THREE-DIMENSIONAL DATA SMOOTHING FOR THE INTERACTIVE DESIGN OF SAILBOAT HULLS

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ABSTRACT

Programs capable of running on small computers accept designer's lines from two-dimensional curves and allow them to be faired into a three-dimensional surface of smoothly blended contours. Hydrodynamic performance is not calculated directly, but information which will help the designer determine this is available from the program outputs. Calculations are speedily performed for displacement, the curve of area, longitudinal centre of buoyancy, and prismatic coefficient. Since the design of sailing yachts is as much of an art as it is a science, the interaction of the designer is needed at many points in the design. He must use his eye to see if the lines produced by the computer follow some good design rules that are difficult to reduce to formulas, and he must check that sufficient room is being allowed for accomodations below the deck. This is accomplished with the help of plotting programs which picture the current design in any type of projection. The hull shape is specified by an array of 30 coefficients which may be adjusted by the designer.

SOMMAIRE

A l'aide de programmes susceptibles de passer sur de petits ordinateurs les courbes conçues, en deux dimensions sont transformées en une surface tridimensionnelle à contours reguliers. Le rendement hydrodynamique doit être calculé indirectement une fois les resultats du programme obtenus. On peut ainsi obtenir rapidement le tirant d'eau, le courbure de la coque, le centre de poussée longitudinal et le coefficient prismatique. La réalisation d'un voilier relevant au moins autant de l'art que de la science, il est important que le concepteur intervienne à différentes stades du projet, c'est son jugement qui décide si les lignes produites par l'ordinateur suivent bien les rêgles empiriques si difficiles à ramener à des formules. Par ailleurs il doit aussi s'assurer qu'on reserve suffisamment d'espace pour loger les passagers et l'equipement sous le pont. On réalise ces objectifs grâce à des programmes qui dessinent les figures en projection sous n'importe quel angle. Une série de trente coefficients qui peuvent êtres modifiés par le projeteur permettent de préciser la forme de la coque.

The design of hulls for sailing yachts is an area in which the computer can be employed to great advantage, but not necessarily in a way that people who are unacquainted with this design art would guess. It would seem that the computer could take over the entire job, and given a waterline length and displacement, could come up with an optimum hull design that would minimize the resistance of the ship to slipping through the water and at the same time offer maximum performance when the boat is heeled and exerting lateral pressure on the keel. There are some indications of progress in this area (1), but the idea has not proven to be generally practical.

Some of the reasons why the computer has made slow inroads into the area of yacht hull design are to be found in references by Herreshoff (2), Gillmer (3), Herreshoff and Newman (4), and Henry and Miller (5,6). One of the difficulties mentioned is in describing a yacht form with a reasonably small number of parameters for the computer to handle. This paper may offer some relief in that respect. Although many characteristics of hull performance of a given shape may be assimilated by the computer, based on the results of towing a model through a towing tank, it is difficult to predict what changes in these characteristics will occur if certain areas of the shape are changed, unless the three-dimensional flow patterns can be determined. The generation of tip vortices off the keel due to cross-flow along the keel, the formation of bow waves and waves alongside the ship, and separation effects near the rudder make this an extremely complex problem. Another problem in hull design that cannot be overlooked is the problem of fitting the accomodations into the space below decks. The combination of owner preferences and the consideration of the uses to be made of the ship will generally determine the basic hull shape. The number of different hull shapes available on the market today shows how these factors can affect the ship design.

This paper reports on a group of computer programs which are to be used by the designer as he goes about determining his lines according to more or less traditional rules and practices. They will tell him how he is doing as his design progresses, what the displacement is, where the longitudinal centre of buoyancy is located, the value of the prismatic coefficient and how good the lateral stability will be as predicted by the "Rayner" analysis. The designer may see his lines plotted in the usual projections: The waterlines, body sections, diagonals and buttocks to determine if the lines appear smooth and pleasing to the eye, and to see if certain angles and curvatures match with generally accepted design rules and practices. A better realization of what these projections mean in terms of a three-dimensional object may be seen through the use of perspective plotting programs that draw the hull surface and deck lines from any selectable vantage point, including a choice of wide and narrow angle fields of view. These programs may be used to study the appearance of the yacht from any angle as if, with the help of the computer, one could take a walking tour around the yet unfinished boat.

The principle use for the programs is the three-dimensional smoothing of data to yield surface contours which are continuous and free from abrupt changes in curvature in any direction. The designer, working in two dimensions on a flat sheet of paper can only hope that his contour lines will join together well in the final product. This is often corrected by building frames to the shape of the body lines and nailing flexible wood splines or battens to them. Discontinuities will show up as kinks in the battens which must be taken out by shimming or cutting away the forms. Since the splines are not used in all directions but are only roughly longitudinally directed, other blemishes in the surface may show up during the final construction, requiring tedious special attention.

