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RESEARCH AND DEVELOPMENT CENTER

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POLYNOMIAL FAMILIES FOR FLAT-FACED UNDERWATER BODIES AND WALL-SIDED SHIP SECTIONS

by

Paul S. Granville

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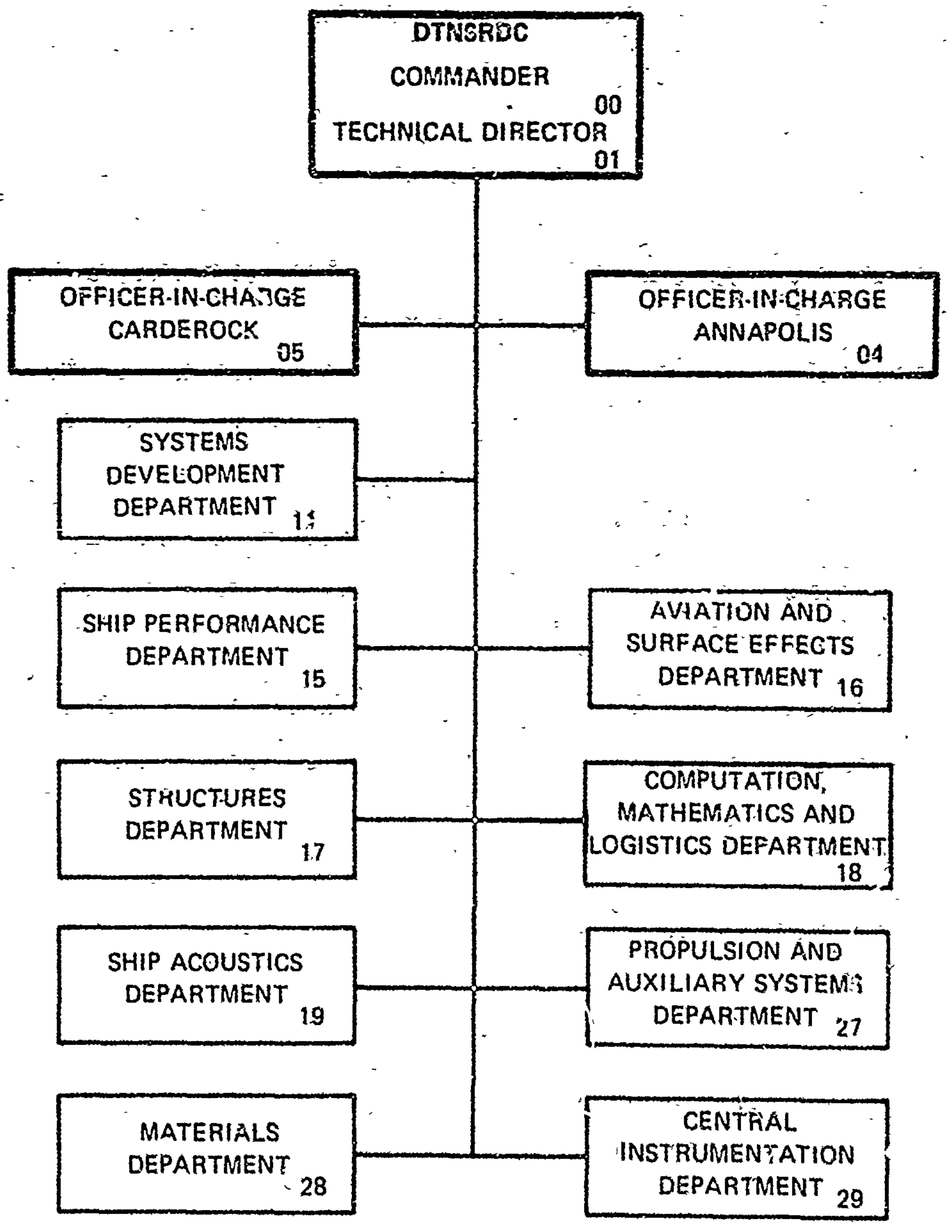

