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PROFILE: Airfoil Geometry Manipulation and Display

User's Guide

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PROFILE

USER'S GUIDE

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1. GENERAL INFORMATION

1.0 Summary

This User's Guide provides user information for program PROFILE, an aerodynamic design utility for manipulating and displaying airfoil coordinates and associated quantities such as local curvature. Conceived in 1982, PROFILE evolved steadily through late 1991 as new capabilities were incorporated. The present manual replaces the November 1984 original and the November 1985 update.

PROFILE's dozen or so "operating modes" are described, along with its input and output data files and its (optional) keyword control file. The theory and implementation details for two of its more complex options are also presented. These are the REFINE option, for smoothing curvature in selected regions while retaining or seeking some specified thickness ratio, and the OPTIMIZE option, which seeks a specified curvature distribution. REFINE uses linear techniques to manipulate ordinates via the finite difference approximation to second derivatives, while OPTIMIZE works directly with curvature using nonlinear least squares methods.

Use of programs QPLOT and BPLOT is also discussed, since all of the plots provided by PROFILE (airfoil coordinates, curvature distributions, and pressure distributions) are produced with the general-purpose QPLOT utility. BPLOT illustrates (again, via QPLOT) the shape functions used by two of PROFILE's options. These three utilities should be distributed as one package.

QPLOT requires the widely-available *CA-DISSPLA*¹ graphics package, which may inhibit some potential users, but PROFILE and BPLOT are readily portable. Adapting the plottable outputs from PROFILE to some other graphics package should be straightforward for those without access to *CA-DISSPLA*. Plots are usually crucial to the effectiveness of PROFILE.

The programs are implemented in FORTRAN 77 with minor enhancements. They were developed on DEC VAX/VMS and SGI IRIS/IRIX systems for the Applied Aerodynamics Branch at NASA Ames Research Center, Moffett Field, California, by staff from the Palo Alto office of Informatics General Corporation (now the Federal Systems Division of Sterling Software, Inc.), under Contract NAS2-11555-307-1. They are in the United States public domain.

Special acknowledgement is due to Robert Kennelly, Ames aero-engineer, who conceived the project of developing a systematic means of manipulating airfoils, provided much of the inspiration during its early years, and produced the QPLOT program as well. The consistent support of Ames's Raymond Hicks is also warmly acknowledged by the authors.

¹ *CA-DISSPLA* is a proprietary product of Computer Associates International, Inc., and is not available from NASA. It may be purchased under license.

1.1 Introduction

Program PROFILE is a utility for computational aerodynamic applications. Originally intended for plotting airfoil coordinates and tabulating derivatives, it has evolved into a more powerful package capable of modifying airfoils in a number of ways. It has thus become a useful design tool. Profiles may be perturbed through interactive application of shape functions, refined by seeking desired second derivative distributions while adjusting thickness ratio, or optimized by seeking target curvature distributions directly.

The simpler options include redistributing the data points in a variety of ways, and renormalizing the coordinates. Four standardized geometry data formats are provided for compatibility with most computational flow codes.

Several of the options must be applied to just a single two-dimensional airfoil section, while the simpler options can handle multiple sections in the same input data file. The more sophisticated options offer "before" and "after" plots of the airfoil, its curvature distribution, and its approximate C_p distribution. Multiple sections may be those of a three dimensional wing, or the elements of a multi-element airfoil (such as a wing with a slat), or simply two or more profiles for comparison. Such sections may appear on the same plot frame or on separate frames, depending on the input control THREEED.

PROFILE provides a cheap and easily-used means of illustrating and refining airfoil geometry data. It should serve as a flexible vehicle for additional capabilities, which airfoil designers are encouraged to incorporate as their needs arise.

1.2 Environment

PROFILE is an interactive program developed on a Digital Equipment Corporation VAX-11/780 under VMS and since moved to a DEC AXP/OpenVMS system. It has also been installed with virtually no changes on Unix-based workstations from Silicon Graphics, Inc. and Sun Microsystems, Inc. It is written in FORTRAN 77, with minor VMS extensions used in certain places where adhering to the strict standard was either out of the question (such as the READONLY keyword on explicit OPEN statements for reading files not owned by the user), or considered too restrictive (as in the case of variable names up to 8 characters, and trailing ! comments). All computations are performed in single precision (32-bit words on current systems).

Plotted results are essential to effective use of PROFILE. However, plotting is invariably installation-specific. This is one reason that PROFILE itself does not perform any graphics—it is more portable that way. The other reason is that some of the plottable data output from one run of PROFILE (specifically, the curvature data) may be reused as input for another run. Instead, advantage has been taken of a general-purpose plot package known as QPLOT, developed under the same contract as PROFILE. QPLOT uses *CA-DISSPLA* (referenced above), and should accompany any distribution of PROFILE. It may be used in preview mode with a

Tektronix-type graphics screen, or its optional PostScript output may be printed or transcribed to other graphics monitors. See Appendix B for more on QPLOT.

A second supplementary program that should accompany distributed copies of PROFILE is known as BPLOT, described in Appendix A. BPLOT produces plots—again, via QPLOT—of the “bump” functions (shape functions) employed by PROFILE in its MODIFY and OPTIMIZE modes.

1.3 Future Directions

An enhanced PROFILE, contemplated at the time of writing but increasingly unlikely in the present budget-restricted NASA environment, would provide for truly interactive graphics as opposed to end-of-run graphics. For instance, in the MODIFY mode, perturbations could be tried, viewed, and perhaps undone and retried, in a single session instead of requiring several runs of PROFILE as at present. The graphics could be fairly crude (given the resolution of typical video display terminals), would probably provide windowing (i.e., enlarging, for the same reason), and could be achieved with a much less bulky graphics package than *CA-DISSPLA*.

Without much effort, PROFILE could be made to go back to its main menu after completing a given mode, rather than having to be rerun for some next manipulation. However, there is some virtue in having access to the multiple intermediate output files that are optionally provided from each run, and these are readily deleted when the desired results are obtained.

Generation of boundary layer displacement thickness distributions is another possibility appropriate to PROFILE, along the same lines as the C_p approximations already provided.

The authors and sponsors of PROFILE encourage users to adapt this tool to suit their needs, in the belief that a sound framework has been provided in the present code for capabilities unforeseen so far. Feedback is welcomed, and conscientious adherence to the standards of modern software engineering is urged upon those designers inclined to perpetuate the programming style (or lack thereof) for which engineers have long been notorious.

2. BASIC INPUT DESCRIPTION

2.0 Input Overview

The basic inputs common to all modes of operation are described here, namely the file of initial coordinates and the optional keyword-type control file.

A few of PROFILE's modes require considerable activity at the keyboard during program execution, although the suggested defaults frequently suffice. Details of such interactive entries are described in the appropriate subsections of Chapter 4.

An input airfoil dataset is required for every run of PROFILE. A separate file containing control inputs may be used to override the default controls. PROFILE prompts for the names of these files. (A few modes require secondary input profiles as well, prompted for once the mode has been entered.)

2.1 Airfoil Data Format

The airfoil dataset may be input in one of four formats, and also may be output in any of the four formats described below. When PROFILE reads a dataset, it automatically determines the format and retains that format for output unless a specific output format is indicated via the optional keyword input *FORMAT* (Section 2.2). Column numbers are unimportant on input—the values are parsed as "tokens" separated by one or more blanks or tabs.

The first format shown is the most common and is known as **STANDARD** or **PROFILE** format.

| | | | |
|-------|-------|---------|-----------------------|
| TITLE | | | <CHARACTER*80> |
| NU | UPPER | SURFACE | <Integer first token> |
| X | | Y | <Two reals> |
| X | | Y | <Two reals> |
| . | . | . | . |
| . | . | . | (May be X/C, Y/C; |
| . | . | . | Xs are increasing.) |
| . | . | . | . |
| NL | LOWER | SURFACE | <Integer first token> |
| X | | Y | <Two reals> |
| X | | Y | <Two reals> |
| . | . | . | . |
| . | . | . | (Xs are increasing.) |
| . | . | . | . |
| . | . | . | . |

The next two formats are wrap-around **CLOCKWISE** and wrap-around **COUNTERCLOCKWISE**, where the coordinates begin at the trailing edge, wrap around the leading edge, and end at the trailing edge. The clockwise case begins with the lower surface, and the counterclockwise case begins with the upper

surface. The format shown below is essentially the same for both cases. NPTS is the total number of points in the dataset.

```

TITLE                <CHARACTER*80>
NPTS                 <Integer first token>
X                   Y                   <Two reals>
X                   Y                   <Two reals>
.                   .                   .           (May be X/C, Y/C;
.                   .                   .           Xs are increasing
.                   .                   .           to the leading edge
.                   .                   .           and then increasing.)
    
```

The fourth format is called **THREE-COLUMN** format. The airfoil is represented in three columns, with the same abscissas for both surfaces in the 1st column and ordinates for the upper and lower surfaces in the 2nd and 3rd columns respectively. Abscissas are increasing as with the standard format. Here NPTS is the number of points on one surface. Further columns may be present in this case only (as for C_p distributions—only the first three columns of the data proper will be read).

```

TITLE                <CHARACTER*80>
NPTS                 <Integer first token>
X                   YU                  YL                  <Three (or more) reals>
X                   YU                  YL
.                   .                   .                   .           (May be X/C, Y/C;
.                   .                   .                   .           Xs are increasing.)
.                   .                   .                   .
.                   .                   .                   .
    
```

FURTHER NOTES:

- With **STANDARD (PROFILE)** format, the lower surface coordinates are optional. Include a zero for NL if no lower surface is present—PROFILE will insert a *symmetric lower surface*. Alternatively, EOF (end-of-file) is equivalent to NL = 0 if there is only one profile in the file.
- If both surfaces are present in the standard format, they must have the *same leading edge point*. The trailing edge points may differ.
- The descriptive first line appears as a *legend*, not a title, on the plots obtainable from the various output files.
- There may be *more than one set of coordinates* in the same file (all formats). PROFILE performs a preliminary scan of the input file (reads to EOF) to count how many profiles are present (but mainly to determine the overall data range for plotting purposes).
- *Multi-element airfoils* may be in any of the four formats, with a set of coordinates for each element. Unless each element is to be represented separately in the plot legend, one title should be included with the first set of coordinates and a blank line should precede any following sets.

2.2 Keyword Control Inputs

Control inputs common to all modes are represented by keywords and values in an *optional* input control file. PROFILE prompts for the name of this control file. If none is present, keyword defaults apply. A keyword description follows, with the default value for each shown in square brackets. The keyword names are italicized to help distinguish them from the keyword values.

Note that synonyms are permitted in some cases. (E.g., **THREE-COLUMN**, **THREE_COLUMN**, **THREECOLUMN** and **TABLE** all have the same effect as values for the *FORMAT* keyword, while *DERIVATIVES* and *CURVATURE* are synonymous keywords.) Note also that several keyword/value pairs may appear on one line, except for the multi-valued keywords *PLTLINE*, *CPSLINE*, *CRVLINE*, and *NOFILE*, which must not appear on a line with other keywords.

| KEYWORD | VALUES | DESCRIPTION |
|----------------|---|--|
| <i>FORMAT</i> | [SAME] PROFILE or STANDARD CLOCKWISE COUNTERCLOCKWISE THREE-COLUMN or THREE_COLUMN or THREECOLUMN or TABLE | One of four formats for output profile(s). May be in standard "PROFILE" format, clockwise or counterclockwise wrap-around format, or three-column format. SAME (the default) means the same format as the input profile. |
| <i>PLTLINE</i> | [DEFAULT] SOLID DASH DOT CHAINDASH CHAINDOT LONGDASH SYMBOLS THICK | Controls line types of curves on profile plots. One value may be included for each curve on the plot. The default is symbols connected by a solid line, with a different symbol type for each successive curve. The first curve typically represents the original profile; the second represents the revised profile. Override the default if lines without symbols are required, or perhaps when plotting multi-element airfoils. |
| <i>CPSLINE</i> | (See <i>PLTLINE</i> above.) | Controls line types on C_p plots as for <i>PLTLINE</i> . |
| <i>CRVLINE</i> | (See <i>PLTLINE</i> above.) | Controls line types on curvature plots as for <i>PLTLINE</i> . |

| | | |
|---|---|--|
| <i>CURVATURE</i> or <i>DERIVATIVES</i> | [NONPARAMETRIC] or [FINITE_DIFFERENCE] SPLINE or PARAMETRIC or WRAPAROUND | Controls calculation of derivatives and curvature. The default treats <i>y</i> as a function of <i>x</i> , and is the only choice appropriate for REFINE mode. The other three keyword values are equivalent, and mean the profile is treated as a single wrap-around curve with both surfaces shown on the plot of the curvature. Specify MAXCURVATURE = 999. and MINCURVATURE = 999. to plot the full range via QPLOT . |
|---|---|--|

NOTE: All derivatives and curvature values in the *.tab, *.plt, *.crv, and *.ypp files are consistent—the calculations are either via parametric splines (*x* and *y* vs. *t* where *t* ~ arc length) or via nonparametric finite differencing. The latter is required for the **REFINE** option because it works with *y*", the second derivative with respect to *x*, not *t*.

| | | |
|--|----------------|--|
| <i>MAXCURVATURE</i> <i>MINCURVATURE</i> | [+5.] [-5.] | Cut-off values for plotting the curvature. Practice shows that ±5. give useful plot scaling by ignoring high values near the leading edge. However, it may well be desired to focus on the leading edge region. |
|--|----------------|--|

| | | |
|---------------|--|--|
| <i>NOFILE</i> | [NONE] DAT PLT TAB CRV YPP CPS SPREAD | Used to suppress any combination of the seven output files. The values correspond to the file name extensions—see the BASIC OUTPUT DESCRIPTION . The default is to produce all of the possible output files. |
|---------------|--|--|

| | | |
|-------------|-------------------------------|--|
| <i>PLOT</i> | [BOTH] ORIGINAL REVISED | Controls plotting of original and revised profiles. The default is to plot both original and revised (if one exists). The *.plt file gives scale plot of coordinates. |
|-------------|-------------------------------|--|

| | | |
|------------------|-----------------------|---|
| <i>PRECISION</i> | [FULL] ENGINEERING | Controls the number of decimal digits in the output *.dat file. The default gives F11.8, or E15.8 if $x \geq 10.0$, and ENGINEERING gives F10.6. |
|------------------|-----------------------|---|

| | | |
|---------------|--|---|
| <i>THREED</i> | [FALSE] or [NO] TRUE or YES | For plotting of multiple sections of a 3D wing. The default is the 2D case, giving all airfoils on the same plot frame. If <i>THREED</i> is TRUE , each of the input sections is plotted on a separate frame. |
| <i>XAXIS</i> | [6.4] | Length of X axis in inches. The default is suited to 8.5 x 11 inch paper in portrait mode. |
| <i>XMIN</i> | [Minima and maxima of the input abscissas and ordinates over all of the profiles found in the input file.] | Minimum abscissa of the plot window. |
| <i>XMAX</i> | | Maximum abscissa of the plot window. |
| <i>YMIN</i> | | Minimum ordinate of the plot window. |
| <i>YMAX</i> | | Maximum ordinate of the plot window. |

A sample input control file follows. Note that keywords and values may be separated by blanks, commas, colons, = signs, or tabs. As mentioned above, keywords with more than one value should appear on a separate line. Keywords (and text-type values) may be truncated to any set of unambiguous leading characters. Upper and lower case are unimportant. Remember that the control file is entirely optional.

```

FORMAT = THREE-COLUMN   PLOT both   THREED: NO
mincurvature = -6.   maxcurv: 6.
XAXIS = 16.3   Xmin = 0.   Xmax: 0.4
PLTLINE = SOLID, DASH
CPSLINE = SOLID, DOT
NOFILE: ypp spread

```


3. BASIC OUTPUT DESCRIPTION

3.0 Output Overview

PROFILE produces up to seven different output files. The *NOFILE* keyword in the input control file (previous section) can be used to suppress any unwanted files. All the output files are named with a common identifier chosen by the user, each with a different extension. The seven possible output files are listed below, using the default identifier *profile*.

| | |
|-----------------------------|---|
| <code>profile.dat</code> | Revised airfoil data file (requested format). |
| <code>profile.plt</code> | Plottable airfoil data file (QPLOT format). |
| <code>profile.tab</code> | Tabulations and diagnostics, for printing. |
| <code>profile.crv</code> | Curvature data file (QPLOT format). |
| <code>profile.ypp</code> | Second derivatives file (PROFILE format). |
| <code>profile.cps</code> | Computed C_p file (QPLOT format). |
| <code>profile.spread</code> | Spreadsheet-compatible tabulation, with more columns than can fit in the printable <code>*.tab</code> file. |

Each output file is described in more detail in the following sections.