The author was approached by Mr. Peter Riordon, who was formerly the manager of a Quebec boat building company, to see if he could use the computer to fair the lines of a design Mr. Riordon had begun for a 50-foot ketch of about 40,000 pounds displacement, with provision for sleeping seven people. It was to be equipped for sailing on round-the-world cruises but could be handled in light weather by one man. The challenge to try smoothing the data would not have been accepted if it were not for the fact that reasonable success had been experienced lately in two-dimensional curve fitting, and this seemed a likely place to start. The original lines drawn by Mr. Riordon, figure 1(a), had been made with flexible spline curves anchored at several points and were generally smooth and continuous, although there was some obvious irregularity between adjacent contours, especially in the lower regions of stations 3 through 5, near the keel. Each body station line was digitized into about 30 to 40 x-y coordinate points, and then the job of curve fitting began.

Different parts of the boat could be fit with different equations, but this did not offer much help. It is quite hard to change equation types in mid-stream. The reverse curve between the bilges and the keel required a type of equation that was not available in the two-dimensional curve-fitting package developed earlier. Finally, an equation was found that could handle all the body section lines from stem to stern with minimum errors. It has the form given below:

$$Y = A + [f_1(X-C,B,F)]^n + f_2(X-D,E) \qquad (1)$$

where Y is the dependent variable in the vertical direction
- X is the independent variable in the horizontal direction
- A is a vertical offset
- C,D are assymtotes describing the location of the keel surface and the gunwales if the section extended infinitely low, or high, respectively
- B,F are slope functions applying to the keel section
- E is a slope function applying to the outer, or canoe body section
- n is an integer power

Using an equation of this type has certain advantages over polynomial series. First, the total number of coefficients is small; there are only six, from A through F, and as it develops later, coefficient F may be derived from a very simple relation with B and a fixed constant. Second, there is no tendency for wild variations to occur in the higher order derivatives as with polynomial series. Although there is no specific disclosure here as to the exact nature of the functions indicated as f_1 and f_2, they are simple expressions wherein all derivatives exist, and they can be integrated in closed form. The third advantage is based on this fact, and is that a simple closed form expression may be written for the area of any section, which allows the rapid calculation of displacements.

When coefficients B and F are zero, the bracketed middle term drops out, leaving only the A and f_2 terms. These define a keel-less section, as used in the bow and transom areas. If the Y-intercept of these sections is known, represented by the value Y_0 when X is zero, then A may be calculated from the relationship.

$$A = Y_0 - f_2(O,D,E) \qquad (2)$$

The complete description of Y_0 from stem to stern is the description of a backbone curve for a keel-less ship or canoe body. Replacement of A in this manner also allows scaling the width of a design in a simple manner. To reduce the width of the ship by a certain percentage reduction in beam, the values of coefficients C and D are reduced by this same percentage and the reduction is obtained. The previous vertical dimensions are retained unchanged.

To show the effects of changing the coefficients in formula (1), figure 2 has been drawn for a typical midships section. Y_0 has been kept constant for all four cases of figure 2 by adjusting the value of A according to formula (2). In figure 2(a), D is plotted with ±10% variation, and figure 2(b) shows a ±50% change in C. Both B and F are varied together by ±40% in figure 2(c), while figure 2(b) shows the results of adjusting E by ±20%.

The general method of solution for the determination of the coefficients from the designer's line data is the least squares fit to transformed data, with offsets. The offsets are linear functions added to the ordinate or abscissa before transformation, yielding non-linear results afterward. The technique was first developed in the two-dimensional curve-fitting package mentioned earlier, but here there was a maximum of four unknowns, two to be found by the slope and intercept of the least squares fit, and two from the optimum combination of offsets found to maximize the index of determination function of the least squares fit. In the characteristic equation of the boat curves there are six unknowns, which requires a different approach. What is done is to divide the search into two parts, each of which looks for one offset and two least squares-determined coefficients. As the program enters the next part with three improved coefficients, the rms accuracy in fitting the data generally improves.

The operator may interact with this program while it is executing by throwing console switches, causing one part of the program to enter a two-dimensional search for offsets, maximizing the index of determination through steepest ascent maximization routines. This causes a greater area to be searched and is more likely to turn up a global rather than a local maximum. By watching the summary of coefficients, index of determination, and rms error of fitting the points, which is printed after each part of the program, the effect of the console switch can be ascertained. The program always stores the values of the coefficient set producing the most satisfactory fit so far, in terms of rms error, so that when an unsuccessful search is initiated, the results of a previous better determination will still be fully tabulated at the end of the program. If eight alternations between the two program halves fail to produce improved results, the program stops and prints out a table of actual data values versus the calculated values using the six coefficients, and the relative error. This makes it easy to spot any data points which may have been incorrectly digitized.

There are two other unique features in the search algorithms used in the least squares fitting program: the increment size is continuously changing--as long as the search yields increasing values of the function being optimized, the step size increases--and, the direction of maximum ascent is calculated only after the maximized function fails to increase, and then it is done from the previous higher-valued point. These features cause the program to run efficiently in terms of computer time. Whether or not they are efficient in picking out maxima from all types of function contour surfaces remains as a subject for further study.