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NOTATION

a_n	Polynomial coefficients
B	Breadth of ship section
B_f	Breadth of flat bottom
D	Diameter or thickness of parallel middle body
D_f	Diameter or thickness of flat face
F	Fullness factor, Equation (26)
$\tilde{K}_0$	Polynomial associated with $\tilde{k}_o$
$\tilde{K}_1$	Polynomial associated with $\tilde{k}_1$
k	Curvature
$\tilde{k}$	Rate of change of curvature with arc length
$\tilde{k}_o$	$\tilde{k}$ at $x = 0$
$\tilde{k}_1$	$\tilde{k}$ at $x = 1$
Q	Polynomial for restraining conditions
s	Arc length
X	Axial coordinate
X_n	Axial length of forebody

x	Normalized axial coordinate
Y	Offset from centerline
y	Normalized offset
Z	Vertical distance
Z_1	Vertical height of curved bilge
α_i	Adjustable conditions
β_j	Restraining conditions

ABSTRACT

Polynomial families that contain a cube-root term are developed to satisfy requirements of infinite slope and zero curvature. Adjustable parameters are used to provide a wide range of curves without inflection points. Applications are to flat-faced underwater bodies and wall-sided ship sections.

ADMINISTRATIVE INFORMATION

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INTRODUCTION

The inability to obtain infinite slope with ordinary polynomial expressions has led to addition of a square-root term in describing round-nosed bodies.[1,2] When zero curvature is also required, the square-root term is inapplicable. It is now proposed to substitute a cube-root term to provide both infinite slope and zero curvature. This is very useful since polynomial expressions, even with the addition of a cube-root term, lend themselves readily to analytical manipulation. Polynomials remain polynomials under either differentiation or integration.

The requirements of infinite slope and zero curvature occur for underwater bodies with flat-faced noses and for curves joining ship bottoms to wall-sided ship sections, among others.

The requirements of infinite slope and zero curvature have also been met by previously proposed "cubic" polynomials,[3] when the dependent variable is cubed and the independent variable is a polynomial expression. The "cube root" polynomial now being proposed may be more convenient to the designer

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[1] Granville, P.S., "Geometrical Characteristics of Streamlined Shapes," Journal of Ship Research, Vol. 13, No. 4, pp. 299-313 (Dec 1969). A complete listing of references is given on page 14.

[2] Granville, P.S., "Geometrical Characteristics of Noses and Tails for Parallel Middle Bodies," International Shipbuilding Progress, Vol. 21, No. 233, pp. 3-19 (Jan 1974).

[3] Granville, P.S., "Geometrical Characteristics of Flat-Faced Bodies of Revolution," Journal of Hydronautics, Vol. 7, No. 4, pp. 166-169 (Oct 1973).

since the dependent variable is linear instead of cubed. Usage will determine the relative merits of these two systems in hydrodynamic applications.

It has been found[1-3] that two adjustable parameters provide a wide range of geometric families and are still not analytically unwieldly as in determining geometric limitations. Polynomial expressions for one adjustable parameter or for none are also readily obtainable from a two-parameter system.

Without loss of generality, the curves to be considered start with infinite slope and zero curvature and end with zero slope and zero curvature. Other conditions may also be considered without difficulty. The two adjustable parameters to be used are the rates of change of curvature at each end of a curve.

Normalized coordinates are employed and the resulting polynomial expressions are examined for suitable ranges of values for the two adjustable parameters. A particularly stringent geometric requirement is absence of inflection points. The allowable range of adjustable parameters is obtained by an envelope analysis.

The requirement for zero curvature at both ends of the curve is used to eliminate discontinuities in curvature at junctions with curves of zero curvature. Discontinuities in curvature are hydrodynamically undesirable since they lead to pressure changes which may result in flow separation and/or cavitation.