3.1 Revised Airfoil Coordinates (*.dat)

The `<identifier>.dat` file contains the airfoil coordinates that have been revised in some way. The file can be in any of the four formats described in the **BASIC INPUT DESCRIPTION** and can be used in subsequent runs of PROFILE.

3.2 Plottable Airfoil Data (*.plt)

The `<identifier>.plt` file contains airfoil coordinates in the plottable form handled by QPLOT (Appendix B). Normally, one plot frame is produced (but see *THREED* keyword usage below). A plot of one single-element airfoil may contain up to two curves—normally the original input coordinates overlaid with the revised coordinates. The keyword *PLOT* in the input control file determines which of the curves are plotted (i.e., original, revised, or both). Mode 2 (normalize or denormalize) is an exception: only the revised coordinates are plotted.

The plot may contain more than two curves (up to 20) in the case of a multi-element airfoil, or when several airfoils are to be superimposed for comparison. If multiple sections of a wing are indicated via the *THREED* keyword, these are plotted separately on multiple frames.

A prompt is issued for a title which will be centered at the top of the plot. This title will also appear as the legend entry in the revised airfoil dataset and is used to identify any revised data in the other output files. An optional subtitle, also prompted for, will be centered under the title.

A variety of line types may be specified in the input control file, using the input keyword *PLTLINE*. (See **BASIC INPUT DESCRIPTION** for details on line types, particularly for the multi-element case.) A legend centered above the axes identifies the curve(s).

3.3 Printable Tabulations (*.tab)

The <identifier>.tab file contains tabulations of the profile coordinates as well as the values of 1st and 2nd derivatives and curvature at each point. When the profile has not been revised, tabulations for only the original profile are printed, otherwise tabulations for both the original and revised profile are included. Details of the iterative computations are also printed here if **REFINE** or **OPTIMIZE** mode is being used. A record of the shape functions selected is included if **MODIFY** mode is chosen. Other statistics written to the *.tab file include the names of the input control and airfoil geometry files, the identifier chosen for the output files, the mode of operation selected, and the number of profiles found in the geometry file. Appendix E contains numerous examples of the *.tab file.

3.4 Spreadsheet-Compatible Tabulations (*.spread)

The <identifier>.spread file contains an expanded tabulation suitable for reading by a spreadsheet program, with columns separated by tabs. The *upper and lower surface abscissas must match* for this tabulation—use **REDISTRIBUTE** mode first if necessary.

The columns appear in the following order, where x and y may or may not be normalized, but probably should be for the derivatives and curvature to be readily interpreted:

x y_U y_L Camber Semithickness y_U' y_L' y_U'' y_L'' K_U K_L

Here, camber refers to the mean-line (average of y_U and y_L) and semithickness refers to half the difference of y_U and y_L , at the matching abscissas.

3.5 Curvature Data (*.crv)

The <identifier>.crv file contains abscissas and curvature values in the form expected by QPLOT. Upper and lower surface curvatures will be plotted on separate frames, with up to three curves on a frame. Original curvatures are included for mode 0, revised curvatures for modes 1 and 2, and original and revised for most other modes, with mode 6 including target curvatures as well. For details of target curvature distributions, see the **OPTIMIZE** mode in Chapter 4.

Line types may be specified with the input keyword *CRVLINE*. By default, the curvature values plotted will range between -5. and +5., but these limits can be redefined using the input keywords *MINCURVATURE* and *MAXCURVATURE*. (All values are written to the *.crv file; it is QPLOT that suppresses those outside the chosen range during plotting.) The curvature data can also be edited and reused as input when running PROFILE in **OPTIMIZE** mode.

3.6 Second Derivatives (*.ypp)

The <identifier>.ypp file is a table of second derivatives (of y vs. x) at each point on the airfoil in standard PROFILE format. When the profile has not been revised (MODE=0), derivatives for the original profile will be in the file, otherwise only derivatives for the revised profile are included. This avoids mistakes when the file is reused (probably after editing) as an input file for PROFILE's **REFINE** mode. In this mode, the Y'' values are used to act as constraints on the curvature. See section 4.6 for more on the reuse of second derivative values.

3.7 Cp Distributions (*.cps)

The <identifier>.cps file contains calculated surface pressure coefficients in QPLOT format. C_p s for both the original and revised airfoil (if any) are plotted on the same frame. Line type may be specified using the input keyword **CPSLINE**.

The C_p s are calculated by an algorithm due to Prof. Ilan Kroo (Stanford University Aero/Astro Department). The version installed at the time of writing models the airfoil with discrete sources and vortices on the X-axis at 1/4-panel locations. The thickness effect is computed from linearized theory with Riegel's correction. A dense square system is solved for the vortex strengths at each ordinate, where the right-hand-side is defined by the flow tangency conditions. The condition number of the matrix is estimated and the user is warned of large values, but the computation proceeds.

C_p s for the panel mid-points are derived from this solution, with corrections for the specified free stream Mach number. Initial experience shows they can be remarkably close to those predicted by full-potential codes in some cases, but significantly different in others. Occasionally, trends seem to be predicted in the wrong direction. Thus a systematic study of the behavior of this C_p calculation is still needed.

The present implementation requires that the abscissas for the upper and lower surfaces be the same—a minor inconvenience given the **REDISTRIBUTE** option of PROFILE. The GETCPS subroutine is self-contained enough for it to be easily reused in other applications.

4. MODES OF OPERATION

Although there are a dozen or so modes of operation available in PROFILE, all of them require the same basic inputs (a file of coordinates, and an input control file when overriding defaults), and nearly all of the output options are available for each mode. This chapter details the different ways the modes manipulate the coordinates. Some operations are much more elaborate than others.

PROFILE can be run in only one mode at a time, selected from a menu. It may be necessary to run the program several times for one task, depending on the operations desired, with the output from one run used as the input for the next.

4.0 Mode 0: Tabulate and/or Plot (No Modifications)

This mode does nothing to modify the input coordinates, with the possible exception of writing the coordinates to disk in a format different from the input format. Select Mode 0 simply to plot an airfoil and/or its curvature distributions, or to generate the second derivatives needed for reuse (after editing) in a **REFINE** mode run, or to generate curvature values to be used similarly in **OPTIMIZE** mode.

4.1 Mode 1: Rectify Leading Edge Definition

This mode is used to "rectify" the leading edge definition in cases where the current leading edge is not the most forward point on the airfoil. For example, some NACA airfoils have negative abscissas on the upper surface and leading edge defined as (0., 0.). This causes the upper surface to be multi-valued, creating problems with spline fitting and the addition of shape functions. Mode 1 finds the minimum abscissa on the airfoil and uses this as the leading edge point common to both surfaces, redistributing the upper and lower surface points accordingly. The result is an airfoil with a "true" leading edge and monotonically increasing abscissas.

In addition, the profile may be shifted vertically by responding to a prompt for a new leading edge ordinate. All the ordinates are then shifted by the difference between this new leading edge ordinate and the current leading edge ordinate. An obvious choice would be to place the new "true" leading edge at (0., 0.), but the profile may be shifted by any value.

4.2 Mode 2: Normalize/Denormalize

This mode renormalizes airfoil coordinates. PROFILE determines the chord of the input airfoil and gives an option of normalizing the coordinates either by this chord (resulting in an airfoil with a chord of 1.) or by some other value. If some other positive value is entered, a prompt will be issued for the coordinates of the leading edge point as well. If the chord value entered is negative, the (presumably

normalized) profile will be denormalized by the absolute value of that chord and new leading edge coordinates which are prompted for. (Note that a simple vertical shift could be achieved with this mode if desired, but **RECTIFY** mode is more direct.)

The following formulas are used, where "X" is either x or y:

$$\text{Normalizing: } X_{\text{new}} = (X_{\text{old}} - X_{\text{old leading edge}}) / \text{chord}_{\text{old}}$$

$$\text{Denormalizing: } X_{\text{new}} = X_{\text{new leading edge}} + X_{\text{old}} * \text{chord}_{\text{new}}$$

Care must be taken when more than one airfoil is processed at a time, as with a 3D case or a multi-element airfoil. The same renormalization is applied to all airfoils in the input dataset. (The chord calculated by PROFILE is from the overall data range, which the program determines from a preliminary scan followed by a rewind of the file. This would be appropriate for an airfoil/slat combination, say.)

4.3 Mode 3: Redistribute Airfoil Coordinates

This mode redistributes the airfoil abscissas in one of several ways, from the menu shown below. Either upper or lower surface or both surfaces may be manipulated. Splines are used to fit the given profile and derive new ordinates. If the leading edge is to be considered "sharp", the surfaces are treated as two distinct curves, permitting use of conventional natural cubic splines. If the leading edge is "blunt" or rounded, the profile is treated as a single curve, requiring parametric cubic splines. In this case, if the trailing edge is also rounded, the curve is closed smoothly. Otherwise, the trailing edge may be sharp or open, with no continuity sought there.

A common requirement is to impose certain abscissas such as nicely rounded ones not easily generated analytically. PROFILE provides for reusing the first column of an input file containing such desired abscissas. If only one surface worth of abscissas is found, that set may be reused for the lower surface.

Where abscissas are generated as opposed to being read, the user is prompted for the number of such points. Half a dozen standard distributions are provided, including an extremely precise form of the Vinokur distribution. The points in these cases may be distributed along the arc (t) if specified. Such arc-based redistributions use a monotonic local spline for x vs. t to avoid possible excursions at the leading edge; y vs. t is splined conventionally. A piecewise linear option is also provided, for wedge-type airfoils.

Details of the redistribution menu follow. All but option -1 may be with respect to either x or arc-length. Option 5, applied to arc length, is probably the best choice for typical airfoils: with the suggested weights of 0.04, 0.0, 0.3, and 0.66, it tends to avoid the somewhat-larger-than-desirable interior increments which can detract from the Vinokur distribution. See Appendix D for some illustrations of options 1 - 5.

| MENU ITEM | DESCRIPTION |
|-----------|--|
| -1 | The new abscissas are to be read from a file in standard PROFILE format. If ordinates are present, they will be ignored. (They need not be present.) The X data range must be identical to that of the profile being manipulated. The name of this file is prompted for. |
| 0 | Uniform spacing. |
| 1 | Sinusoidal bunching towards the leading edge. |
| 2 | Sinusoidal bunching towards both the leading and trailing edges. |
| 3 | Sinusoidal bunching around an internal point. |
| 4 | Vinokur distribution (first and last increments specified). |
| 5 | Linear + quadratic + sine + cosine combination. |

4.4 Mode 4: Modify Airfoil Using Perturbing Functions

MODIFY mode allows the user to perturb each of the airfoil surfaces by applying shape functions interactively, according to the following menu. The airfoil x coordinates should be normalized.

| | | | |
|-----|-------------|---|---------------------------|
| 1: | SCALE | $\delta y = (P1 - 1) y$ | i.e., $y \leftarrow P1 y$ |
| 2: | RAMP | $\delta y = P1 x$ | |
| 3: | FLAP | $\delta y = -(x - P1) \tan P2$ | $x > P1$ |
| 4: | SLAT | $\delta y = -(P1 - x) \tan P2$ | $x < P1$ |
| 5: | TRAILING | $\delta y = x^{P1}$ | |
| 6: | DROOP | $\delta y = (1 - x) e^{-P1 x}$ | |
| 7: | LEADING | $\delta y = (1 - x)^{P1}$ | |
| 8: | EXPONENTIAL | $\delta y = x^P (1 - x) e^{-P2 x} / P1^P (1 - P1) e^{-P2 P1}$ | $P = P(P1)$ |
| 9: | SINE | $\delta y = \sin^{P2}(\pi x^{\log 0.5 / \log P1})$ (unsymmetric about $x = 0.5$) | |
| 10: | SINF | Flipped form of SINE (left & right halves swapped) | |
| 11: | SIN1 | Symmetric form of SINE (left half) | |
| 12: | SIN2 | Symmetric form of SINE (right half) | |
| 13: | COSL | $\delta y = 1/4$ cosine, peak at left; $P1 =$ power | |
| 14: | COSR | $\delta y = 1/4$ cosine, peak at right; $P1 =$ power | |
| 15: | LCOS | $\delta y = 1 - 1/4$ cosine, peak at left; $P1 =$ power | |
| 16: | RCOS | $\delta y = 1 - 1/4$ cosine, peak at right; $P1 =$ power | |
| 17: | WAGNER | $\delta y =$ Wagner function; $P1 =$ order of requested term | |

These are the Hicks-Henne shape functions plus a few additions, long used in various automated design-by-optimization applications, but also suited to application by "hand" via PROFILE's **MODIFY** mode. Each airfoil surface may be perturbed independently with as many shape functions as desired. For instance, a thick trailing edge might be closed by perturbing each surface with a **TRAILING** function, using a **POWER** of 5.0 and **MULTIPLIERS** of \pm half the edge thickness. An option to start over is provided in case of error. The selections may be made by name or number, and each shape function's parameters (**P1**, **P2**, ...) are prompted for by name (**CENTER**, **WIDTH**, **MULTIPLIER**, etc.). The selected shape functions and their parameters are logged in the *.tab file, which may be printed for future reference.

The Wagner functions [5] are included here for consistency with the underlying **BEVAL** subroutine used to evaluate all airfoil-related shape functions. See **OPTIMIZE** mode for the Wagner function definitions, and **SMOOTH** mode for their use not as perturbing functions but as smoothing functions combined in the linear least squares sense. This menu of shape functions is also employed for the chordwise weighting of the implicit and explicit smoothing schemes offered by **SMOOTH** mode as alternatives to fitting of Wagner functions.

See Appendix C for illustrations of all of the nontrivial shape functions.

4.5 Mode 5: Refine Airfoil by Manipulating Y''

4.5.1 Motivation and Analysis

The REFINE option that is now part of PROFILE arose from a requirement to adjust the thickness/chord ratio of an airfoil which had been produced by the design-by-optimization program FLO6QNM [4]. Simple scaling of all of the ordinates is known to cause loss of some of the properties that have been laboriously achieved through the optimization process. The curvature in the leading edge region, and perhaps the trailing edge region, plays a significant role in the flow characteristics, so a technique was sought which would retain the original curvature distribution as much as possible while producing a desired thickness.