The coefficients as obtained from the designer's lines through least squares determination should vary smoothly when arranged in station number order. In general this does not happen and the coefficients must be readjusted slightly to put them on some smoothly varying curve. It is fortunate that equation (1) can be used to do this work as well, not only because it avoids writing a new computer program for other equation types, but because this equation resists abrupt curvatures, resulting in coefficients that vary gradually as a function of stem-to-stern position. All six coefficients including F from the least squares fit program are used to describe the variation in one of the five parameters, or variable coefficients, of the body section curves. This results in a total of 30 fixed coefficients to describe the three-dimensional curved surface of the hull. Figure 3 shows a graph of the variable coefficients, or parameters, Y_0, B, C, D, and E versus station number position.

Once these curves have been determined it is possible to describe the hull profile at all points along the ship, not just at the station points. Figure 4 indicates the shading effect when five body section lines are drawn per station, and also shows how the fairing has produced a smooth progression in the spacing of the lines.

Interactive design is most conveniently worked out on plots of the coefficient variation such as figure 3, rather than by going back to the original digitized data. By keeping in mind the effect of each coefficient as shown in figure 2, it is possible to make adjustments to properties in one particular area of the ship by moving the appropriate coefficient curve in that zone. Some of the simple moves of the coefficient curves that may be accomplished without least squares refitting are: a displacement of the curve in any direction, vertical, horizontal, or combinations of the two; a compression or expansion in the horizontal or vertical scale, or combinations of both. If a localized change is desired, such as to steepen the slope of the body lines in the bow, or to flatten the transom, etc., a few data cards are typed for the values versus station number in the affected area and the least squares program is run again with these cards replacing the original data cards.

The feedback to the designer on the effects of his modifications is obtained by running displacement/stability and plotting programs. A few additional items of data are required to delimit the hull boundaries for these programs. The waterline length and the beam coordinates must be given the right linear dimensions to calculate displacement, and the maximum draft will locate the bottom surface of the keel. The deck line is specified as a singly curved surface which may be approximated by a parabolic curve, or a more complicated function if desired. From the points where the hull intersects this singly curved surface, the deck surface itself is constructed. It is a crowned surface of roughly parabolic shape, defined in terms of the vertical height of the crown at the maximum beam of the ship. This same fixed curve is used at all other points of the deck.

The displacement/stability program is concerned only with the areas of the ship below the design waterline or the waterline that exists when the ship heels or rolls. The station-to-station variation of the part of the body sections that is below the waterline is called the curve of areas, and there are certain preferred shapes that it should follow. The volume displaced by the ship is the integral of the curve of areas. Since the area of any section may be written directly in closed form, it is not difficult to calculate the displaced volume. Multiplication by fresh water or sea water density gives the pounds displacement of the ship. The prismatic coefficient is the ratio of the displacement volume to a volume given by the maximum section area multiplied by the waterline length. The longitudinal centre of buoyancy is found by the area-moment method. As the ship heels, the longitudinal centre of buoyancy should not tend to drift too far fore or aft. The "Rayner" analysis shows tendencies that may occur in these directions, however this program will calculate the longitudinal centre of buoyancy position at every 5° of heel up to 45° for two conditions. One is for the ship to pivot about the line of intersection of the design waterline and the vertical centre plane, as in the "Rayner" analysis. This causes the displacement to increase with heeled angle. The other condition is to allow the waterline intersection to move down the centerline plane until the ship's displacement at 0° heel is established. Then the longitudinal centre of buoyancy is reported for this condition, as well as the distance that the centre plane comes out of the water. This information is very important for establishing where the centre of gravity should be located.

Figure 5 shows the buttocks lines, sectioned parallel to the centre plane at 0.5-foot intervals. This is finer sectioning than the four lines at quarter points of the beam which are usually drawn. The keel leading edge should be rounded to more of a torpedo shape than shown in the waterline sections, figure 6. When this is done during the construction phase of the ship, the profile will be brought back to the dotted line in figure 5, which is more conventional for this type of yacht. The waterlines show that the keel is widest at a point that is forward of the station where the ship reaches maximum beam, and this is as it should be.

The diagonals, or 45° heeled waterlines in figure 7 are very smooth and clean, an indication that the hull design has been executed properly. Waterlines at any other angle of heel may be selected for plotting. It is sometimes interesting to plot a chart such as figure 7 at an angle such as 30° on the lower half of the chart, and then complete the upper half at -30°, which gives the complete waterline intercept of a tilted plane.