CUBE-ROOT POLYNOMIALS

In general, a cube-root polynomial y[x] is

$$y = a_{\frac{1}{3}} x^{\frac{1}{3}} + \sum_{n=0}^{n=N} a_n x^n \tag{1}$$

where $a_{\frac{1}{3}}$ and a_n are coefficients with values to satisfy boundary conditions.

Derivatives are

$$\frac{dy}{dx} = \frac{1}{3} a_{\frac{1}{3}} x^{-\frac{2}{3}} + \sum_{n=1}^{n=N} n\, a_n\, x^{n-1} \tag{2}$$

$$\frac{d^2y}{dx^2} = -\frac{2}{9} a_{\frac{1}{3}} x^{-\frac{5}{3}} + \sum_{n=2}^{n=N} n\,(n-1)\, x^{n-2} \tag{3}$$

etc.

At $x = 0$, $\frac{dy}{dx} \to \infty$ or the slope is infinite as required.

Curvature k may be expressed as

$$k = \frac{d^2y}{dx^2} \left[1 + \left(\frac{dy}{dx}\right)^2\right]^{-\frac{3}{2}} \tag{4}$$

or

$$k = -\frac{d^2x}{dy^2} \left[1 + \left(\frac{dx}{dy}\right)^2\right]^{-\frac{3}{2}} \tag{5}$$

It follows by substitution of Equations (2) and (3) into Equation (5) that $k=0$ at $x=0$ as required.

TWO-PARAMETER CUBE-ROOT POLYNOMIALS

The convenient adjustable parameters are the rates of change of curvature at the ends of the curves. Normalized coordinates $0 \leq x \leq 1$, $0 \leq y \leq 1$ are to be used. The case considered here will have zero slope and zero curvature at $x=1$.

From the curvature given by Equation (5), the rate of change of curvature with arc length s, $\frac{dk}{ds} = \tilde{k}$ is

$$\tilde{k} \equiv \frac{dk}{ds} = -\left(\frac{d^3x}{dy^3}\right)\left[1 + \left(\frac{dx}{dy}\right)^2\right]^{-2} + 3\left(\frac{dx}{dy}\right)\left(\frac{d^2x}{dy^2}\right)\left[1 + \left(\frac{dx}{dy}\right)^2\right]^{-3} \tag{6}$$

where $ds = \left[1 + \left(\frac{dx}{dy}\right)^2\right]^{1/2} dy$ is used.

At $x = 0$, $\frac{dx}{dy} = \frac{d^2x}{dy^2} = 0$.

Then

$$\tilde{k}_o = \tilde{k}_{x=0} = -\left(\frac{d^3x}{dy^3}\right)_{x=0} \tag{7}$$

For curvature written in the form of Equation (4), there results

$$\tilde{k} \equiv \frac{dk}{ds} = \left(\frac{d^3y}{dx^3}\right)\left[1 + \left(\frac{dy}{dx}\right)^2\right]^{-2} -3\left(\frac{dy}{dx}\right)\left(\frac{d^2y}{dx^2}\right)\left[1 + \left(\frac{dy}{dx}\right)^2\right]^{-3} \tag{8}$$

at $x = 1$. $\frac{dy}{dx} = \frac{d^2y}{dx^2} = 0$

Then

$$\tilde{k}_1 = \tilde{k}_{x=1} = \left(\frac{d^3y}{dx^3}\right)_{x=1} \tag{9}$$

In the case of being considered, the cube-root polynomial has two adjustable parameters α_i, i=1, 2, the rates of change of curvature at x=0 and x-1, and four boundary conditions β_j, j=1, 2, 3, 4, the two end coordinates and zero slope and zero curvature at x=1. This requires a cube-root polynomial of the fourth degree

$$y = a_{\frac{1}{3}}x^{\frac{1}{3}} + a_o + a_1x + a_2x^2 + a_3x^3 + a_4x^4 \tag{10}$$