Curvature κ is defined in terms of derivatives y' and y'' as:

$$\kappa = \frac{y''}{(1+y'^2)^{3/2}} \quad (4.5.1)$$

The motivation for the method is that, if y' is small, then curvature κ is very like second derivative y'' . Now y'' can be represented as a finite difference expression which is a linear combination of ordinates y :

$$y'' = \frac{2(\delta x_i y_{i-1} - (\delta x_{i-1} + \delta x_i) y_i + \delta x_{i-1} y_{i+1})}{\delta x_{i-1} \delta x_i (\delta x_{i-1} + \delta x_i)} \quad (4.5.2)$$

Reading Eq. 4.5.2 the other way around suggests a set of simultaneous equations in the *unknown* ordinates y_i with *desired* values of the second derivative (and hence, approximately, the curvature) on the right hand sides. Furthermore, airfoil thickness can be modified by some sort of scaling of the original ordinates. This suggests an additional set of equations. Thus an overdetermined system of linear equations for the ordinates can be set up, the optimal solution of which tends to satisfy the combined requirements involving thickness and curvature.

The basic idea of posing the problem as a linear least squares one proves to be more powerful than was initially envisioned, as will be explained. But first, a look at the system that is set up and solved for n points defining one surface:

$$z_i = \text{scale}_i y_i \quad i = 2:n-1 \quad (4.5.3)$$

$$z_i'' = y_i'' \quad i = 2:n-1 \quad (4.5.4)$$

where z represents the revised form of ordinates y , and scale is the (normally nonlinear) distribution of scale factors which yields the specified thickness/chord ratio in an iteration to be described below.

Note that end points $i=1$ and $i=n$ are omitted because the central difference formula does not apply there. This is not a problem, since the values for z_1 and z_n must equal $\text{scale}_1 z_1$ and $\text{scale}_n z_n$ —not just approximately—in order that the two surfaces retain their common leading edge (and possibly trailing edge) point.

The system shown as Eq. 4.5.5 is of order $2(n-2) \times n-2$, and is very sparse since the upper half is strictly diagonal and the lower half is tridiagonal. The two terms

b in the right hand side represent the desired values of y'' for $i=2$ and $i=n-1$, adjusted in the usual way by the appropriate multiples of the known values for y at $i=1$ and $i=n$. The sy terms represent $scale_i y_i$.

$$\begin{array}{rcl}
 i=2 & \longrightarrow & \begin{array}{|c|c|c|} \hline x & |z| & |sy| \\ \hline x & |z| & |sy| \\ \hline x & |z| & |sy| \\ \hline . & |.| & |.| \\ \hline . & |.| & |.| \\ \hline . & |.| & |.| \\ \hline & x & |z| & |sy| \\ \hline & x & |z| & |sy| \\ \hline \end{array} \\
 i=n-2 & \longrightarrow & \\
 i=2 & \longrightarrow & \begin{array}{|c|c|c|} \hline xx & & \approx & |b| \\ \hline xxx & & & |y''| \\ \hline xxx & & & |y''| \\ \hline \dots & & & |.| \\ \hline \dots & & & |.| \\ \hline \dots & & & |.| \\ \hline & xxx & & |y''| \\ \hline & xx & & |b| \\ \hline \end{array} \\
 i=n-2 & \longrightarrow &
 \end{array} \tag{4.5.5}$$

4.5.2 Weighting the Y'' Equations

Since values of y'' tend to be considerably larger than values of y (particularly near the leading and trailing edges), the two halves of Eq. 4.5.5 require equilibrating in some sense. This is achieved by applying multiplicative weights less than unity to the lower half, so that Eq. 4.5.4 becomes

$$wt_i z_i'' = wt_i y_i'' \quad i = 2:n-1 \tag{4.5.6}$$

Furthermore, nonuniform weighting of the y'' values is advisable, just as nonuniform scaling of the y values is necessary, but for different reasons. In Eq. 4.5.3, $scale_i$ must vary from a value of 1.0 at leading and trailing edges to that factor at the point of maximum thickness which gives the desired thickness. In the case of the second derivative weights, smooth variation over an order of magnitude has been found to give best results: typically 0.004 at leading and trailing edges up to 0.04 at some interior point (yet to be specified). (This sort of nonlinearity reflects to some extent the fact that y'' is much smaller in magnitude in the mid-section than it is fore and aft—several orders of magnitude, typically. The goal is to retain the curvature as much as possible towards the extremes, so the outer equations of Eq. 4.5.6 still tend to dominate in terms of residual over the inner equations.) The weighting prevents the residuals of Eq. 4.5.3 from being swamped by those of Eq. 4.5.4.

4.5.3 Smoothing the Y'' Right-Hand-Side Values

Selection of the point with maximum weight cannot be described until an unanticipated benefit of this computation is explained. The reader may be surprised

if he plots a few typical curvature distributions: they can be remarkably spiky and far from smooth. It makes little sense to strive to retain these spiky distributions. Smoothing out the y'' values used on the right-hand-side of Eq. 4.5.6 is highly desirable. We now see the aptness of the term **REFINE**: we have a means of tailoring the y'' distribution (and hence the curvature) to any reasonable, smooth, shape we choose. Since smoothness and general shape are more fundamental than absolute values here, it does not matter that all equations in the overdetermined system cannot be solved exactly. Moreover (and this answers any objection that y' is *not* negligible in the fore and aft regions of most interest), it does not matter that we are working with y'' rather than curvature κ . For if the right-hand-side values used in Eq. 4.5.6 are related to, or varied systematically from, the original y'' values, and the revised values z for ordinates y bear some relationship to the original y values (as they do by construction), then the first derivatives of the z values, and hence the revised curvature values, cannot help but bear some relationship to the original values—smoothed out in the qualitative way that is now seen to be desirable.

4.5.4 Nonlinear Weights and Scales

Returning to the question of where to choose the peak weight for the y'' values, the answer is that point where some spike or unwanted bump in the original curvature distribution showed up. We have a means of zeroing in on the offending features of the distribution (not necessarily all in the same run, though!).

Thus the kind of nonlinearity sought (for both the weights and the scales) involves known values at the end points and a known value at a known interior point—the center of some glitch in a region of the curvature in the case of the weights, or the abscissa where the airfoil thickness is greatest in the case of the scale factors. A function with the necessary properties is given by

$$P_3 \sin^{P_2}(\pi x^{\log 0.5 / \log P_1}) \quad (4.5.7)$$

where

- P1 locates the peak of the modified sine shape in the desired place;
- P2 is a "width" parameter, where 2.0, 3.0, or 3.5, say, give more and more "peaky" distributions, while 1.0, 0.5, ... give broader distributions; and
- P3 is a multiplier to alter the peak value, which is 1.0 for any P1 and P2.

The scale factors of Eq. 4.5.3 require further explanation. If the equation for the point where maximum thickness occurs were solved exactly, it can be shown that the desired thickness would be obtained by using

$$P_3 = 1 - \langle \text{desired thickness} \rangle / \langle \text{original thickness} \rangle$$

and also using $1 - P_3 \sin \dots$ rather than $P_3 \sin \dots$. Note that this scaling is applied to either surface or to both, since $s(y_U - y_L) = s y_U - s y_L$ in the case of both surfaces.

However, none of the equations of the overdetermined system is solved exactly. This means an iteration is necessary, whereby the $\langle \text{desired thickness} \rangle$

above is treated as a target which is adjusted away from the true desired thickness until a match is obtained to within some suitably small tolerance. The algorithm for adjusting the "target" involves two "calibration" computations, after which linear interpolation between the two most recent estimates suffices till convergence. An oscillation may be observed between two abscissas showing maximum thickness if the thickness calculation is confined to the original, discrete, abscissas. This tends to slow the convergence, but should not be a problem. (More continuous computation of thickness using a spline on one surface must be used if the two surfaces are not defined at the same abscissas. However, the present implementation switches to the more correct calculation only if it detects different sets of abscissas.)

4.5.5 *Setting Up the Target y'' Values*

Preparation of the target y'' values also requires explanation. This has been made as convenient as possible. If the curvature distributions are already smooth and about as good as the user knows how to ask for, then **REFINE** can compute and use these with no other inputs.

Alternatively, some single region at a time may be targeted for smoothing simply by responding to prompts for a constant value of y'' over some x range. This works well for spikes, or broader bumps, in the mid-section curvature, and can also be handy for constraining curvature away from zero, where the airfoil may be excessively flat or reflexed. It can also work in noisy regions near the leading or trailing edges, since constant y'' (which tends to lead to smooth y and hence y') can still lead to smoothly varying curvature as required. To repeat an earlier statement: it does not matter that we are constraining y'' rather than curvature.

More generally, **REFINE** has the option of reading a table of y'' values so that more than one unsatisfactory region can be refined in a single run. This table is prepared in exactly the same format as for the airfoil itself, and may start out as the table saved by an earlier run of **PROFILE**. The table does not have to be complete: linear interpolation is done for abscissas in the table range (meaning chunks can be edited out where linear variation of y'' is considered acceptable), while the original y'' values are used for abscissas outside the table range. This kind of tailoring of the second derivative targets may take practice to get a feel for what is achievable and what is not. It is certainly flexible, but the user should keep in mind the simpler mechanism for "zapping" isolated spikes or bumps in the curvature described previously.

Note: For the leading edge region, it can be helpful to plot both y'' and κ on log-log axes. The closer to the extreme leading edge ($x/c < 1\%$, say), the more one needs help from the κ plot when preparing the target y'' distribution.

4.5.6 *Solution of the Overdetermined System:*

While the system set up and solved can be thought of as two groups of constraints—one on ordinates, one on second derivatives—it is treated here as an ordinary overdetermined system of equations with no constraints in the linear programming sense. In the original implementation, no attempt was made to take advantage of the sparsity of Eq. 4.5.5. The simplicity of a good direct method for

dense systems, using the QR factorization [6] as in subroutine HDESOL, was preferred to existing alternatives for sparse systems that were likely to be iterative.

However, this meant a lot of storage for the $2m \times m$ matrix ($m = n-2$), and a lot of computation for typical values of m — a computation that is usually iterated 3-5 times till the desired thickness is achieved. (The storage requirement was about $300 \times 150 = 45,000$ words for up to 150 points per surface to be handled, while the CPU time per iteration of the refinement calculation (both surfaces refined) was measured at about 16 seconds on a VAX-11/780 for the typical value of 72 points per surface.)

A specialized scheme has therefore been implemented for this diagonal-plus-tridiagonal structure. Subroutine DTDLSQ still forms the QR factorization, but much more efficiently than the general-purpose HDESOL. (The coding for use of HDESOL has been left in the source for REFINE, commented out, as an aid to understanding the set-up of the overdetermined system.) The above storage requirement has been reduced to $4 * 150 = 600$ words, while the CPU time per refinement iteration has become about 0.8 seconds on the -11/780 (both surfaces, 72 points per surface).

Note that working with the QR factorization [6] of this matrix A is preferable to setting up and solving the often-seen "Normal Equations" (involving $A^T A$). The latter method requires double the precision (word length) to give an accuracy comparable to that of the single-precision computation used here.

4.5.7 *Some Further Notes on Usage*

The available before-and-after plots of curvature, plus the tabulations, should help the user to decide how to vary some of the interactively-entered inputs. It may take several tries to achieve acceptable results. Sometimes one should use REFINE on the results of the last REFINE application; in other cases, it may be better to discard a result and back up for a retry.

Another point to remember is that the default range for the curvature plots is intended for a good presentation of the mid-section by suppressing the handful of large values that appear near the leading edge and possibly trailing edge. The user may not want to ignore these larger values: plotting them either by switching to log-log axes as mentioned above and/or by enlarging the values of PROFILE's control keywords *MINCURVATURE* and *MAXCURVATURE* is advisable, along with observing them in the tabulation.

Note that finite differencing is used for estimating y' and y'' , and hence curvature, rather than the analytic derivatives that splines can provide. The experience of the authors is that interpolating splines tend to produce surprisingly wavy distributions for the higher derivatives, even for "good" airfoils. The sign of y'' can be very sensitive to small changes. Finite differences, on the other hand, exhibit steadier behavior. More importantly, since the essence of the REFINE algorithm is to use a central difference expression for y'' to define the lower half of the left-hand-side matrix of Eq. 4.5.5, consistency demands that the right-hand-side terms also be derived using central differences. Thus PROFILE eschews splines for these computations, though it does use them for redistributing data points.

If the airfoil is defined on too fine a mesh, using the traditional 2F10.6 format, zeros can easily show up for the y'' estimates near the leading edge where they are clearly not reasonable. This is due to catastrophic cancellation in the presence of too few significant digits. Going to, say, E15.6, helps superficially, but makes little sense because airfoils cannot be constructed to one part in a million. The moral? Avoid excessively fine airfoil geometries: 192 points in the range [0., 1.] is too many if finite difference techniques are being employed.

4.5.8 Summary of Interactive Inputs Used in REFINE Mode

Short descriptions of the quantities for which REFINE prompts the user are given below. All have defaults where possible, as indicated by <CR> (Carriage Return). The user is urged to experiment with various combinations till some sort of feel for cause and effect is attained. However, the defaults frequently suffice.

- **Desired % thickness:** <CR> retains present thickness.
- **Width param. for y :** Affects the nonuniform scaling applied to the ordinates (both surfaces). The default is 2.0. Larger (3.0–4.0) tends to retain leading/trailing edge shape more; 1.0 would constrain fore and aft less.
- **Input y'' table:** <CR> means there is none, else the file name is entered. This file should be in the same "PROFILE" format as the airfoil coordinates. It can cover any range of abscissas. (Linear interpolation is used.) It may be an edited version of the file from a previous run of PROFILE, or it may be much cruder.

WARNING: If you delete points as you smooth out this distribution, it is easy to forget to update the integer number of points at the beginning of the data for each surface. Incorrect counts here can lead to obscure errors.

- **Constant y'' value:** <CR> means no such constraint; retain existing curvature values as much as possible. Otherwise, a value of y'' entered will be sought in the abscissa range that is prompted for next.
- **Corresp. x range:** Enter low and high x values on the same line. Allow for the fact that strict inequalities are used when the program tests for being within this range. E.g., enter .39 .61 or .39,.61 if you intend the constraint to apply over [0.4, 0.6].
- **Width param. for y'' :** Default is 3.0. Affects nonuniform weighting of the equations representing second derivative constraints in the over-determined system being solved. Since the actual values of the second derivatives being sought also act in a weighting sense, effects of this variable are not easy to predict. Values of 2.0 or 1.0 should tend to let y'' change more.
- **X for peak y'' weight:** Default is 0.5. The absolute values of y'' are so much bigger than those of y that they all need to be scaled down in the system being solved. If you are trying to flatten the curvature plot in some region, then pick the center of the region for this input. Otherwise, use the mid-chord value.

- **Y" weights, X/C = 0, 1:** Default is 0.004. See next.
- **Peak y" weight:** Default is 0.04. These provide for the fact that the absolute values of y" are typically smaller in the midsection than near the leading/trailing edges, so they should be weighted more, especially in view of the fact that any y" constraints applied are typically in the midsection. See above.

4.6 Mode 6: Optimize Airfoil by Manipulating Curvature

4.6.1 Motivation and Analysis:

The **OPTIMIZE** option incorporated in PROFILE is a natural generalization of the ideas embodied in the **REFINE** option. This mode of perturbing an airfoil works directly with the curvature distribution rather than the second derivatives. The price paid is that linear techniques can no longer be employed. Nonlinear optimization is typically much more expensive in terms of CPU time. On the other hand, **OPTIMIZE** mode offers a design method that is much cheaper than working with pressure distributions, which normally involve a flow field solution for each evaluation of the objective function being minimized. The hope is that at least some of the work it takes to optimize airfoils can be done on a modest scale by tailoring the curvature distribution first.