The perspective plotting program allows viewing the ship design from any azimuth and elevation, and with any angle of view and magnification. The location of the station point of the observer and the picture plane distance are figured out from the field of view and magnification inputs which are typed in from a keyboard at the time of execution. The rotation and elevation are also input at this time, as are the first and last station numbers to be plotted and the spacing interval between body section lines. Figures 8 and 9 were drawn with 0.2-station intervals, while figure 10 was drawn with 0.5-station spacing. A console switch may be activated to drop out half of the body section lines as in figure 8.

All of these programs were developed and run on a General Electric GEPAC-4020 computer at the DATAC Laboratory at McGill University. The computer is used for real time data acquisition, measurement and control of experiments in surrounding laboratories of the Mechanical Engineering Department, and also in the Civil and Metallurigical Department laboratories. It can also interleave several free time programs at the same time.

It has 24,000 words of core and a one-million word disc memory. The ship design programs are of a convenient length to run on this machine, the maximum size is about 11,000 octal words in the compiled form including subroutine linkages to the Calcomp plotter, however, they could be run on a smaller computer as well. They are written in ANSI standard Fortran IV.

Most of the frames for this ship have been welded by Mr. Riordon of 3/8" steel rod and structural "T" section reinforced by 3/16" diameter webbing: The boat is to be constructed by the Ferrocement technique. Armed with computer printouts giving complete coordinates for the sections every 1/2 station along the length and every 2 inches in width, he found that direct layout of the shapes was very convenient and that the lofting stage usually required when working from small-scale plans was eliminated. The launching date is projected a little too far out into the future to state definitely when this example of computer-smoothed design will be ready to sail.

ACKNOWLEDGEMENTS

The author wishes to thank Mr. Peter Riordon for supplying the original design lines for the 50-foot ketch, and the Mechanical Engineering Department of McGill University and Mr. Louis J. Vroomen, supervisor of the DATAC Computer Centre, for making the GEPAC-4020 system available for a considerable amount of program development time. The perspective plotting subroutines are a joint development with Dr. Paul Zsombor-Murray, also of the DATAC Computer Centre.

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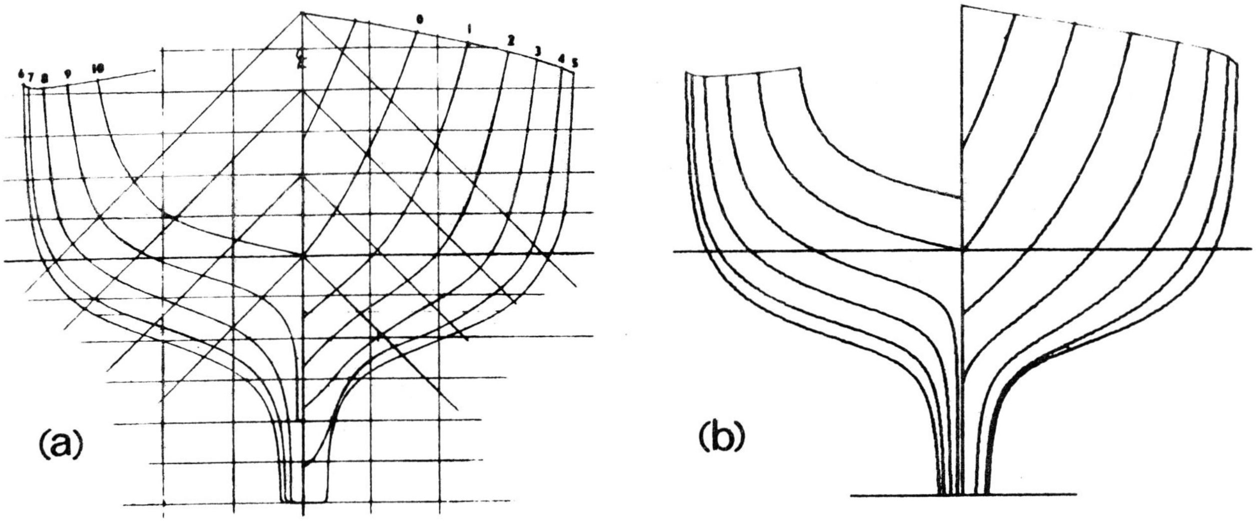

Figure 1. Body section lines. Lines produced by the designer (a), and lines from the computer (b), after three-dimensional fairing.