To evaluate the coefficients, the adjustable parameters α_i and boundary conditions β_j are substituted into the cube-root polynomial equation, Equation (10)

$$\alpha_1: \quad \tilde{k}_o = \left(\frac{d^3x}{dy^3}\right)_{x=o} \text{ or } a_{\frac{1}{3}} = \left(\frac{6}{\tilde{k}_o}\right)^{\frac{1}{3}} \tag{11}$$

$$\alpha_2: \quad \tilde{k}_1 = \left(\frac{d^3y}{dx^3}\right)_{x=1} \text{ or } \frac{10}{27}\, a_{\frac{1}{3}} + 6a_3 + 24a_4 = \tilde{k}_1 \tag{12}$$

$$\beta_1: \quad x = 0,\ y = 0 \text{ or } a_o = 0 \tag{13}$$

$$\beta_2: \quad x = 1,\ y = 1 \text{ or } a_{\frac{1}{3}} + a_o + a_1 + a_2 + a_3 + a_4 = 1 \tag{14}$$

$$\beta_3: \quad x = 1,\ \frac{dy}{dx} = 0 \text{ or } \frac{1}{3}\, a_{\frac{1}{3}} + a_1 + 2a_2 + 3a_3 + 4a_4 = 0 \tag{15}$$

$$\beta_4: \quad x = 1,\ \frac{d^2y}{dx^2} = 0 \text{ or } -\frac{2}{9}\, a_{\frac{1}{3}} + 2a_2 + 6a_3 + 12a_4 = 0 \tag{16}$$

Solving as simultaneous equations results in $a_{\frac{1}{3}} = \left(\frac{6}{\tilde{k}_o}\right)^{\frac{1}{3}}$,

$$a_o = 0,\ a_1 = 4 - \frac{220}{81}\left(\frac{6}{\tilde{k}_o}\right)^{\frac{1}{3}} - \frac{\tilde{k}_1}{6},\ a_2 = -6 + \frac{88}{27}\left(\frac{6}{\tilde{k}_o}\right)^{\frac{1}{3}} + \frac{\tilde{k}_1}{2},$$

$$a_3 = 4 - \frac{55}{27}\left(\frac{6}{\tilde{k}_o}\right)^{\frac{1}{3}} - \frac{\tilde{k}_1}{2} \text{ and } a_4 = -1 + \frac{40}{81}\left(\frac{6}{\tilde{k}_o}\right)^{\frac{1}{3}} + \frac{\tilde{k}_1}{6} \tag{17}$$

Substitution of these values of coefficients and gathering of terms results in the adjustable parameters as coefficients of independent polynomials of the form

$$y = \left(\frac{6}{\tilde{k}_o}\right)^{\frac{1}{3}} \tilde{K}_o[x] + \tilde{k}_1 \tilde{K}_1[x] + Q\ [x] \tag{18}$$

where

$$\tilde{K}_o = x^{\frac{1}{3}} + \frac{x}{81}\,(40x^3 - 165x^2 + 264x - 220) \tag{19}$$

$$\tilde{K}_1 = \frac{x}{6}\,(x - 1)^3 \tag{20}$$

and

$$Q = 1 - (x - 1)^4 \tag{21}$$

This is the desired two-parameter cube-root polynomial satisfying the specified boundary conditions.

PERMISSIBLE VALUES OF $\tilde{k}_o$ AND $\tilde{k}_1$

Not all combined values of $\tilde{k}_o$ and $\tilde{k}_1$ result in desired shapes. A stringent limitation is to have no inflection points. The range of such values is given by a limiting envelope curve which is derived as follows. Two conditions are to be satisfied, $\frac{d^2y}{dx^2} = 0$ and $\frac{d^3y}{dx^3} = 0$, which result in two simultaneous equations

$$\left(\frac{6}{\tilde{k}_o}\right)^{\frac{1}{3}} \left[-\frac{2}{9}\,x^{-\frac{5}{3}} + \frac{2}{27}\,(80x^2 - 165x + 88)\right] + \tilde{k}_1\,(2x^2 - 3x + 1)$$
$$- 12\,(x - 1) = 0 \tag{22}$$

$$\left(\frac{6}{\tilde{k}_o}\right)^{\frac{1}{3}} \left[\frac{10}{27}\left(x^{-\frac{8}{3}} + 32x - 33\right)\right] + \tilde{k}_1\,(4x - 3) - 24(x - 1) = 0 \tag{23}$$