The implementation is analogous to that of optimizing flow codes such as FLO6QNM [4]: set up some target distribution and seek to match it as well as possible in the least squares sense by applying appropriate shape functions or "bumps." As is true with flow optimization, constraints of some kind are almost essential. Here, it is most likely to be the maximum thickness that has to be constrained somehow. Given that the minimization algorithm used, QNMDIF [1], is an unconstrained one, we have two choices: use a penalty function to keep thickness within reasonable limits (and then perhaps use **REFINE** mode on the result to give the preferred thickness precisely); or hope for the best by solving without constraints and, again, relying on **REFINE** to adjust the result. If the target curvatures are at all reasonable, the second approach may well be adequate.

Note that there is no "multiple design point" complication (referring to the desirability of optimizing airflow characteristics at more than one flight condition at the same time). In fact, no attempt is made to manipulate more than one surface at a time; the upper and lower surfaces can be optimized independently in separate runs of PROFILE, with little loss of generality and significant simplification.

Prospective users of the **OPTIMIZE** option should be aware that it will probably take a lot of tries with different shape functions, initial airfoils, target curvature distributions, and scale factors, before an acceptable result is achieved from a sufficiently well-posed, well-scaled optimization problem. The initial airfoil is included here as a variable, because if it is not smooth to start with, perturbing it with smooth shape functions cannot be expected to produce smooth curvature distributions close to the (presumably smooth) target distribution. Use of the **REFINE** option first may be desirable, which raises the question of staying with the reliability and greater simplicity of **REFINE** in favor of **OPTIMIZE**'s uncertain behavior. (The optimizing package may not converge to a minimum of the objective function, though it will almost certainly reduce its value below the initial value. But a lowered objective function does not necessarily represent an acceptably smooth solution, as in the case of oscillations observed occasionally when just Wagner functions are applied.)

To this, the response must be that one does not know until one tries both possibilities. The **OPTIMIZE** option is presented as a potentially useful tool, exercised by the authors on only a limited number of applications at the time of

writing. Feedback from adventurous users is welcomed. An outline of the **OPTIMIZE** method used in PROFILE follows:

- Select upper or lower surface, and save the original coordinates for repeated application of varying shape functions.
- Display present thickness ratio; prompt for desired one. Defaulting means either to retain the same thickness, or that the user doesn't care; in the latter case, the prompt for the penalty parameter to be used to impose a thickness constraint should be defaulted (to zero, meaning no such constraint).
- Set up the user-defined "bumps" either by parsing a file of keywords and values prepared ahead of time (more on this below), or by choosing the first n Wagner functions, which are easily definable without such a file.
- Read the target curvature distribution, which is most likely an edited form of an output file from an earlier run of PROFILE.
- Extract the active variables from the given set. (Not all of the parameters involved will be free to change—some may be specified as inactive or fixed.)
- Compute the initial value of the objective function, and estimate optimal finite differencing intervals.
- Minimize the objective function (quasi-Newton method, with finite-difference first derivatives).
- Repeat the best function evaluation, and update the airfoil surface permanently.
- Display the thickness actually achieved; perform the rest of PROFILE's plotting and tabulations.

4.6.2 *Preparing the Target Curvature Distribution*

One of PROFILE's options is to generate a plottable file of curvature data. Typically, the plot for one of the surfaces, or both, will exhibit imperfections that the designer would like to eliminate. PROFILE offers two choices: the **REFINE** option (section 4.5), which uses second derivative distributions rather than curvature; and the **OPTIMIZE** option which works directly with curvature. The designer edits the imperfect values to smooth them out in some way, assisted by the original plot, then reruns PROFILE in **OPTIMIZE** mode, hoping that the new plots of curvature (showing the revised distribution superimposed on the original and target distributions) will show a good match in the least squares sense.

Remember that **OPTIMIZE** mode can work with only one surface at a time. The input file of target curvatures is assumed to contain only the relevant surface. It is also assumed to retain the title and two axis labels that the original QPLOTfile contained. The title is transmitted to the output tabulation, along with the target curvature values; the labels are ignored. (More precisely: the target file may contain both surfaces, but only the first surface is read, so it must be the appropriate one.)

The question arises of how many chordwise values to retain in the the target curvature distribution. There are considerations such as the fact that the values near the leading edge, being larger in magnitude, may tend to dominate the sum-of-squares objective function. (Extreme leading and trailing edge values, however, are suppressed by PROFILE in the plottable files and tabulations.) In the absence of a scheme for weighting the elements of the sum of squares (which could be implemented in much the same way has it has been in the **REFINE** option), it is recommended to retain target values for all interior abscissas, to avoid surprises in any region omitted.

4.6.3 *Selecting the Shape Functions*

Appropriate selection of the shape functions is probably the most difficult aspect of using PROFILE's **OPTIMIZE** option. There is no single choice for any given situation. Experience is desirable to help pick a subset that should do the job. In general, all of the bumps selected should be distinctly different in some sense—it is unwise to include two functions that have similar effects, as this adds unnecessary variables and blurs the minimum from the optimizing algorithm's point of view. If the changes being sought in the curvature are localized in some way, then some of the functions can be localized or centered similarly.

The **OPTIMIZE** option offers two basic sets of perturbing functions: fourteen "bump" functions [3], and a family known as the Wagner functions [5]. All of these are illustrated in Appendix C. They may be defined as follows:

| | | |
|-------------|---|---------------------------------------|
| SCALE | $\delta y = (\text{FACTOR} - 1) y$ | i.e., $y \leftarrow \text{FACTOR } y$ |
| RAMP | $\delta y = \text{FACTOR } x$ | |
| TRAILING | $\delta y = x^{\text{POWER}}$ | |
| DROOP | $\delta y = (1 - x) e^{-\text{WIDTH } x}$ | |
| LEADING | $\delta y = (1 - x)^{\text{POWER}}$ | |
| EXPONENTIAL | $\delta y = x^{\text{POWER}} (1 - x) e^{-\text{WIDTH } x} / \text{CEN}^{\text{P}} (1 - \text{CEN}) e^{-\text{WIDTH } \text{CEN}}$ | |
| SINE | $\delta y = \sin^{\text{WIDTH}} (\pi x^{\log 0.5 / \log \text{CENTER}})$ | [& SINF & SIN1 & -2] |
| COSL | $\delta y = (1/4 \text{ cosine})^{\text{POWER}}$ | [& COSR & LCOS & RCOS] |
| WAGNER | $\delta y = \text{Wagner function (N = order of requested term)}$ | |
| | $= (t + \sin t) / \pi - \sin^2(t/2)$ | (N = 1) |
| | $= (\sin(N t) / N + \sin((N - 1) t)) / \pi$ | (N > 1) |
| | | (t = 2 sin ⁻¹ √x) |

The perturbing functions to be used may be specified in two ways: in a previously-prepared file containing keywords and values; and a simpler way that is convenient if only the Wagner functions are to be used. (See below for more on the use of the Wagner functions.)

Specification of the bump functions to be used has been made as mnemonic and straightforward as possible. There is no need for hard-coding the set of

bumps—a keyword-driven input scheme is used, involving preparation of a small file that will look something like the following sample, where the keyword names are **bolded** to help distinguish them from their values:

```

BUMP: SINE
CENTER: 0.5   STATUS: INACTIVE
WIDTH: 3.0   STATUS: INACTIVE
MULTIPLIER: 0.   STATUS: ACTIVE   SCALE: 100.

BUMP = exp
POWER = 15.   STATUS = fixed
WIDTH = 10.   STATUS = fixed   SCALE = 1.
MULT = .001  STATUS = variable SCALE: 10.

.
.
.

```

POINTS TO NOTE:

- Format is free, with several possible delimiters; blank lines are optional, but good for separating bumps.
- Keywords need only be long enough to be unambiguous.
- Either upper or lower case is permitted.
- Keywords for a given bump must begin with the **BUMP** keyword, which must be the only keyword on the line.
- The ordering of subsequent lines describing that bump's variables or parameters is unimportant, but if some are omitted, they will be detected as undefined, and execution will halt. There is *no attempt to default* values.
- Variable names for a given bump (e.g. **WIDTH**) must be the *first* keyword on a line, one per line.
- **SCALE** here is a design variable scale factor, and should not be confused with the SCALE shape function.
- **STATUS** and **SCALE** may be in either order within a line.
- **SCALE** is optional if **STATUS** is FIXED/INACTIVE/CONSTANT.
- **SCALE** is defaulted if **STATUS** is ACTIVE/FREE/VARIABLE and no entry is given. (1.0 is the default.)
- End-of-file signals end of data.

The terminology requires further explanation. First, all of the perturbing functions (including the Wagner functions) have **MULTIPLIERS** which are almost certain to be included among the optimizing variables. Second, all of the functions are additive—multiples of the basic shapes are added to the original airfoil. Third,

each bump type is specified by name, and is a function of a *normalized* abscissa x and of parameters with descriptive names, as shown above. (The SCALE shape function is an exception to all of these statements—it simply scales the ordinates y directly, although it is implemented in an additive way so as not to require special handling.)

4.6.4 *Simplified Specification of Wagner Functions*

If the only shape functions required for a particular run are the first n Wagner functions [5], then the keyword input file can be dispensed with since the set-up for these functions is easily generated. The only likely reason that the file input might still be preferred is that the given scaling of the variables may prove less than satisfactory. The present automated scheme generates all of the scale factors from a "seed" entered by the user. The relative scaling for $N = 1, 2, 3, 4, 5, \dots$ at the time of writing is 1, 1, 1, 1, 1, 3, 3, 3, 3, 3, 10, 10, 10, 10, 10, 30, 30, 30, 30, 30, 100, 100, ..., based on very little empirical evidence. Such values should be established more systematically than experience has permitted so far, although optimal scaling of variables in general remains an open question. See 4.6.6 *Choice of Scale Factors* below.

4.6.5 *Quasi-Newton Method For Nonlinear Optimization*

The nonlinear optimization algorithm adopted here is that developed by Kennelly for program FLO6QNM [4], itself a refinement of the QNMDIF implementation of Gill, Murray, *et al.* [1]. Only a brief outline of this revised quasi-Newton method can be provided here. QNMDIF, in combination with the algorithm of subroutine FDSTEP (below), is a robust and efficient package for the unconstrained minimization of functions (not necessarily sums of squares) of n variables. It uses finite difference approximations for first derivatives, which in turn are used to build, through successive updates, a matrix having Hessian-like properties. (The Hessian for a function of n variables is the $n \times n$ matrix of second derivatives.) The approximate gradient and Hessian are used to compute a Newton-type search direction at each step, with descent ensured by controlling the positive-definiteness of the matrix via its Cholesky (LDL^T) factors.

A safeguarded line search routine chooses adequate step lengths efficiently, with account taken of functions that are calculable to less than full machine precision, and automatic switching between forward and central differencing in response to function behavior.

This package is appropriate for the present application since analytic derivatives of the objective function are almost as out of the question as they are in the case of target pressure distributions. Furthermore, a good general-purpose package tends to behave as well as, or better than, typical packages specially adapted to sum-of-squares-type functions. Also, the relative simplicity of an unconstrained algorithm is preferred to a general constrained algorithm, since the only likely constraint is one on thickness, which can be handled with a penalty function (below).

Experience so far suggests that single precision (32-bit) arithmetic is adequate for QNMDIF to solve reasonable OPTIMIZE problems. The significant QNMDIF

parameter settings chosen with no provision for interactive changes include $ETA = 0.1$, $TOL = 0.001$, $EPSMCH = 5.0E-8$, and $EPSOBJ = EPSMCH*100$. The initial Hessian-like approximation is a diagonal matrix containing estimates for the subset of second derivative elements provided by the preliminary CENDIF/FDSTEP calculations (based on algorithm FD of [2]), which are not optional either, as they play a large part in QNMDIF's success by determining good finite differencing intervals.

An arbitrary upper limit of 100 optimization iterations or steps is imposed. This can lead to thousands of function evaluations if the problem is poorly posed, so the airfoil designer is urged to be careful in setting up the **OPTIMIZE** option.

Restarting an **OPTIMIZE** solution is always a possibility. The improved finite difference intervals may make a difference on difficult problems. However, no provision has been made for saving the accumulated curvature information represented by the current Cholesky factors **L** and **D**, as this application of QNMDIF (to a relatively well-behaved function) is most likely to find solutions in a single run in a modest amount of CPU time.

4.6.6 *Choice of Scale Factors*

The scale factors applied to active variables are intended to assist the optimizing algorithm, which behaves best if the solution lies in the unit sphere and the rows of the Hessian matrix of second derivatives at the solution are approximately equilibrated. (Ideally, the function should not exceed unity in the unit sphere, but it may not be possible to meet any of these criteria.) Many aspects of the scaling problem are discussed in [1] and [2]. To some extent, less-than-ideal scaling is handled satisfactorily through the dynamic selection of intervals for finite differencing by routines CENDIF and FDSTEP.

4.6.7 *Choice of Target Thickness And Penalty Parameter*

OPTIMIZE prompts the user for a target maximum thickness ratio (as a percentage of chord). Unlike the **REFINE** option, it cannot guarantee this target thickness precisely. The target is used in a penalty function of the form

$$\rho (\text{current \% T/C} - \text{target \% T/C})^2$$

which is added to the rest of the sum-of-squares-type objective function. The user can seek the same thickness as the original airfoil by entering just a carriage-return (but it is unlikely to be retained precisely). The user can also choose to suppress the constraint by entering either zero or a carriage-return in response to the prompt for the penalty parameter ρ . QNMDIF should find a minimum, but the problem may need to be reformulated if the user doesn't like the best fit that was found.

In principle, successive runs of **OPTIMIZE** with increasingly larger values for the penalty parameter ρ can produce the desired thickness, but the availability of the much more precise, and cheap, **REFINE** option argues for an **OPTIMIZE** run with, say, penalty parameter = 100., followed by a refinement run (with numerous options open) if the thickness is required to be some precise value.

4.6.8 Comparison of Curvature With The Target Distribution

The same table-look-up with linear interpolation that was implemented for the **REFINE** option's target y'' requirements is used in routine **CFDISTRIB**. This means that, in principle, the target and current curvature distributions do not have to be defined at the same abscissas, though in practice it is most likely that the two sets of abscissas will be identical. No attempt has been made to weight the elements of the sum of squares, in the interest of simplicity.

4.6.9 Displaying Results

The user is prompted for minimal or comprehensive output of **QNMDIF**'s progress. Normally, brief output should be all that is needed. Upon termination of **PROFILE**, the recommended sequence is as follows (where *<ident>* refers to the identifier prompted for at the beginning of the **PROFILE** run):

| | |
|--|--|
| QPLOT <i><ident></i> .plt | Revised-versus-original airfoil plot. |
| QPLOT <i><ident></i> .crv | Old/new/target curvature plots, with upper and lower surfaces on separate frames. |
| PRINT <i><ident></i> .tab | Tabulations of the original airfoil, the target information, bump function description, CENDIF results, QNMDIF results, and the revised airfoil. |

4.7 Mode 7: Transform Ordinates \longleftrightarrow Camber/Thickness, or Decamber

This mode provides for transforming airfoil representations from upper/lower surface coordinates to thickness/camber distributions, or vice versa. More precisely, semithickness is used, while "camber" is taken to be the mean line:

$$C = \frac{(y_U + y_L)}{2} \quad y_U = C + T$$

$$T = \frac{(y_U - y_L)}{2} \quad y_L = C - T$$

Provision is also made for decambering an airfoil in one step, where otherwise two runs through Mode 7 would be required along with some editing (zeroing) of the camber distribution. **PROFILE** ensures zero camber at the leading edge by subtracting any nonzero leading edge ordinate from both surfaces prior to the transformation.

