that, for Fig. 11, only the three default stations and three para-meters for each (keel height, deadrise and flare) were given. Solely the same three default stations were also given for Figs. 16 and 18, but since in Fig. 18 there are
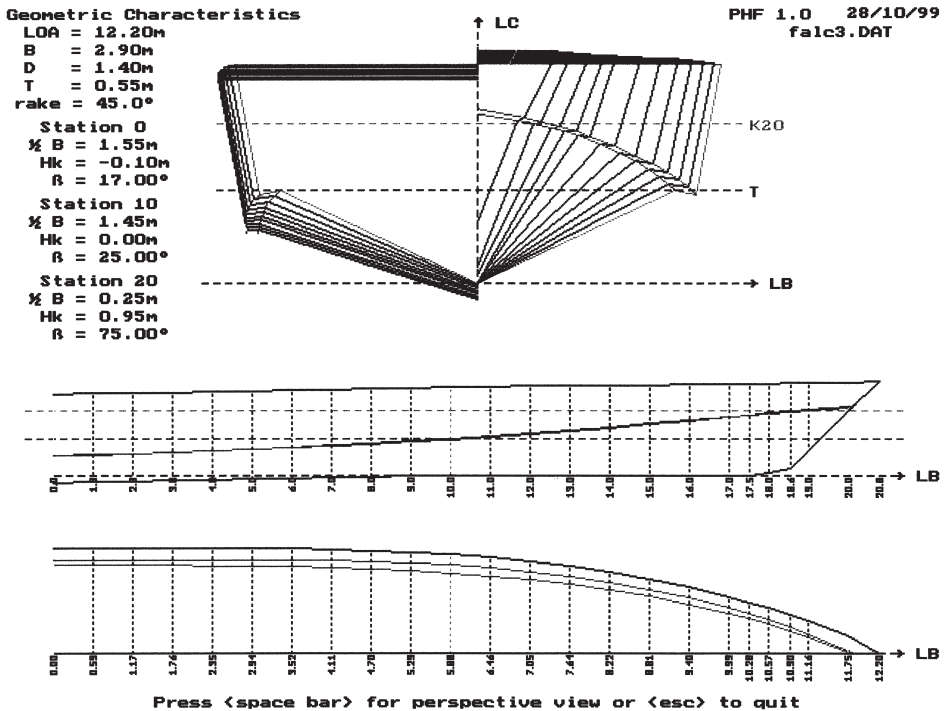

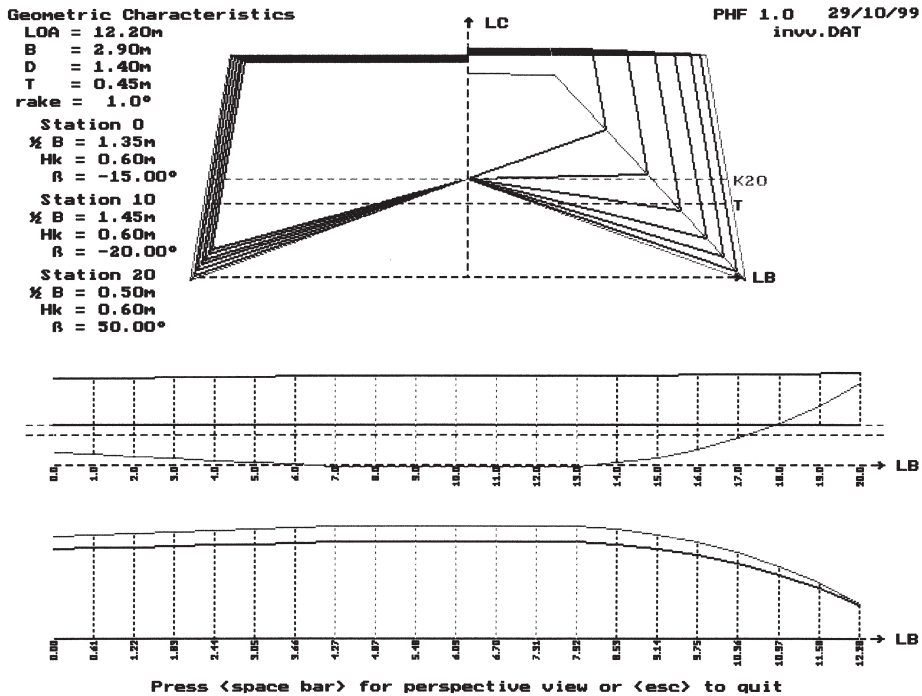Fig. 15.   'Falling keel' planing hull.