A solution by the Cramer rule is

$$\left(\frac{6}{\tilde{k}_o}\right)^{\frac{1}{3}} = \frac{162(x-1)^2}{x^{-\frac{8}{3}}(22x^2 - 24x + 5) + 3(30x^2 - 64x + 33)} \tag{24}$$

and

$$\tilde{k}_1 = \frac{-12(x-1)\left[x^{-\frac{8}{3}}(11x + 5) - 5x + 11\right]}{x^{-\frac{8}{3}}(22x^2 - 24x + 5) + 3(30x^2 - 64x + 33)} \tag{25}$$

where x is now an implicit parameter. For the range of values $0 \leq x \leq 1$, the result is the envelope curve of Figure 1. Values of the adjustable parameters $\left(\frac{6}{\tilde{k}_o}\right)^{\frac{1}{3}}$ and $\tilde{k}_1$, which give noninflected curves, are bounded by the axes and the envelope curve.

RELATIVE FULLNESS OF SHAPE

A simple measure of fullness is a prismatic coefficient F

$$F = \int_o^1 y dx \tag{26}$$

which for the cube-root polynomial, Equation (18), becomes

$$F = \frac{1}{27}\left(\frac{6}{\tilde{k}_o}\right)^{\frac{1}{3}} - \frac{\tilde{k}_1}{120} + \frac{4}{5} \tag{27}$$

For constant values of F, straight lines are drawn in Figure 1. Fuller shapes are in the lower right-hand part of the figure.