The abscissas for the upper and lower surfaces must be the same. **PROFILE** checks for discrepancies and stops prematurely if abscissas do not match. The **REDISTRIBUTE** mode should be used first in this case.

Since the (semi)thickness distribution is airfoil-like, it can be treated as one surface of a symmetric airfoil and manipulated with any of **PROFILE**'s other major options. Thus the camber can be taken out, the thickness modified in some way (working on just one profile instead of two), then the camber can be reincorporated.

The camber distribution might also be modified before the recombination. A camber profile is not necessarily airfoil-like, so the normal PROFILE options may not be appropriate. For instance, in one application at NASA Ames, a polynomial of 5th degree, fitted in the least squares sense and constrained to pass through the origin, was found to smooth a certain camber distribution usefully. (Splines might also be used effectively.) These general purpose techniques have not found their way into PROFILE because at Ames they are offered by another utility known as SMOOTH, which can fit a variety of curves to given data and illustrate results via QPLOT.

4.8 Mode 8: Rotate Coordinates, With Renormalize Option

The ROTATE option applies twist about a center of rotation selected from a menu: the leading edge, the trailing edge, the quarter-chord point (on the straight line connecting the leading and trailing edges), or some specified point. The amount of twist is entered in degrees; positive means anticlockwise.

An option to renormalize the coordinates is provided if the initial section is in normalized form. Note that this does not in general recover the original abscissas.

If the leading edge point is no longer the true leading edge as a result of the rotation, the user is warned. Any renormalization will have been affected. Use of PROFILE's RECTIFY option is recommended in this case, possibly followed by the NORMALIZE option and/or the REDISTRIBUTE option.

4.9 Mode 9: Combine Two Profiles (Add or Subtract)

The COMBINE option was prompted by the need to add or remove boundary layer displacement thickness distributions. It may find broader application. Since it is one of PROFILE's major modes, a "primary" airfoil is assumed to be read in the usual way, and a secondary profile is prompted for by COMBINE. The abscissas are required to match. (Any discrepancies are trapped, whereupon the user is urged to apply REDISTRIBUTE mode before trying again.)

COMBINE distinguishes the case of combining an airfoil and a displacement thickness distribution from combining two airfoils with an appropriate prompt. Treatment of the lower surface is different in the two cases: "metal" is added to both surfaces if a boundary layer is being applied, meaning positive quantities are actually subtracted from the lower ordinates in this case. Combination of two airfoils, on the other hand, is strictly algebraic for both surfaces.

4.10 Mode 10: Loft Between Two Profiles

The LOFT option performs the simplest type of lofting between two sections by linear interpolation in the third dimension. Because it is implemented as one of PROFILE's high-level modes, it assumes that a "primary" airfoil is read in the usual way and prompts for a "secondary" airfoil at the LOFT level. The two airfoils must match in terms of numbers of points, and the point distributions should be

comparable, although an original check for the same relative distributions (along the arc?) has been suppressed as impractical. When in doubt, apply PROFILE's REDISTRIBUTE mode first.

The primary and secondary airfoils may or may not be normalized upon input. If either section is normalized, prompts allow for imposing specified leading edge coordinates and chord prior to the lofting. *USER NOTE:* It may be incorrect to loft in normalized space—the sections should typically be denormalized first. Note also that, in the presence of chord taper, linear lofting of coordinates does *not* produce linear variation in twist.

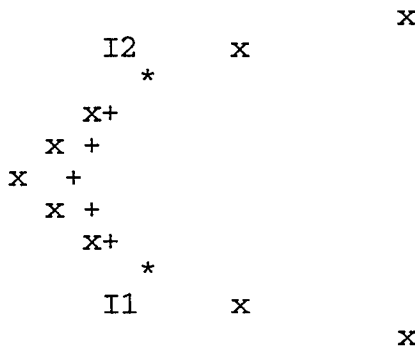
4.11 Mode 11: Nose-job Option: Round or Sharpen Leading Edge

The **Nose-job** option performs various modifications to airfoil leading edges. Initially, it has the following options (others may arise):

- Round off a sharp leading edge
- Sharpen a rounded leading edge

After the leading edge is modified, the original chord and thickness could in principle be retrieved here through in-line reuse of PROFILE's REFINE module, but this has yet to be implemented.

A menu is presented for the various options. The input coordinates are overwritten by the modified coordinates. The number of points on each surface is held the same. In the modified nose region, the relative point distribution in terms of arc length is also held the same. The rounding and sharpening options are thus as reversible as possible. The user is asked to specify the points I1, I2 for each surface at which the modified surface should blend with the original:



Rounding is achieved by rotating the x axis to be parallel to the bisector of the angle between the tangents at I1 and I2, then fitting a conventional spline to the region near the nose where the "abscissas" (rotated y coordinates) are monotonic. Evaluating this spline at points spaced along the arc in the same relative way as the original points is awkward! Conservatively careful approximations are achieved by evaluating the rounded surface at ~30 points spaced uniformly in the abscissa, refitting those points parametrically, and working with cumulative chord lengths from there.

Sharpening the nose is achieved by determining where the extrapolated surfaces intersect, offering that point to the user as the default for the new leading edge, then allowing an alternative point to be entered interactively. Much the same steps as above are then taken to preserve the original point distribution along the modified portions of each surface, although local splines (4-point method with just first derivative continuity) are used instead of conventional splines (second derivative-continuous), because the 4-point technique should be quite adequate for sharp noses, and is what the intersection utility uses anyway.

4.12 Mode 12: Smooth Airfoil (Implicit/Explicit Schemes or Fitting of Wagner Functions)

Airfoil coordinates may be noisy from digitization errors, or contain high frequencies as a result of design procedures which allow too many ripples in the curvature distribution. Such imperfections will be reflected all-too-faithfully in the surface pressure distributions. Some convenient means of eliminating general noise is desirable, and PROFILE now offers two main choices within its **SMOOTH** mode. In both cases, the input coordinates need not be normalized—PROFILE normalizes and denormalizes the airfoil in-place. Appendix E includes illustrations of airfoil smoothing.

4.12.1 *Implicit /Explicit Smoothing*

A form of local averaging is provided by the diffusion-type equation:

$$\tilde{y} = (1 + \varepsilon \delta x^2 \partial_{xx})y \quad (\text{explicit})$$

or

$$(1 - \varepsilon \partial_{xx})\tilde{y} = y \quad (\text{implicit})$$

The implicit form leads to solution of a tridiagonal system (no iteration), while provision is made for iterating the explicit smoothing. PROFILE applies either or both of these to one surface of an airfoil at a time, and provides for varying the smoothing parameter ε along the arc. (The second derivatives are actually with respect to normalized arc length s rather than x .) For instance, the smoothing might be weighted towards the trailing edge via a TRAIL shape function s^5 , say, with multiplier 0.01, but a full menu of shape functions is provided as for **MODIFY** mode.

PROFILE prompts for a *peak* value of ε for each of the implicit and explicit modes. Enter 0. to suppress one or the other. As a rule, implicit smoothing tends to take out the lower frequencies, while explicit smoothing deals with the higher frequencies. Application is case-dependent, so use these schemes with discretion. It may be desirable to use **REFINE** mode as a final step to impose a preferred T/C_{\max} .

4.12.2 *Linear Least Squares Fitting of Wagner Functions*

An effective means of smoothing airfoil coordinates is provided by the Wagner functions [5]. This option smooths the upper and/or lower surface by fitting a combination of the first N Wagner functions to the y coordinates in the linear least squares sense. If the trailing edge y is not at zero, a ramp function is first applied to zero it, the fit is performed, then the ramp is added back.

The default number of Wagner functions is ten. Too many tends to give undesirable waviness towards the trailing edge, as might be expected from the Appendix C illustrations. A root-mean-square-deviation measure of the goodness of fit is provided. A smoothed airfoil should be checked against the original with a surface pressure calculation before assuming that the shape has not changed significantly.

In view of the possible waviness towards the trailing edge, an option is also provided to replace n points forward of the trailing edge, via spline interpolation across the gap. Choose $n \geq 0$ (with 3 a likely choice).

REFERENCES

1. Gill, P. E., W. Murray, and R. A. Pitfield, "*The Implementation of Two Revised Quasi-Newton Algorithms for Unconstrained Optimization*," National Physical Laboratory, Division of Numerical Analysis and Computing Report No. NAC 11, April, 1972.
2. Gill, P. E., W. Murray, and M. H. Wright, "*Practical Optimization*," London: Academic Press, 1981.
3. Hicks, R. M., and G. N. Vanderplaats, "*Application of Numerical Optimization to the Design of Supercritical Airfoils Without Drag Creep*," SAE Paper 770440, 1977.
4. Kennelly, R. A. Jr., "*Improved Method for Transonic Airfoil Design-by-Optimization*," NASA Ames Research Center CR-166497, July 1983.
5. Ramamoorthy, P. and K. Padmavathi, "*Airfoil Design by Optimization*," in J. Aircraft, Vol. 14 (Feb. 1977), 219-221.
6. Stewart, G. W., "*Introduction to Matrix Computations*," New York: Academic Press, 1973.
7. Vinokur, M., "*On One-Dimensional Stretching Functions for Finite-Difference Calculations*," in J. of Computational Physics, Vol. 50, No. 2, May, 1983.

APPENDIX A: Related Software (1) – BPLOT

Program BPLOT generated the data for the perturbing function plots shown in Appendix C. Actually, it generates a plottable file of the form expected by program QPLOT (Appendix B). BPLOT employs the GETBUMPS routine that is part of PROFILE's OPTIMIZE option. This means that the "bumps" are either prepared first in a text file, as described in 4.6, or they are the first N Wagner functions, which can be plotted without such a file.

BPLOT enables checking of the selection of perturbing functions that are about to be used in an airfoil optimization run (of either PROFILE's OPTIMIZE, or FLO6QNM, or similar design codes). Proper choice of the bump subset is one of the elements crucial to success with the optimizing algorithm, and such a visual aid might save some grief.

Use of PROFILE's MODIFY option should benefit from BPLOT illustrations. Noteworthy features of BPLOT include the following:

- Perturbing functions are selected by name (family).
- If all functions in the subset to be plotted are from the same family, BPLOT automatically generates the plot title from the name of the family, and the plot subtitle from the corresponding formula. Otherwise, the user is prompted for a suitable title (with no subtitle).
- Any unit MULTIPLIERS are suppressed, as this gives more room in the legend that is constructed by BPLOT to make the plot as self-descriptive as possible.
- All functions in the subset are plotted on the same frame, and only one frame is produced per run of BPLOT.
- BPLOT prompts for all its inputs—no additional control file is used, and no logical unit assignments are necessary prior to running it.
- An arbitrary limit is imposed on the number of abscissas in the range [0,1] at which each function is evaluated. This limit was 257 at the time of writing.

A sample input dataset, with corresponding QPLOTtable output dataset, is shown on the following page. Note that BPLOT takes advantage of some of DISSPLA's (and hence QPLOT's) embedded-command capabilities in its generation of the shape function names and formulas used in the plot titles and subtitles. See Section 4.6 for a description of the keywords used here. Remember: just one BUMP or associated keyword per line. (The STATUS and SCALE keywords needed by PROFILE's OPTIMIZE option would be ignored by BPLOT if present. They have been omitted in the sample to avoid confusion.)

Sample Input File For BPLOT:

BUMP: EXP
CENTER: 0.05
WIDTH: 0.5
MULT: 1.0

BUMP: EXP
CENTER: 0.05
WIDTH: 1.0
MULT: 1.0

BUMP: EXP
CENTER: 0.05
WIDTH: 2.0
MULT: 1.0

BUMP: EXP
CENTER: 0.05
WIDTH: 5.0
MULT: 1.0

BUMP: EXP
CENTER: 0.05
WIDTH: 10.0
MULT: 1.0

BUMP: EXP
CENTER: 0.05
WIDTH: 20.0
MULT: 1.0

Corresponding Output File From BPLOT (See Plot in Appendix C):

<Everything starts in column 2>

```
[EH1.4]EXPONENTIAL
[L.8]x[LX]P[L.8](1-x) e[LX]-WIDTH[L-.25]*[LX]x[L.8] / CENTER ...
X/C
Shape function
$OPTIONS
GRID      =          0,
LEGEND    = `CENTER  0.050  WIDTH  0.500
LINE      = `SOLID
$END
0.000000 0.000000
:
:
1.000000 0.000000
:
:
```

APPENDIX B: Related Software (2) – QPLOT

Program QPLOT produced all of the plots shown in these Appendices, which illustrate results generated by PROFILE or BPLOT. This approach keeps plotting out of the program generating the data. QPLOT and BPLOT were both developed under the same contract as PROFILE.

QPLOT is a general-purpose plotting package suited to the bulk of every-day applications, with minimal knowledge of graphics required on the part of the user. It handles any number of curves on a frame, with self-scaling as the default, and any number of frames per run. Titles and labels precede the data (typically two columns of numbers, though QPLOT can select from more than two); an optional NAMELIST provides legends, specific scaling, and so on, if these are desired. QPLOT runs on DEC systems (OpenVMS), SGI workstations (IRIX), or CRAY systems (UNICOS). It employs the *CA-DISSPLA* graphics library of Computer Associates. (*CA-DISSPLA* is proprietary and not available for normal distribution from NASA.)

Those in possession of PROFILE, BLOT, and QPLOT should find broader application for QPLOT, but a thorough description of QPLOT is beyond the scope of this user guide. A separate QPLOT booklet is available from the authors.

Those without access to *CA-DISSPLA* should have little difficulty in adapting the outputs from PROFILE to some comparable plotting utility. Adapting BPLOT's plot title outputs (with their embedded formatting commands) would be more of a challenge, but plain text is commented out within the code in case that suffices.