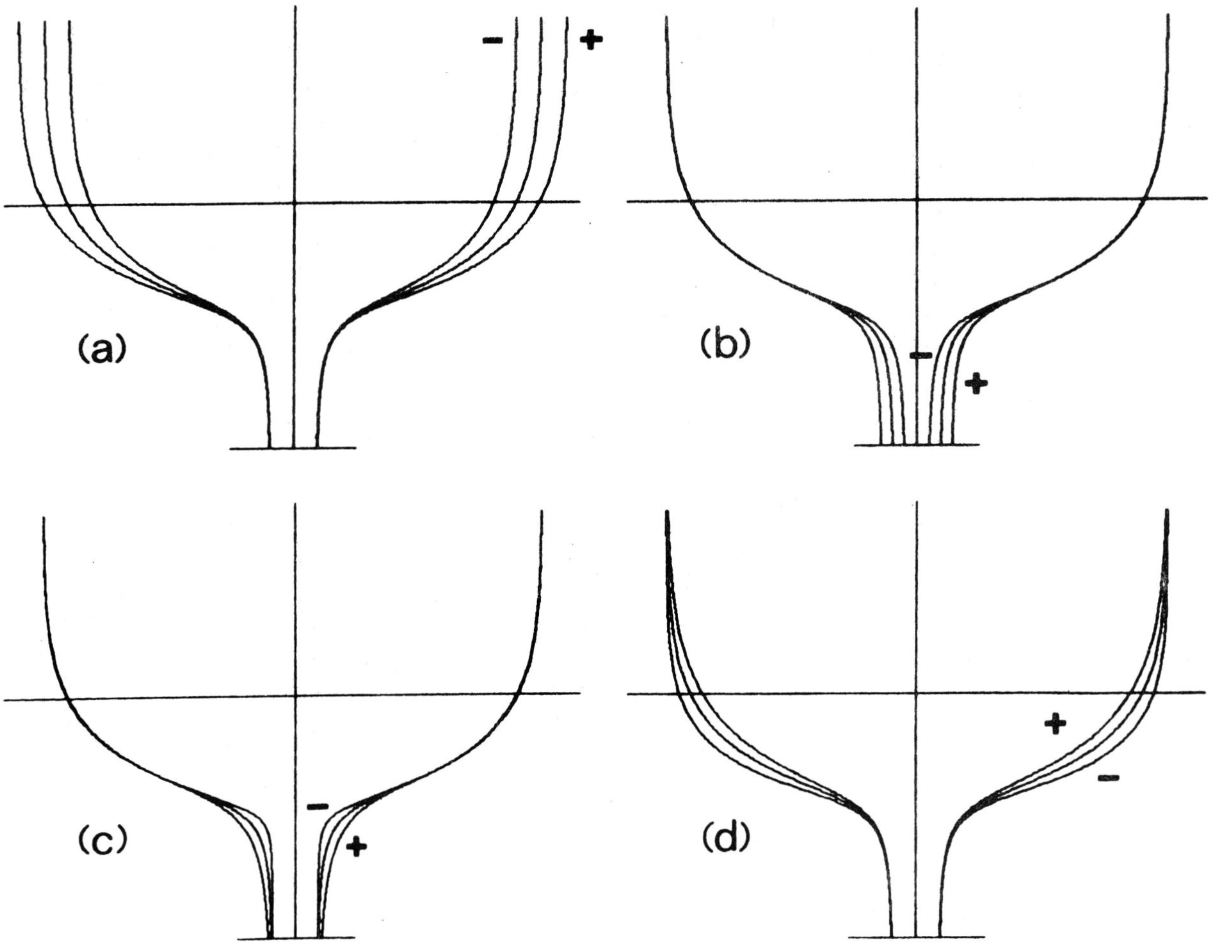

Figure 2. Effects of changing the parameters of equation (1) on a body section located amidships. (a) ±10% variation in D, (b) ±50% variation in C, (c) ±40% variation in B and F, both adjusted simultaneously, (d) ±20% variation in E.