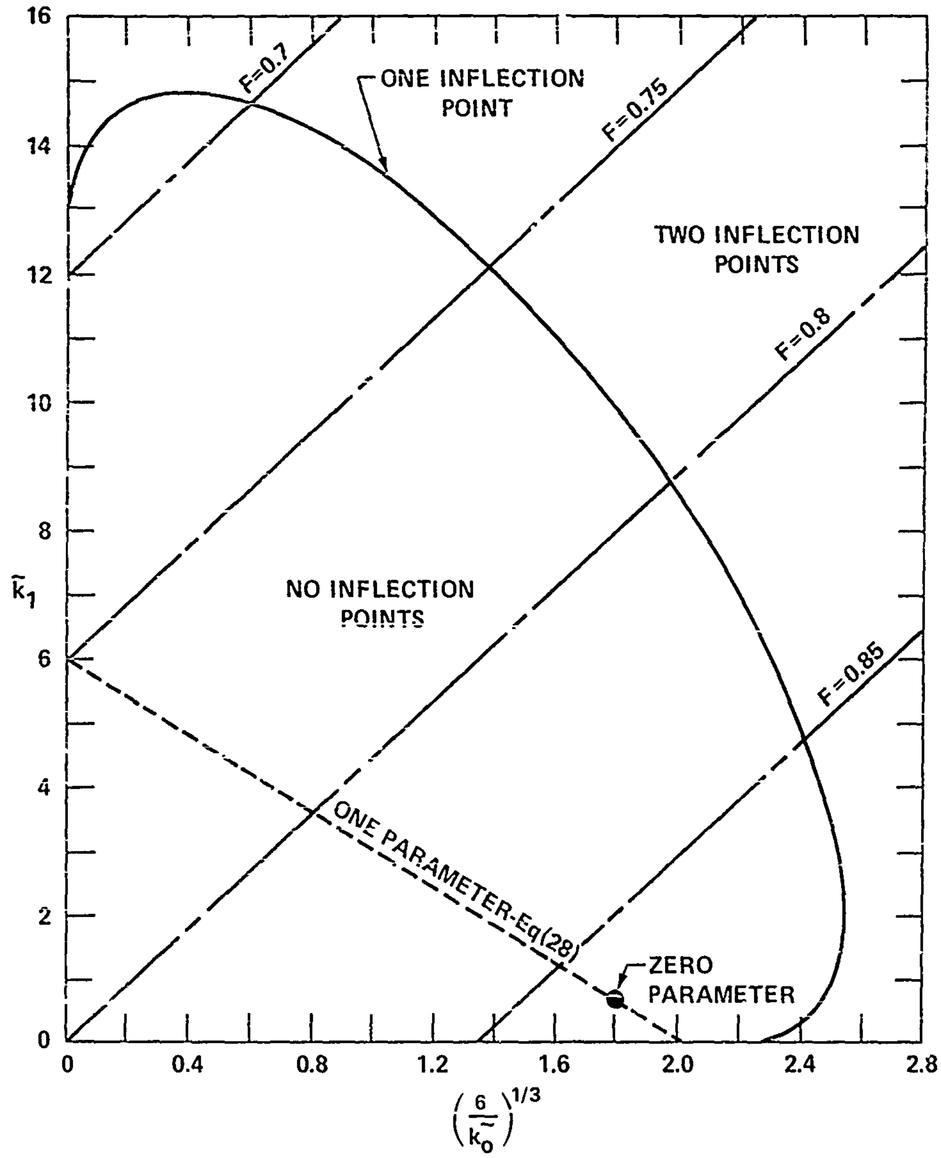

Figure 1 - Inflection-Point Limits for Two-Parameter Cube-Root Polynomials

ONE-PARAMETER CUBE-ROOT POLYNOMIALS

A one-parameter family of cube-root polynomials may also be developed if $\left(\frac{6}{\tilde{k}_o}\right)^{\frac{1}{3}}$, for example, is designated as the only adjustable parameter. The result is a cube-root polynomial, one degree less or a cubic cube-root polynomial. In this case a_4 is zero, and Equation (17) gives

$$\frac{40}{81}\left(\frac{6}{\tilde{k}_o}\right)^{\frac{1}{3}} + \frac{\tilde{k}_1}{6} - 1 = 0 \tag{28}$$

Figure 1 shows the equation. It is to be noted that the permissible values of $\tilde{k}_o$ and $\tilde{k}_1$ for the two-parameter system are much greater than those for the one-parameter system. Substitution of Equation (28) into the two-parameter polynomial, Equation (18), produces the one parameter system

$$y = \left(\frac{6}{\tilde{k}_o}\right)^{\frac{1}{3}} \tilde{K}_o[x] + Q[x] \tag{29}$$

where

$$\tilde{K}_o = x^{\frac{1}{3}} - \frac{x}{9}(5x^2 - 16x + 20) \tag{30}$$

and

$$Q = 1 + (x - 1)^3 \tag{31}$$

A study of the inflection point condition $\frac{d^2y}{dx^2} = 0$ indicates a permissible range of values of $\tilde{k}_o$ given by

$$\frac{27}{16} \leq \left(\frac{6}{\tilde{k}_o}\right)^{\frac{1}{3}} \leq \frac{81}{40} \tag{32}$$

for no inflection points. Figure 2 shows the curves with these limiting values.