Fig. 16.   Inverted 'vee' hull.

six chines, besides keel height, deadrise and flare, five extra chine coordinates had to be given. For Figs. 13–15 and 17, extra stations with all chine coordinates were prescribed for each.

10. Program limitations

So far there are a few limitations of the program, some due to the conception philosophy and some detected with tests. Most of them can be easily overcome with some more working effort, and it is intended to follow through with these adjustments. The present state of the program was found to be reasonable for the present design and research purposes of the group, and to be put forward for judgement and further detection of limitations.

The first limitation is due to the intention of simplifying the input data: all stations must close at the centerline, i.e., the first and last points given have a breadth (not asked) of zero. Moreover, the upper limits of all stations are always equal to the depth of the given station; i.e., it is not possible to prescribe cambers. As a consequence of these two factors, it is not possible for the program to produce and draw indented decks, like for example a catamaran where the double hulls extend beyond the deck between them. It is also not possible to prescribe or have automatically done stations
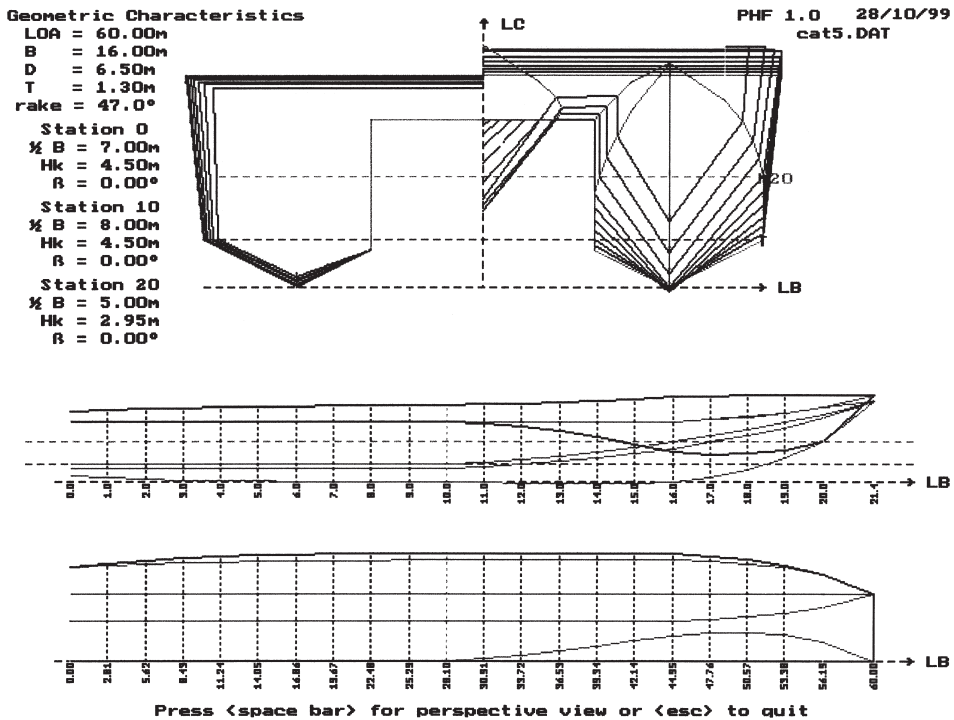
Fig. 17.   Anti-slam bow catamaran.

with lines closing away from the centerline, as would be the case in the most forward stations of the example mentioned above.

Also, for the sake of input data simplification and automation, the number of chines given must be included in all stations, which means the user must make them converge to special points at stations where they no longer exist. The stern rake angle was also left out and is always taken as nil. Another limitation is the lack of the production of waterplanes, which could be seen as a program that produces only stations, profile and offsets. At the moment the research being carried out requires very quick good hull form definitions, and this is the great advantage of the program.

For the waterplanes, buttocks, as well as other routines to produce hydrostatic characteristics, cross curves, etc., a commercial naval architectural software is currently used. As mentioned, one of the three offset files produced by the program is for immediate use in that software. Obviously, once converted, the hull form can be modified to overcome the above-mentioned limitations, but this is temporary and not the intended purpose of the research. The consequence of this is that the offsets produced so far are simplified to those heights where inflections occur (base line, chines and upper deck), instead of waterlines. The trade-off between priorities and time consumption led to leaving out, for the moment, a better definition of these features. The intention here is to test how this design philosophy works with planing boats.