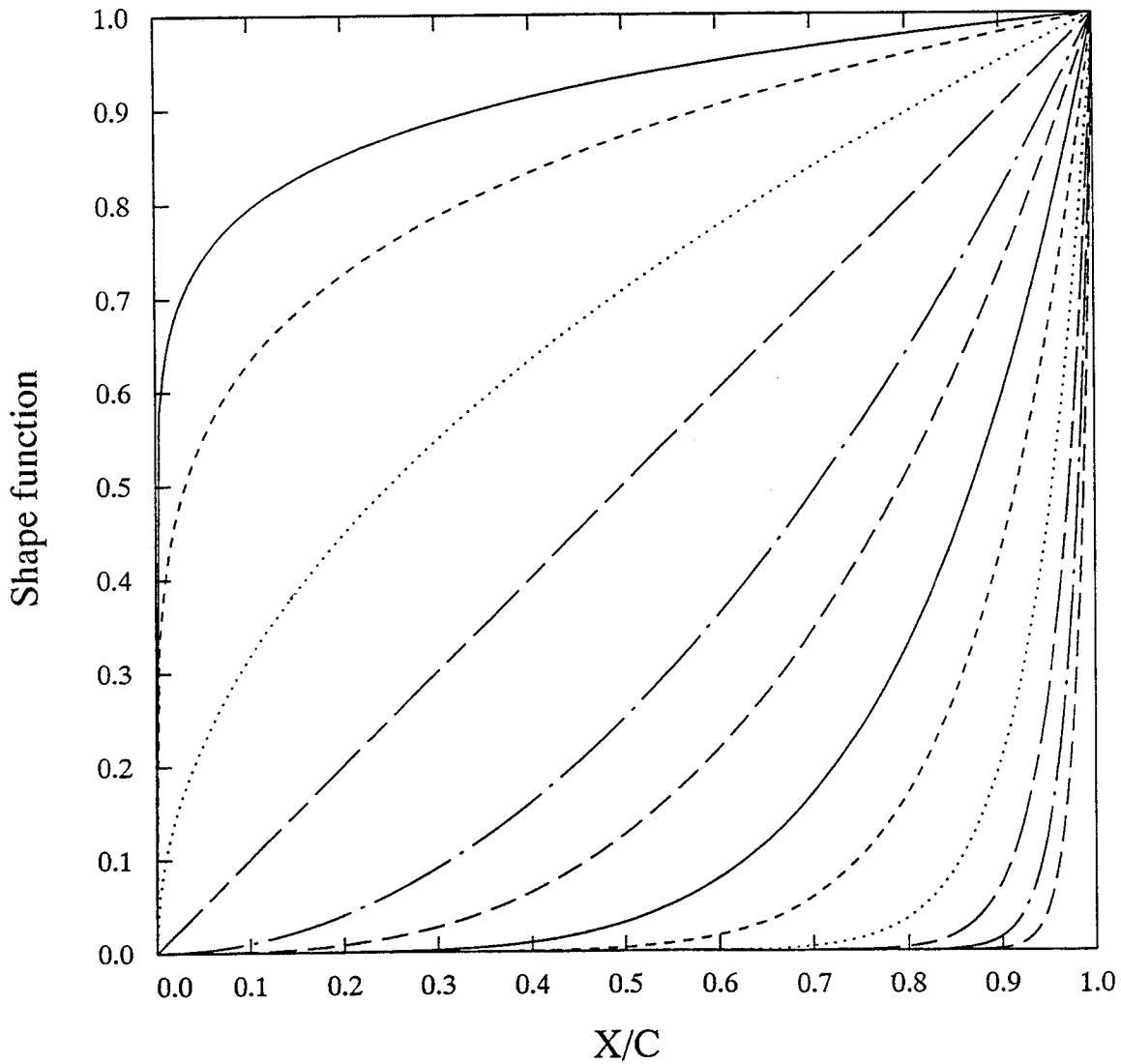
APPENDIX C: Perturbing Function Illustrations

The following plots of representative airfoil shape functions were generated by programs BPLOT and QPLOT.

TRAILING

x^{POWER}

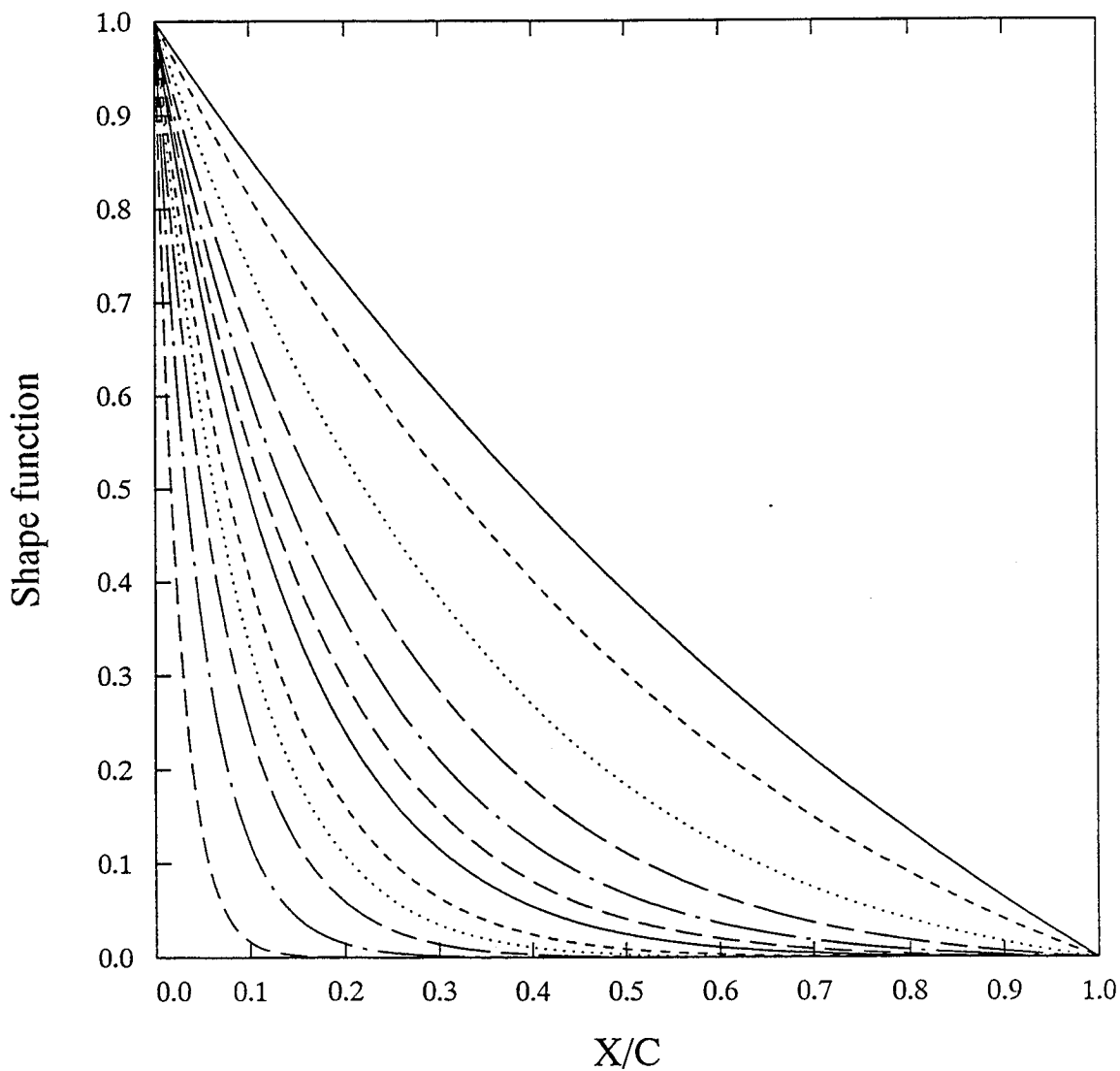
| | | | |
|-----------|-------------|-----------|--------------|
| ———— | POWER 0.100 | ———— | POWER 5.000 |
| - - - - - | POWER 0.200 | - - - - - | POWER 8.000 |
| ..... | POWER 0.500 | ..... | POWER 15.000 |
| - · - · - | POWER 1.000 | - · - · - | POWER 25.000 |
| ————· | POWER 2.000 | ————· | POWER 40.000 |
| - - - - - | POWER 3.000 | - - - - - | POWER 60.000 |



DROOP

$$(1-x) e^{-\text{WIDTH} \cdot x}$$

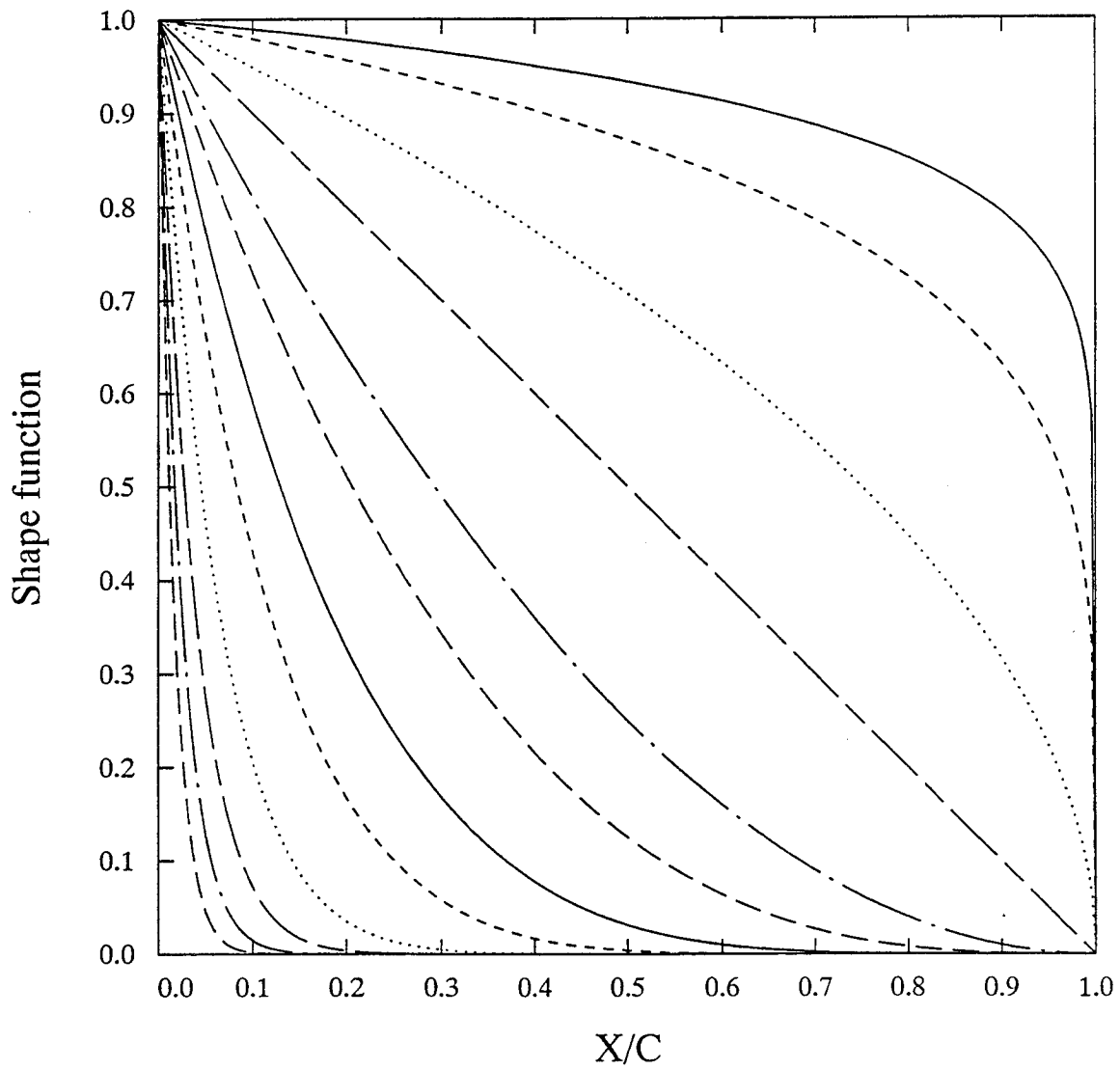
| | | | |
|---------|-------------|---------|--------------|
| ———— | WIDTH 0.500 | ———— | WIDTH 6.000 |
| - - - - | WIDTH 1.000 | - - - - | WIDTH 8.000 |
| ..... | WIDTH 2.000 | ..... | WIDTH 10.000 |
| — · — · | WIDTH 3.000 | — · — · | WIDTH 13.000 |
| — · — · | WIDTH 4.000 | — · — · | WIDTH 20.000 |
| - - - - | WIDTH 5.000 | - - - - | WIDTH 40.000 |



LEADING

$$(1-x)^{\text{POWER}}$$

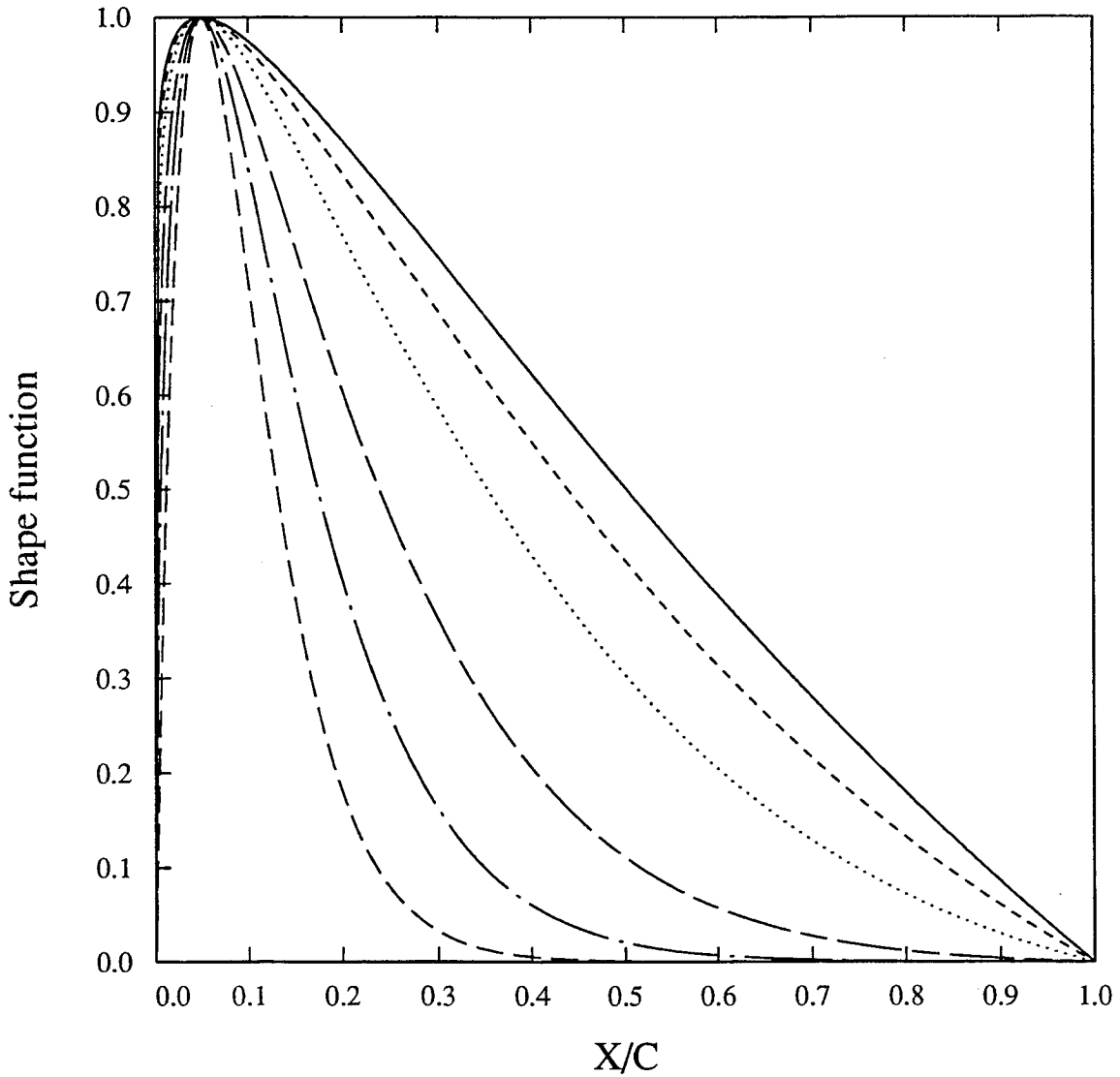
| | | | |
|-----------|-------------|-----------|--------------|
| ———— | POWER 0.100 | ———— | POWER 5.000 |
| - - - - - | POWER 0.200 | - - - - - | POWER 8.000 |
| ..... | POWER 0.500 | ..... | POWER 15.000 |
| - - - - - | POWER 1.000 | - - - - - | POWER 25.000 |
| ———— | POWER 2.000 | ———— | POWER 40.000 |
| - - - - - | POWER 3.000 | - - - - - | POWER 60.000 |