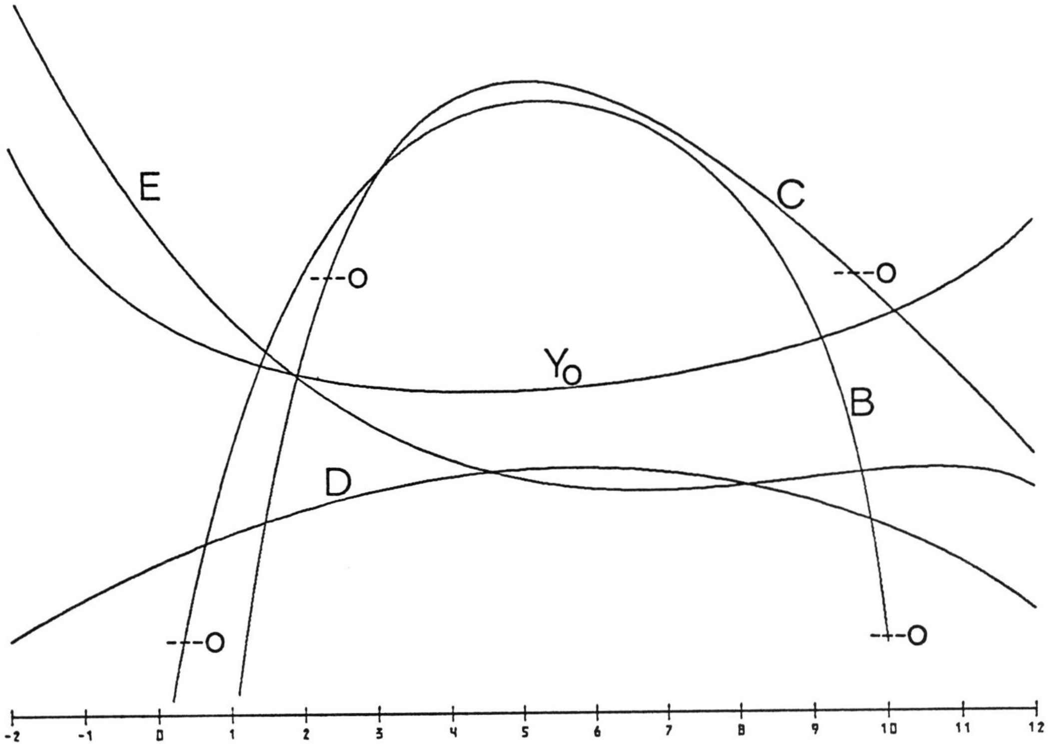

Figure 3. Stem-to-stern variation in the five coefficients Y_o, B, C, D, E after best-fit smoothing using equation (1).

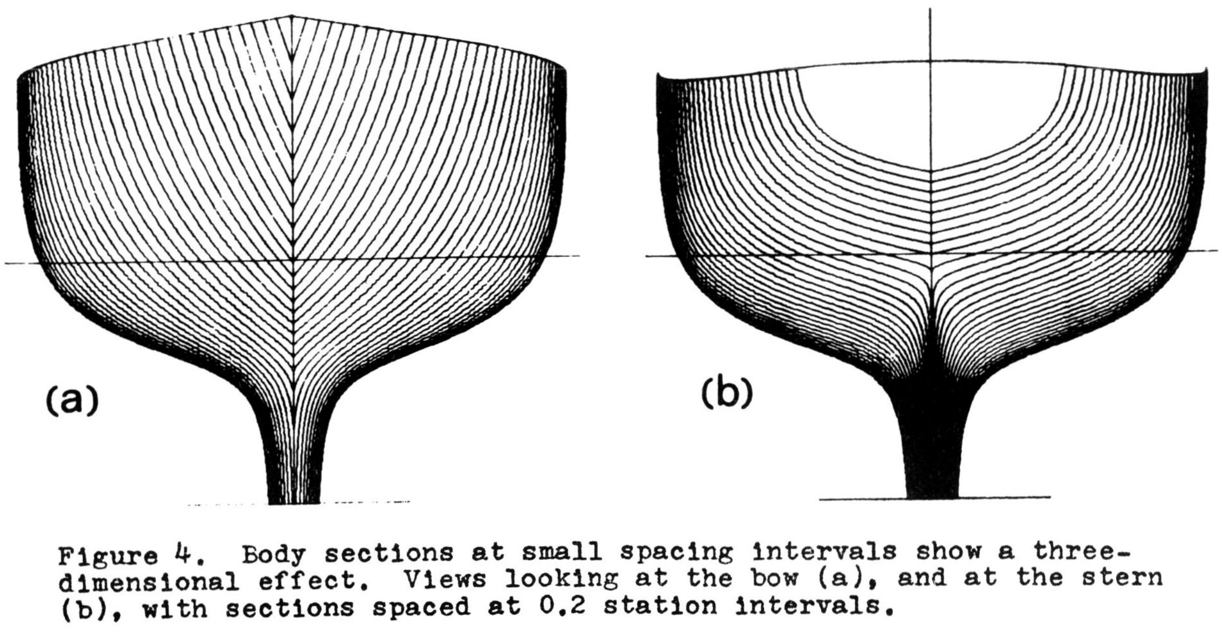

Figure 4. Body sections at small spacing intervals show a three-dimensional effect. Views looking at the bow (a), and at the stern (b), with sections spaced at 0.2 station intervals.