Table 6
Anti-slam bow catamaran offsets

No.	LWL/20	Xsta	Yk	Zk	YC1	ZC1	YC2	ZC2	YC3	ZC3
0	0.00	0.000	0.000	4.500	0.000	4.500	3.000	4.500	3.000	1.000
1	1.00	2.810	0.000	4.500	0.000	4.500	3.000	4.500	3.000	1.000
2	2.00	5.619	0.000	4.500	0.000	4.500	3.000	4.500	3.000	1.000
3	3.00	8.429	0.000	4.500	0.000	4.500	3.000	4.500	3.000	1.000
4	4.00	11.239	0.000	4.500	0.000	4.500	3.000	4.500	3.000	1.000
5	5.00	14.048	0.000	4.500	0.000	4.500	3.000	4.500	3.000	1.000
6	6.00	16.858	0.000	4.500	0.000	4.500	3.000	4.500	3.000	1.000
7	7.00	19.668	0.000	4.500	0.000	4.500	3.000	4.500	3.000	1.000
8	8.00	22.477	0.000	4.500	0.000	4.500	3.000	4.500	3.000	1.000
9	9.00	25.287	0.000	4.500	0.000	4.500	3.000	4.500	3.000	1.000
10	10.00	28.097	0.000	4.500	0.000	4.500	3.000	4.500	3.000	1.000
11	11.00	30.906	0.000	4.319	0.184	4.500	3.000	4.500	3.000	1.127
12	12.00	33.716	0.000	4.069	0.447	4.500	3.000	4.500	3.000	1.295
13	13.00	36.526	0.000	3.741	0.771	4.500	3.000	4.500	3.000	1.511
14	14.00	39.335	0.000	3.326	1.138	4.500	3.000	4.500	3.000	1.780
15	15.00	42.145	0.000	2.815	1.530	4.500	3.000	4.500	3.000	2.108
16	16.00	44.954	0.000	2.200	1.930	4.500	3.000	4.500	3.000	2.500
17	17.00	47.764	0.000	2.026	2.093	4.622	3.122	4.641	3.122	2.953
18	18.00	50.574	0.000	2.056	2.127	4.802	3.302	4.853	3.302	3.462
19	19.00	53.383	0.000	2.346	1.948	5.081	3.581	5.139	3.581	4.053
20	20.00	56.193	0.000	2.950	1.472	5.500	4.000	5.500	4.000	4.750
21	21.35	60.000	0.000	6.500	−0.000	6.500	5.000	6.000	5.000	6.000

No.[a]	LWL/20	Xsta	YC4	ZC4	YC5	ZC5	Yd	Zd	YLC	ZLC
0	0.00	0.000	5.000	0.400	7.000	1.300	7.000	5.200	0.000	5.200
1	1.00	2.810	5.000	0.298	7.128	1.300	7.256	5.325	0.000	5.325
2	2.00	5.619	5.000	0.214	7.233	1.300	7.466	5.420	0.000	5.420
3	3.00	8.429	5.000	0.147	7.317	1.300	7.633	5.492	0.000	5.492
4	4.00	11.239	5.000	0.095	7.382	1.300	7.763	5.544	0.000	5.544
5	5.00	14.048	5.000	0.056	7.430	1.300	7.860	5.581	0.000	5.581
6	6.00	16.858	5.000	0.029	7.464	1.300	7.928	5.608	0.000	5.608
7	7.00	19.668	5.000	0.012	7.486	1.300	7.971	5.628	0.000	5.628
8	8.00	22.477	5.000	0.002	7.497	1.300	7.995	5.647	0.000	5.647
9	9.00	25.287	5.000	−0.001	7.501	1.300	8.003	5.670	0.000	5.670
10	10.00	28.097	5.000	−0.000	7.500	1.300	8.000	5.700	0.000	5.700
11	11.00	30.906	5.000	−0.019	7.500	1.447	8.000	5.751	0.000	5.751
12	12.00	33.716	5.000	−0.060	7.500	1.646	8.000	5.825	0.000	5.825
13	13.00	36.526	5.000	−0.101	7.500	1.898	8.000	5.920	0.000	5.920
14	14.00	39.335	5.000	−0.120	7.500	2.206	8.000	6.032	0.000	6.032
15	15.00	42.145	5.000	−0.094	7.500	2.573	8.000	6.159	0.000	6.159
16	16.00	44.954	5.000	−0.000	7.500	3.000	8.000	6.300	0.000	6.300
17	17.00	47.764	5.000	0.366	7.397	3.441	7.817	6.379	0.000	6.379
18	18.00	50.574	5.000	0.906	7.249	3.910	7.547	6.429	0.000	6.429
19	19.00	53.383	5.000	1.743	6.977	4.425	7.128	6.452	0.000	6.452
20	20.00	56.193	5.000	3.000	6.500	5.000	6.500	6.450	0.000	6.450
21	21.35	60.000	5.000	6.000	5.000	6.000	5.000	6.500	0.000	6.500