EXPONENTIAL

$$x^P (1-x) e^{-\text{WIDTH} \cdot x} / \text{CENTER}^P (1-\text{CENTER}) e^{-\text{WIDTH} \cdot \text{CENTER}}$$

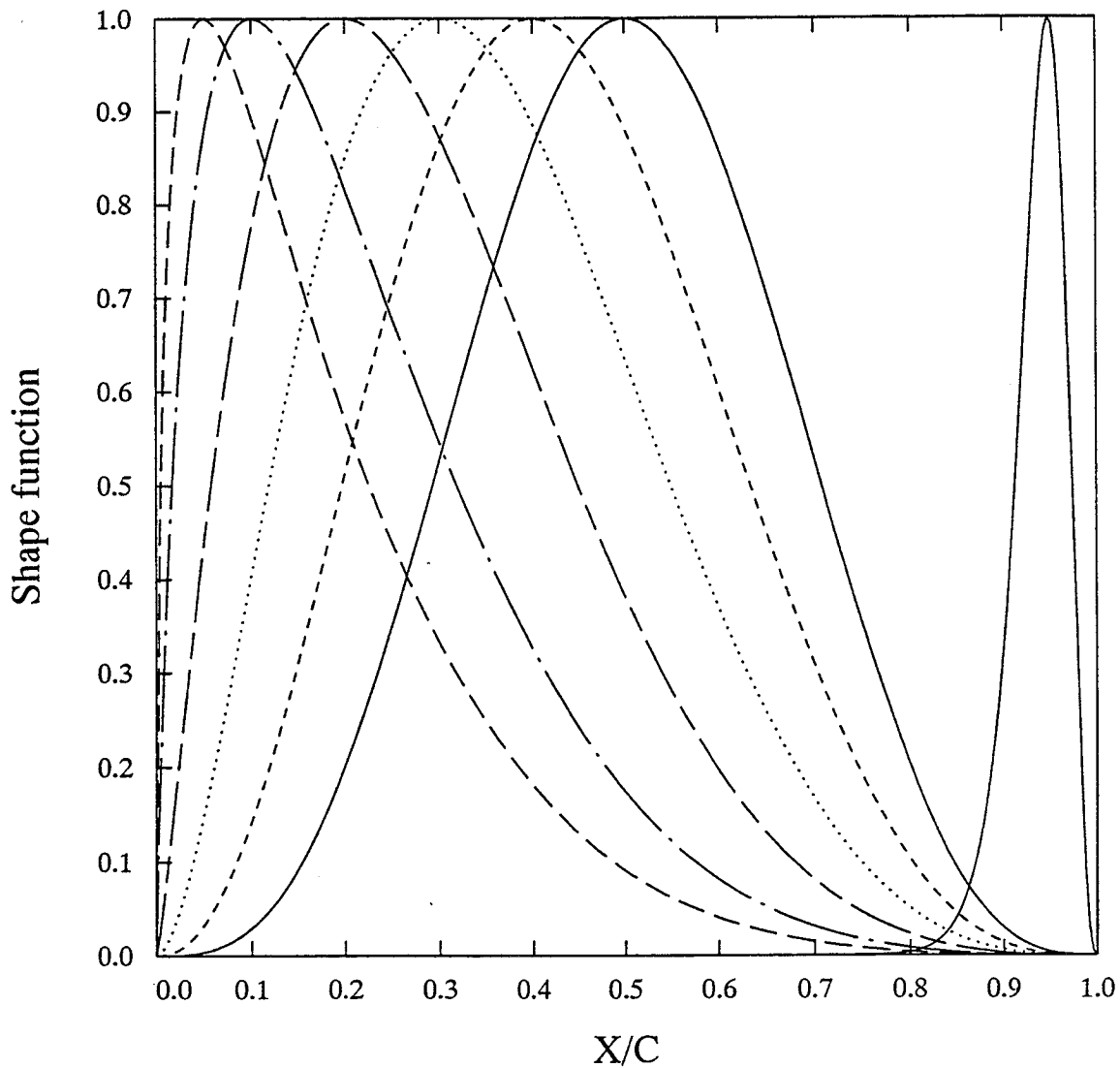
- | | | | |
|-------|--------------------------|----------|---------------------------|
| ———— | CENTER 0.050 WIDTH 0.500 | —— — | CENTER 0.050 WIDTH 5.000 |
| ----- | CENTER 0.050 WIDTH 1.000 | —— — — | CENTER 0.050 WIDTH 10.000 |
| ..... | CENTER 0.050 WIDTH 2.000 | —— — — — | CENTER 0.050 WIDTH 20.000 |



SINE

$\sin \text{WIDTH} \left(\pi x \log 0.5 / \log \text{CENTER} \right)$ (unsymmetric)

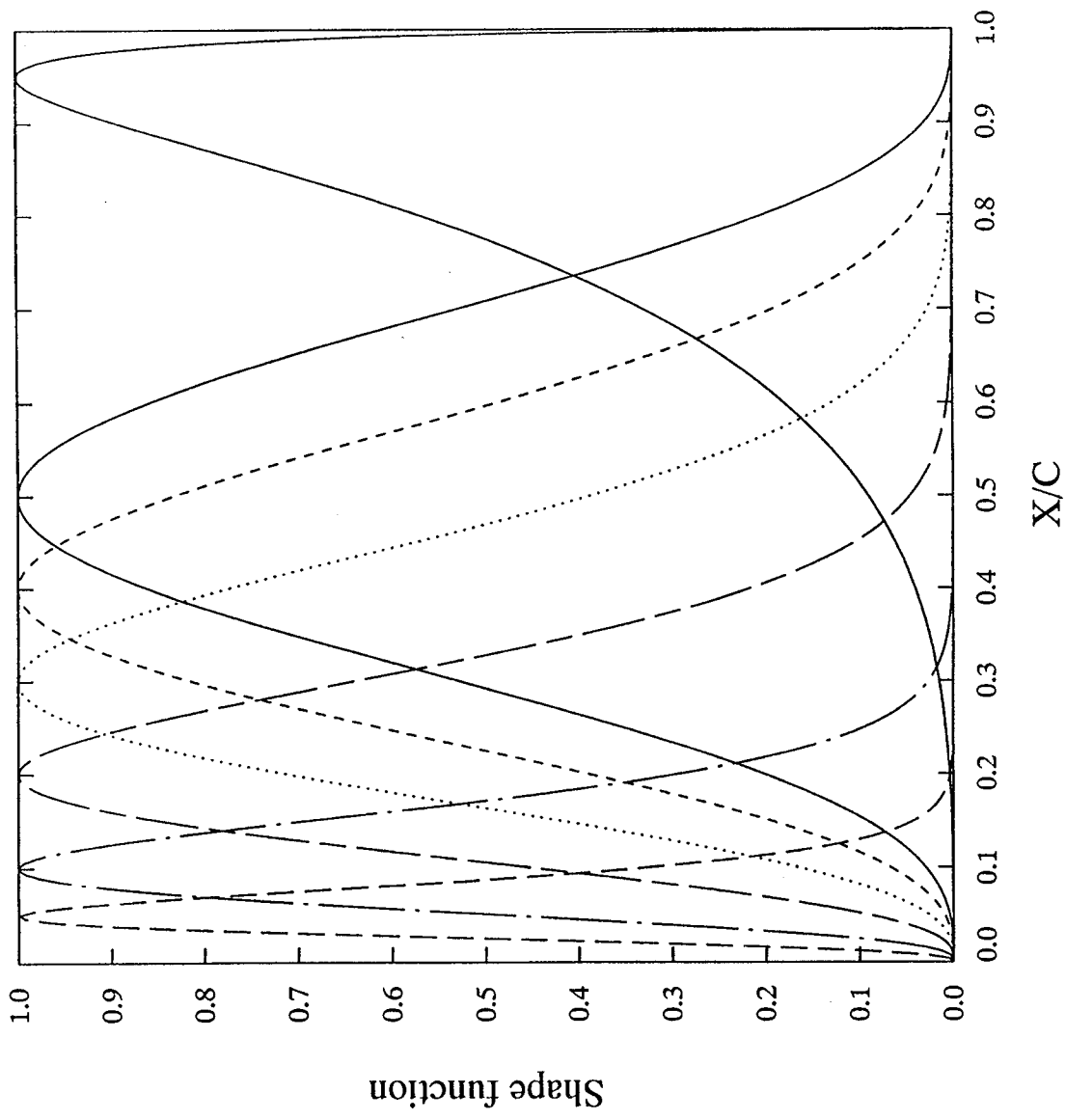
- | | | | |
|---------|--------------------------|-------|--------------------------|
| ———— | CENTER 0.500 WIDTH 3.000 | ———— | CENTER 0.100 WIDTH 3.000 |
| ----- | CENTER 0.400 WIDTH 3.000 | ----- | CENTER 0.050 WIDTH 3.000 |
| ..... | CENTER 0.300 WIDTH 3.000 | ———— | CENTER 0.950 WIDTH 3.000 |
| — — — — | CENTER 0.200 WIDTH 3.000 | | |



SINF

SINE flipped (R/L, unsymmetric)

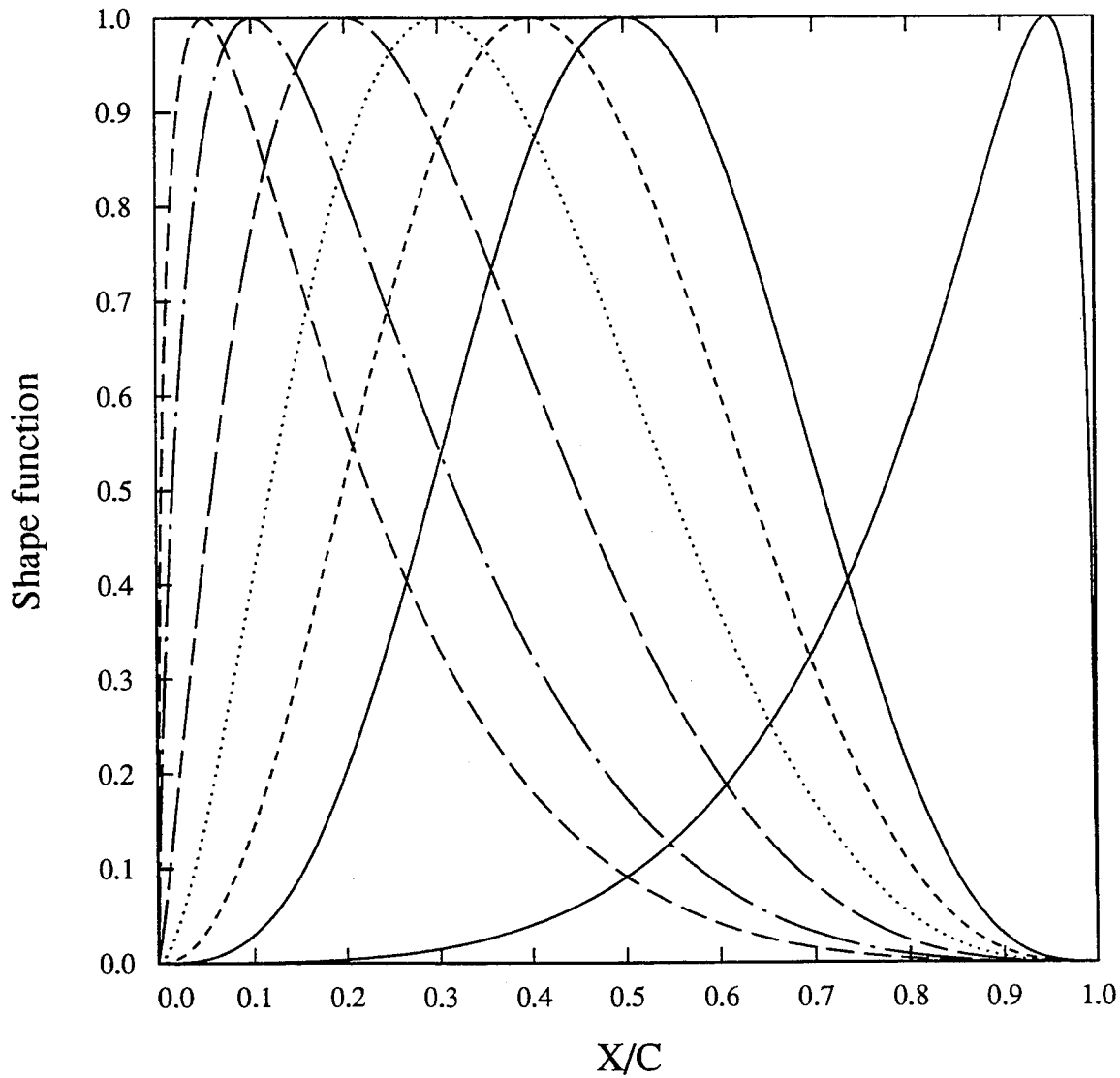
- | | | | | | |
|-------|--------------|-------------|-------|--------------|-------------|
| — | CENTER 0.500 | WIDTH 3.000 | — | CENTER 0.100 | WIDTH 3.000 |
| - - - | CENTER 0.400 | WIDTH 3.000 | - - - | CENTER 0.050 | WIDTH 3.000 |
| ..... | CENTER 0.300 | WIDTH 3.000 | — | CENTER 0.950 | WIDTH 3.000 |
| — | CENTER 0.200 | WIDTH 3.000 | | | |



SIN1

Symmetric form of modified SINE (L/L)