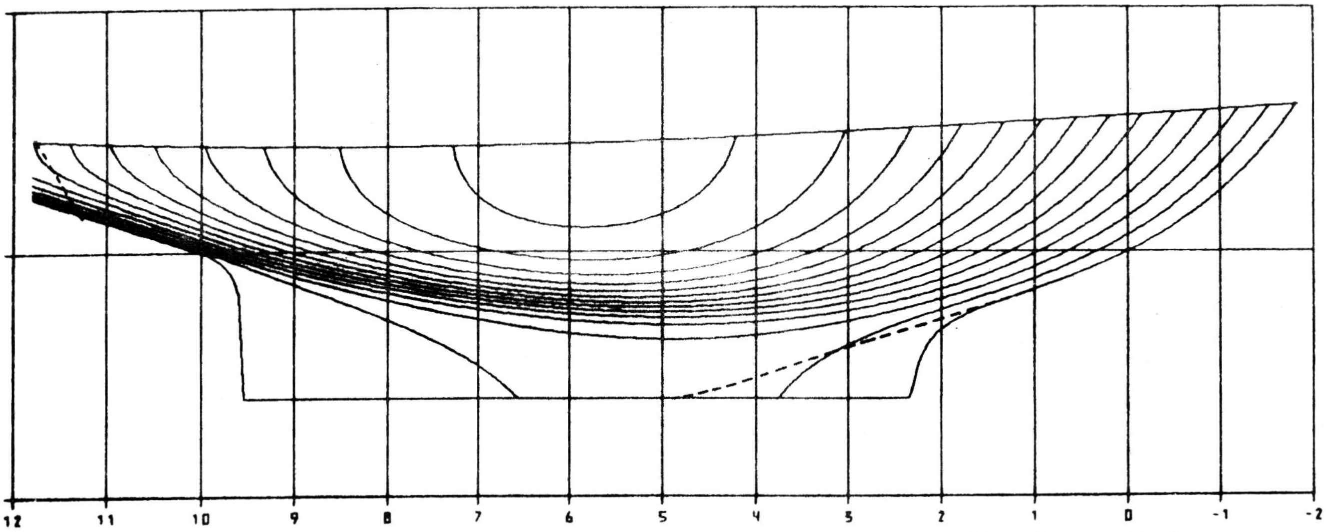

Figure 5. Buttocks sections with station numbers indicated. Waterline length of the ship (37.5 feet) is measured between stations 0 and 10. Dotted line indicates final rounding of keel leading edge to be done during construction.

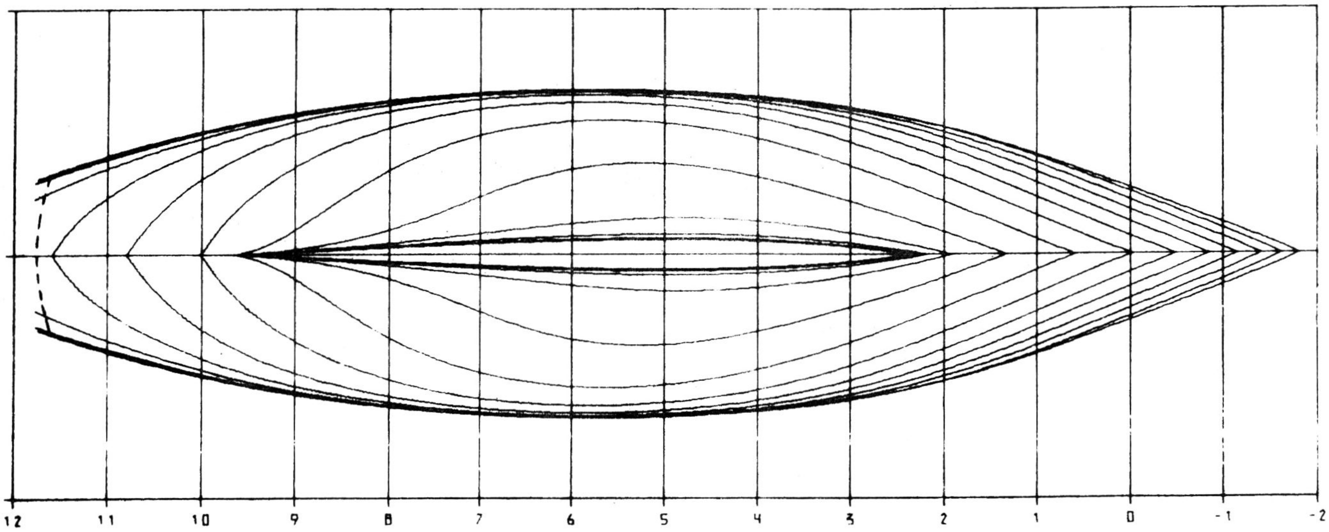

Figure 6. Waterlines at 1.0-foot intervals plotted versus station numbers. Outermost line is the deck line.

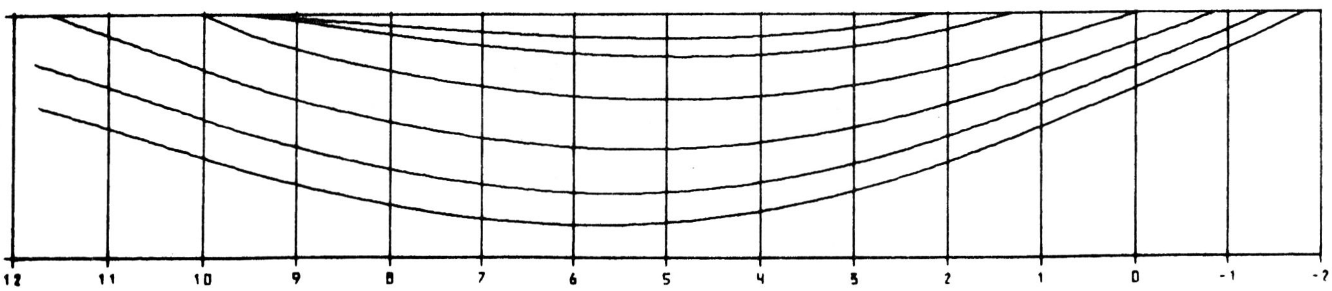

Figure 7. 45-degree heeled waterlines at 2.0-foot intervals. Cutting planes for the four outer lines are shown on the designer sketch, Figure 1(a). Planes for the two inner lines are further down the keel.