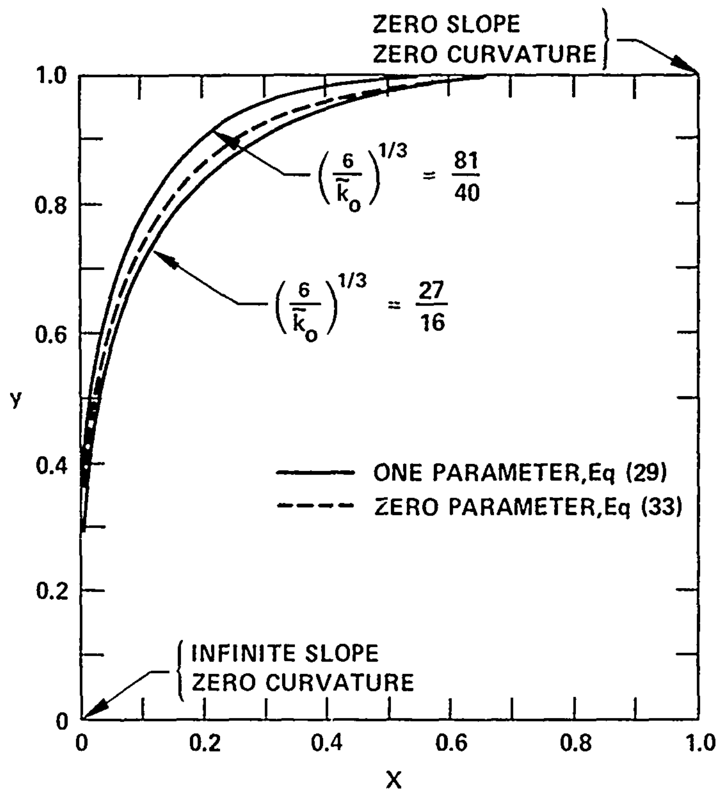

Figure 2 - One- and Zero-Parameter Cube-Root Polynomials

(Normalized Coordinates)

ZERO-PARAMETER CUBE-ROOT POLYNOMIAL

A nonadjustable cube-root polynomial may also be designated where $\tilde{k}_o$ and $\tilde{k}_1$ are not adjustable parameters. In this case a_3 and a_4 are zero, and from Equation (17) it follows that $\left(\frac{6}{\tilde{k}_o}\right)^{\frac{1}{3}} = \frac{9}{5}$ and $\tilde{k}_1 = \frac{2}{3}$; this point is plotted in Figure 1. The cube-root polynomial then reduces to

$$y = \frac{9}{5} x^{\frac{1}{3}} - x + \frac{x^2}{5} \qquad (33)$$

which does not have an inflection point for $x < 1$. A plot of the zero-parameter cube-root polynomial is shown in Figure 2.

FLAT-FACED NOSES

The cube-root polynomial developed here may be used to bridge a flat-faced nose and a parallel middle body as shown in Figure 3. Both two-dimensional and axisymmetric bodies may be accommodated. If D_f is the width or diameter of the flat face, and D is the width or diameter of the parallel middle body, the normalized coordinates are

$$x = \frac{X}{X_n} \tag{34}$$

and

$$y = \frac{2Y - D_f}{D - D_f} \tag{35}$$

where X is longitudinal or axial distance from the flat face

X_n is length of the nose

Y is normal or radial distance from the centerline

The origin of the bridging curve is at the outer edge of the flat face, and the terminal is the junction with the parallel middle body. At both junctions, zero curvature is satisfied.