[a] Where: sta=station; k=keel; d=deck; C=chine; LC=centerline. Hull File: CAT5.DAT. Units: m; *LOA*=60.000; *LWL*=56.193; Breadth=16.000; Depth=6.500; Draught=1.300; *K20*=2.950; Parallel body=0 station(s); Number of stations=5; Number of chines=5; Rake angle of bow=47.00°; Height of rake end=3.000.
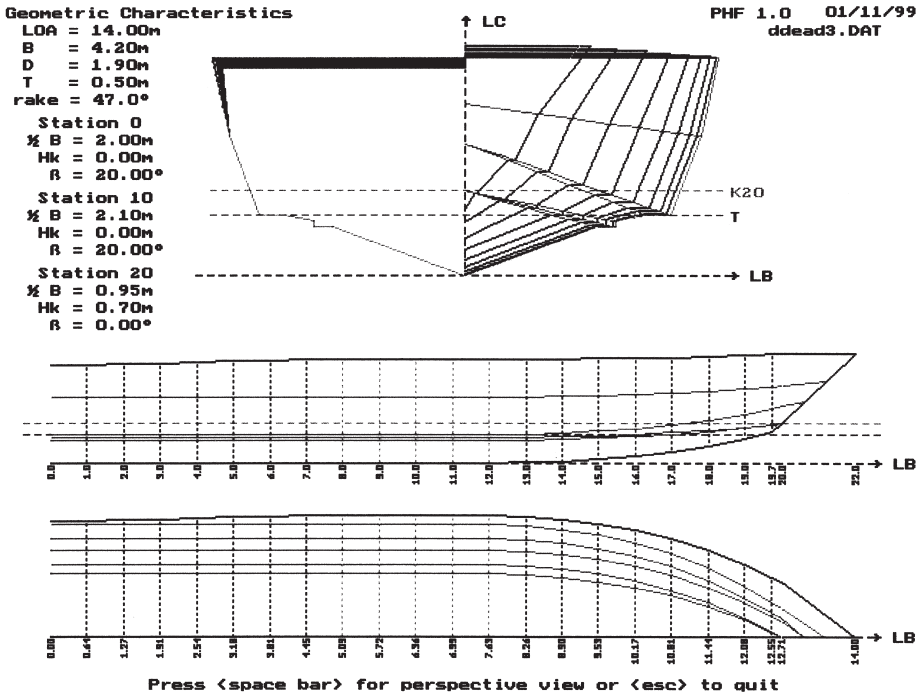
Fig. 18.   Double deadrise deep-vee hull.

11. Conclusions

As can be seen, quite detailed hull forms can be defined very quickly. It has also been shown that the method is flexible enough to allow a great number of variations of forms that creativity may require. The offsets can be used by other programs or be printed out for ready use in drafting the lines plan. Another ability of the method is that the same program allows quick definitions of complex hull forms with a minimum of parameters, at the same time that an existing lines plan can be input in detail to the system through the program. The "feature extraction" technique has shown that different hull forms can be represented mathematically, and this representation can be transcended from its original ranges successfully. The features of a hull form can be used to completely define the geometry of the hull design.

Quite a few of the observed limitations of the method can be overcome with little extra programming effort. Nonetheless, some refraining is necessary in order not to include improvements that will allow better forms to be defined, but would jeopardize both the automatic capability of defining hull forms solely with numbers and its use for very quick estimates using experienced designers' guesses.

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