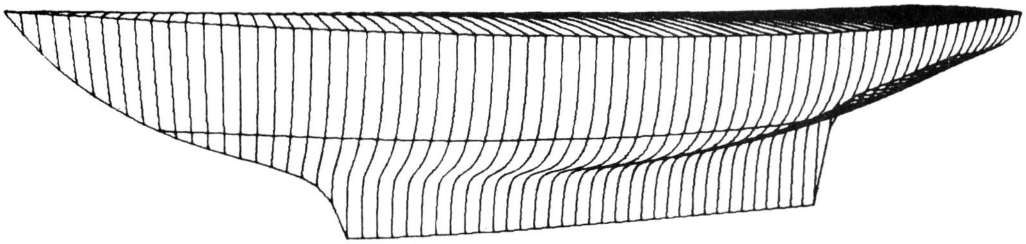

Figure 8. True perspective view of the ship from a selected angle which minimizes the need for a hidden line routine. Stem-to-stern line through the ship has been rotated 82° clockwise from the observer's line of sight, and a slight downward (6°) angle of view has been used. The field of view approximates that of a camera with a 75° lens. These parameters and the magnification are selectable in the plotting program.

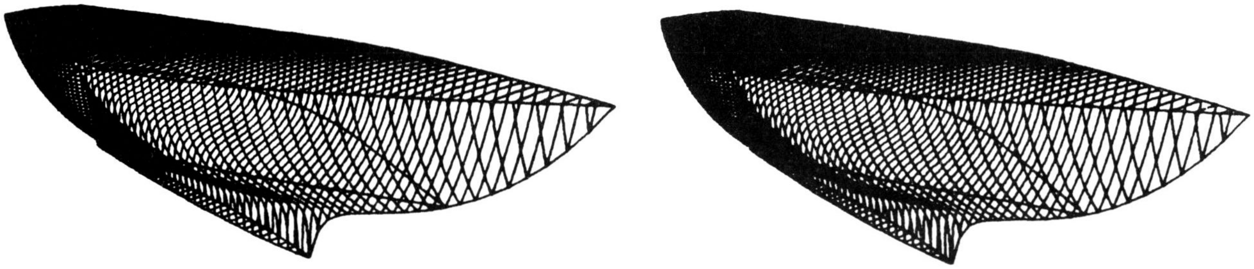

Figure 9. Stereo pair of images produced by rotating the ship behind the perspective picture plane 40° CCW for the right eye and 42° CCW for the left eye, as seen from a 15° elevation angle with the same field of view as above.

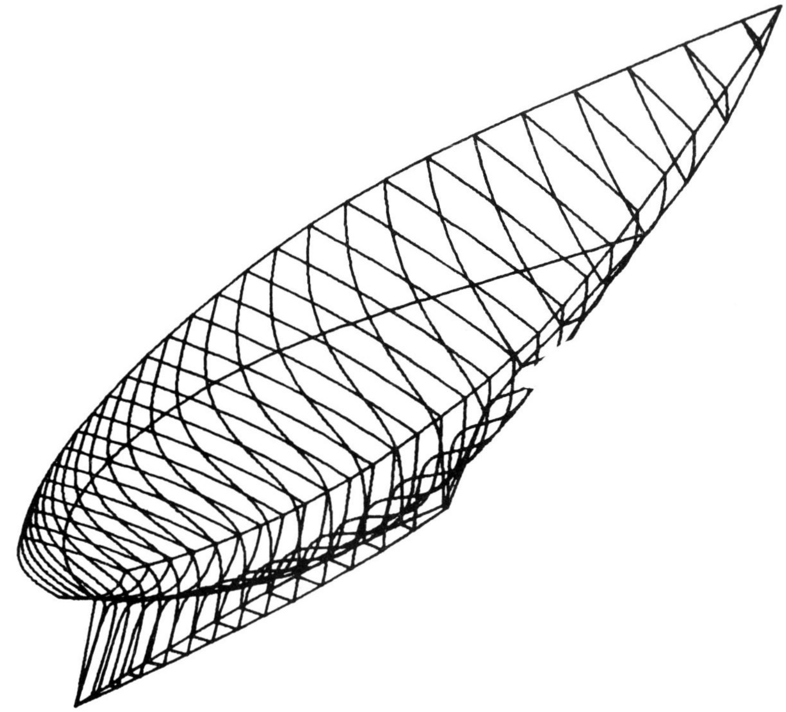

Figure 10. View of the underside of the ship looking upward at an angle of 45° to the plane of the waterline. Angle of ship's heading is also 45° from line of sight.