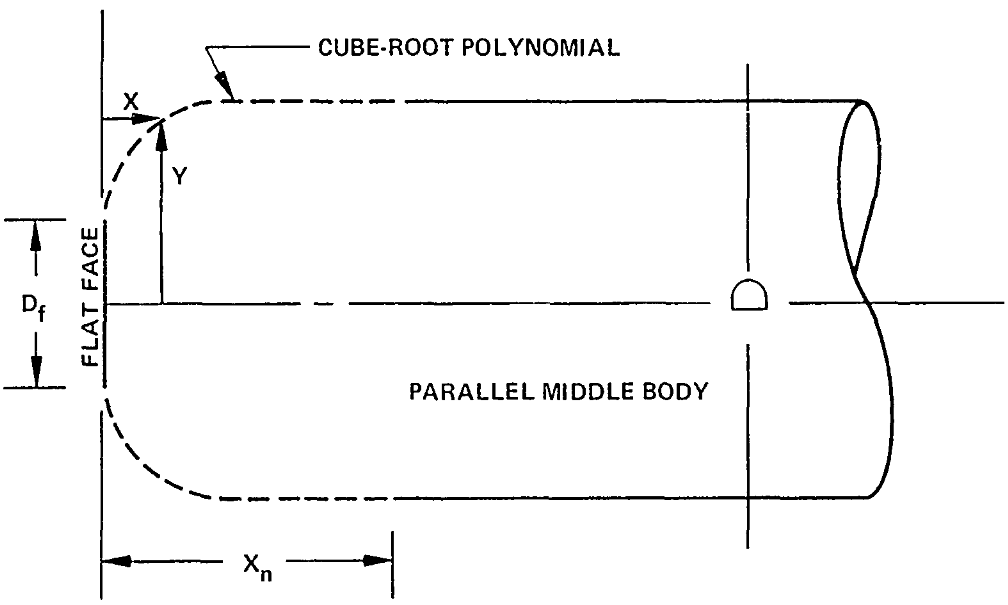

Figure 3 - Geometry of Flat-Face Noses

WALL-SIDED SHIP SECTIONS

The cube-root polynomials developed here may also be used to bridge wall sides and flat bottoms of ship sections as shown in Figure 4. Here the normalized coordinates are given by

$$x = \frac{B - 2Y}{B - B_f} \tag{36}$$

and

$$y = \frac{Z_1 - Z}{Z_1} \tag{37}$$

where Y is the offset from the center plane

B is the breadth of the ship section

B_f is the breadth of the flat bottom

Z is the vertical distance

Z_1 is the vertical height of the bridging curve

The origin is the junction with the wall side, and the terminal is the junction with the bottom. At both junctions, zero curvature is satisfied.

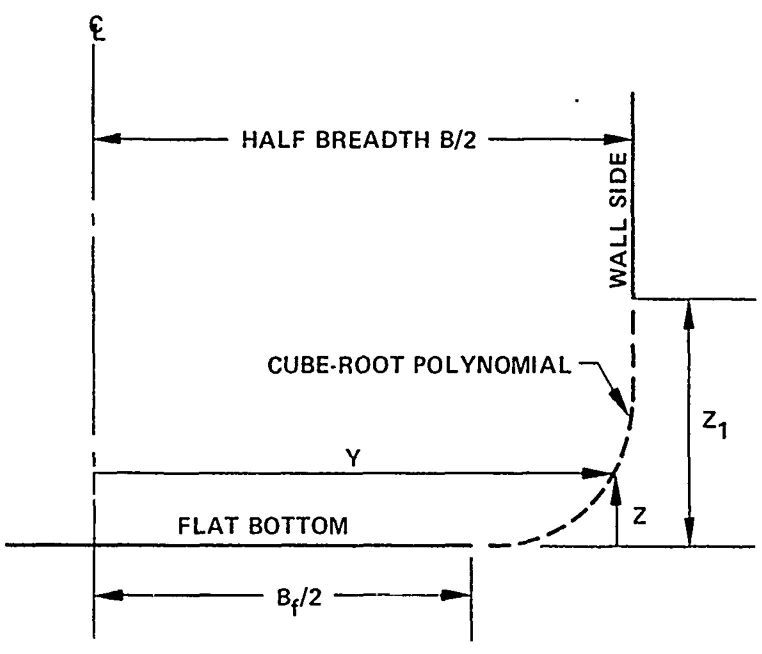

Figure 4 - Geometry of Wall-Sided Ship Sections

Previous efforts[4] to use ordinary polynomials to fit wall sides resulted in approximate expressions with terms to the 200th power. The cube-root polynomial serves the same purpose quite readily in an exact fashion.

[4]Kerwin, J.E., "Polynomial Surface Representation of Arbitrary Ship Forms," Journal of Ship Research, Vol. 4, No. 1, pp. 12-21 (Jun 1960).

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