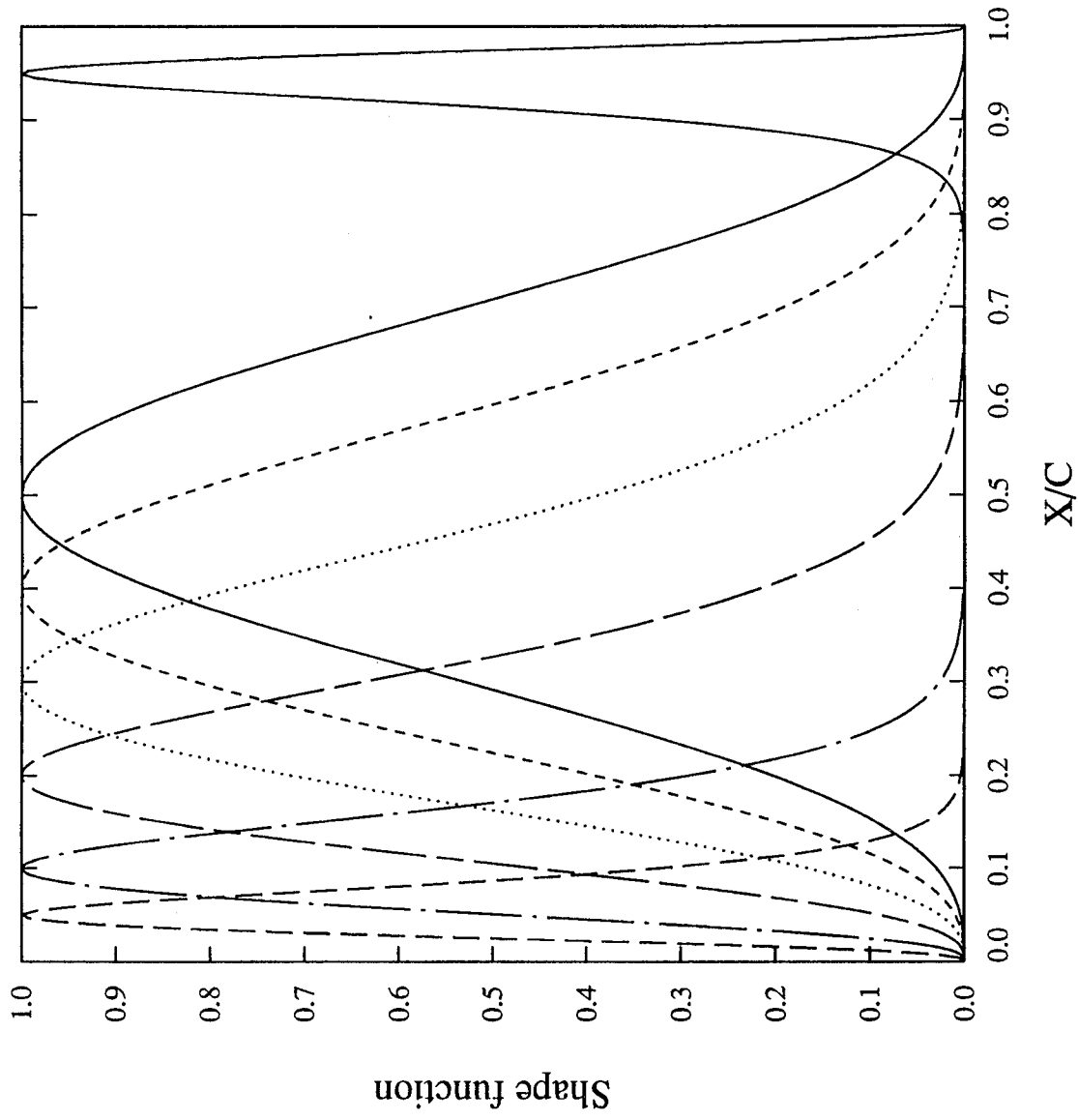
- | | | | |
|---------|--------------------------|---------|--------------------------|
| ———— | CENTER 0.500 WIDTH 3.000 | ———— | CENTER 0.100 WIDTH 3.000 |
| - - - - | CENTER 0.400 WIDTH 3.000 | - - - - | CENTER 0.050 WIDTH 3.000 |
| ..... | CENTER 0.300 WIDTH 3.000 | ———— | CENTER 0.950 WIDTH 3.000 |
| - - - - | CENTER 0.200 WIDTH 3.000 | | |



SIN2

Symmetric form of modified SINE (R/R)

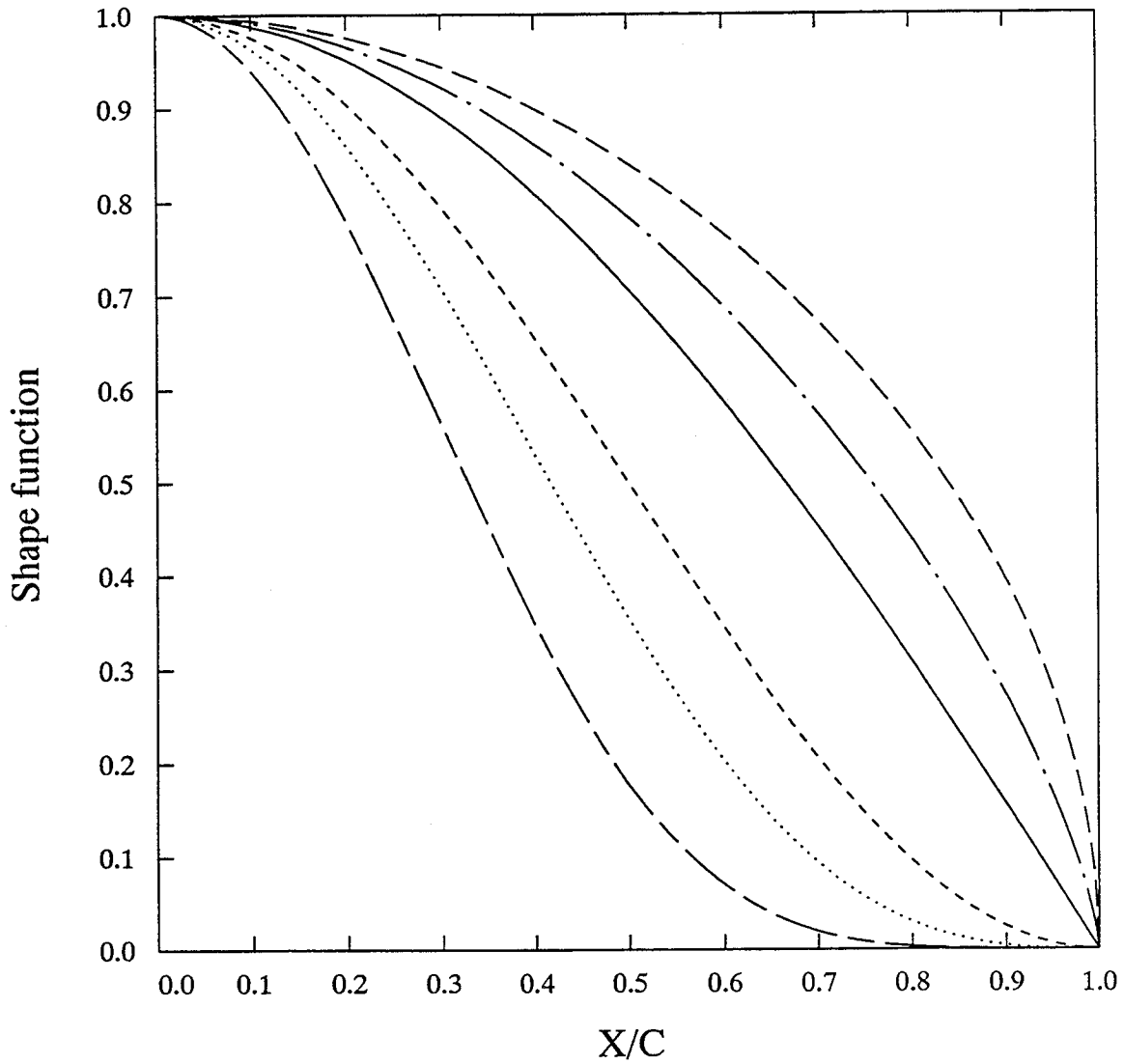
| | | | | | |
|-------|--------------|-------------|---------|--------------|-------------|
| — | CENTER 0.500 | WIDTH 3.000 | - - - | CENTER 0.100 | WIDTH 3.000 |
| - - - | CENTER 0.400 | WIDTH 3.000 | - - - - | CENTER 0.050 | WIDTH 3.000 |
| ..... | CENTER 0.300 | WIDTH 3.000 | — | CENTER 0.950 | WIDTH 3.000 |
| — | CENTER 0.200 | WIDTH 3.000 | | | |



COSL

(1/4 cosine, peak at left) POWER

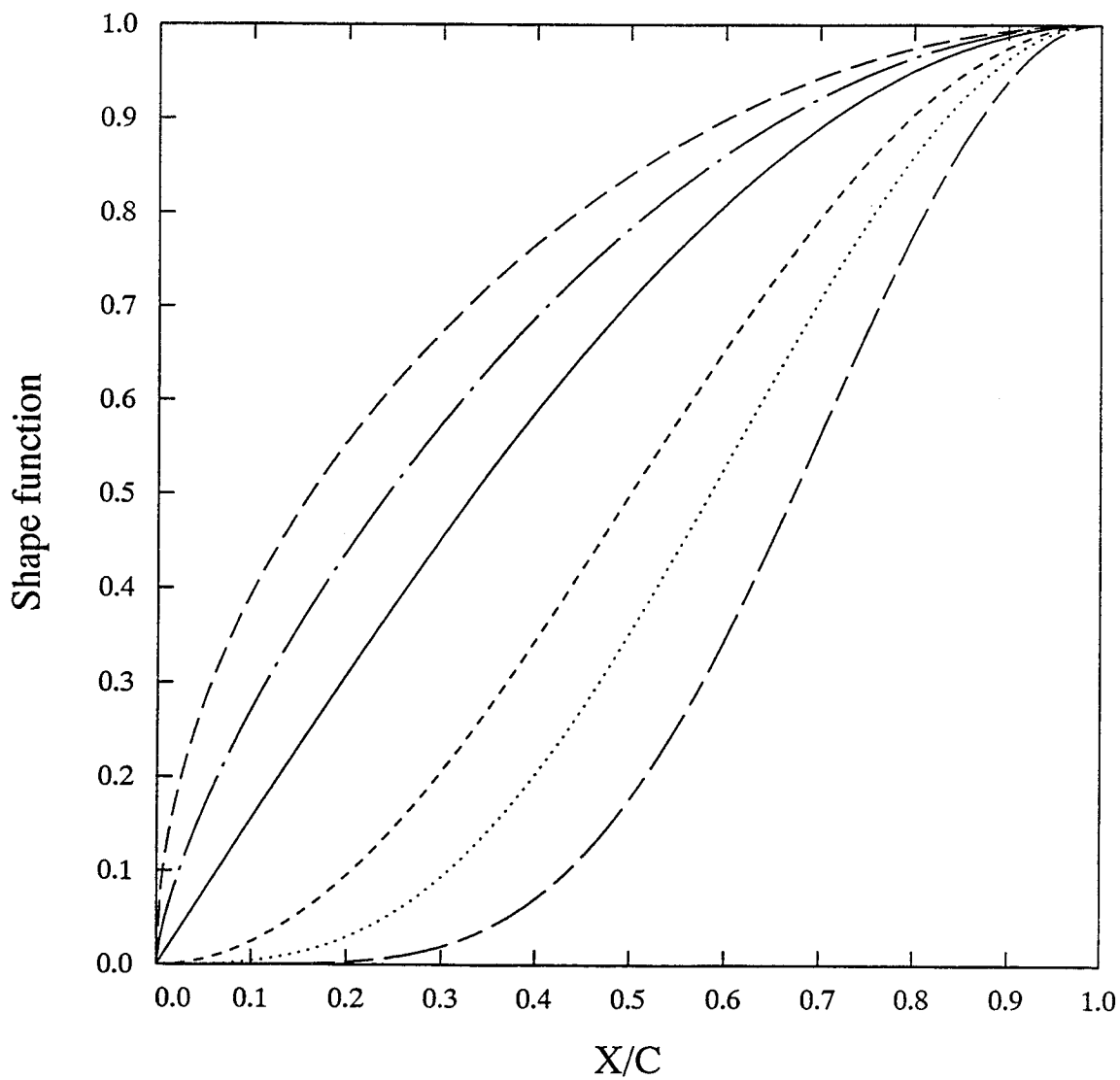
- | | | | |
|-------|-------------|-------|-------------|
| — | POWER 1.000 | — — | POWER 5.000 |
| - - - | POWER 2.000 | — · — | POWER 0.700 |
| · · · | POWER 3.000 | - - - | POWER 0.500 |



COSR

(1/4 cosine, peak at right) POWER

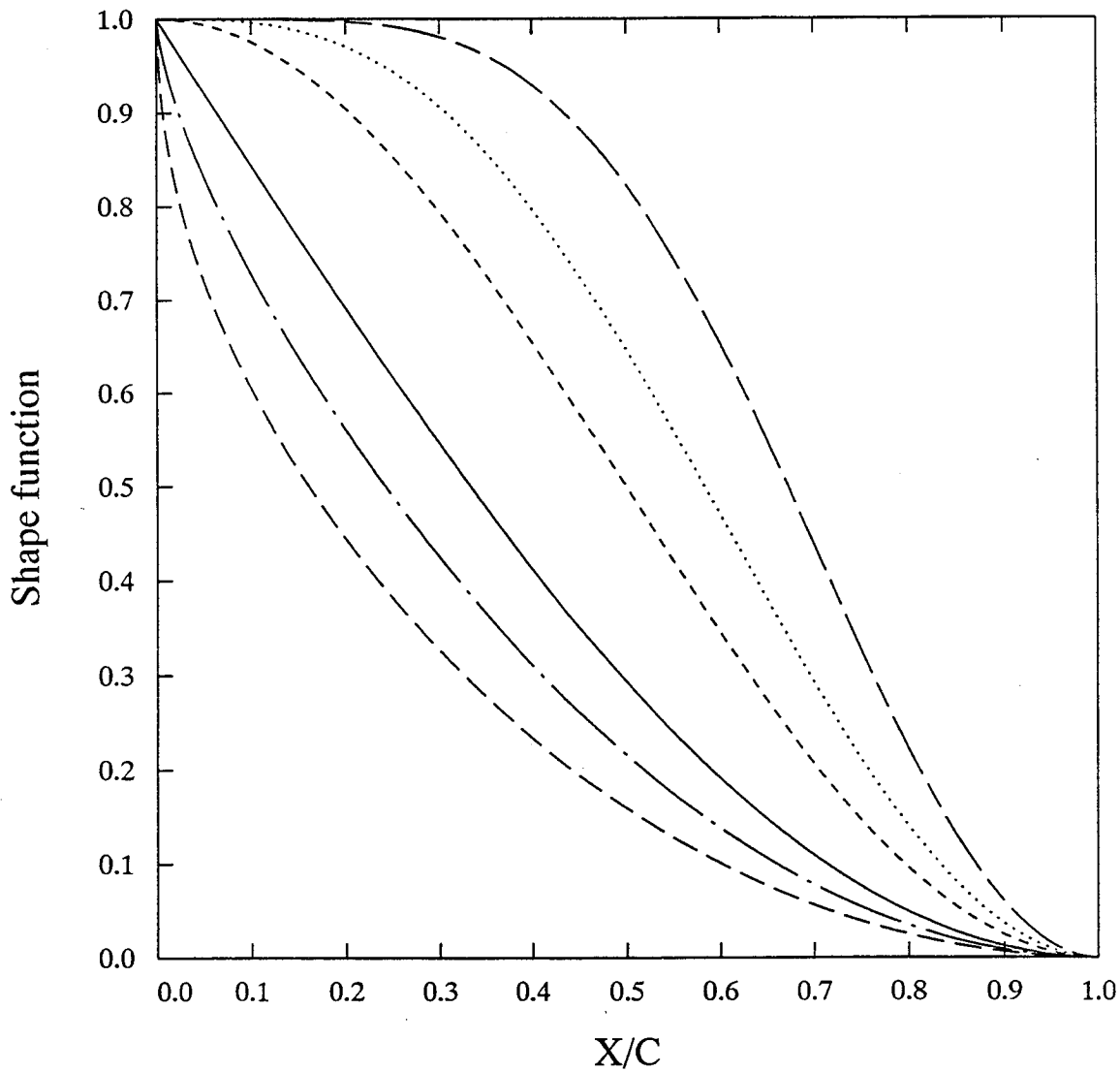
- | | | | |
|-------|-------------|-------|-------------|
| — | POWER 1.000 | — — | POWER 5.000 |
| - - - | POWER 2.000 | — · — | POWER 0.700 |
| ····· | POWER 3.000 | - - - | POWER 0.500 |



LCOS

(1 - 1/4 cosine, peak at left) POWER

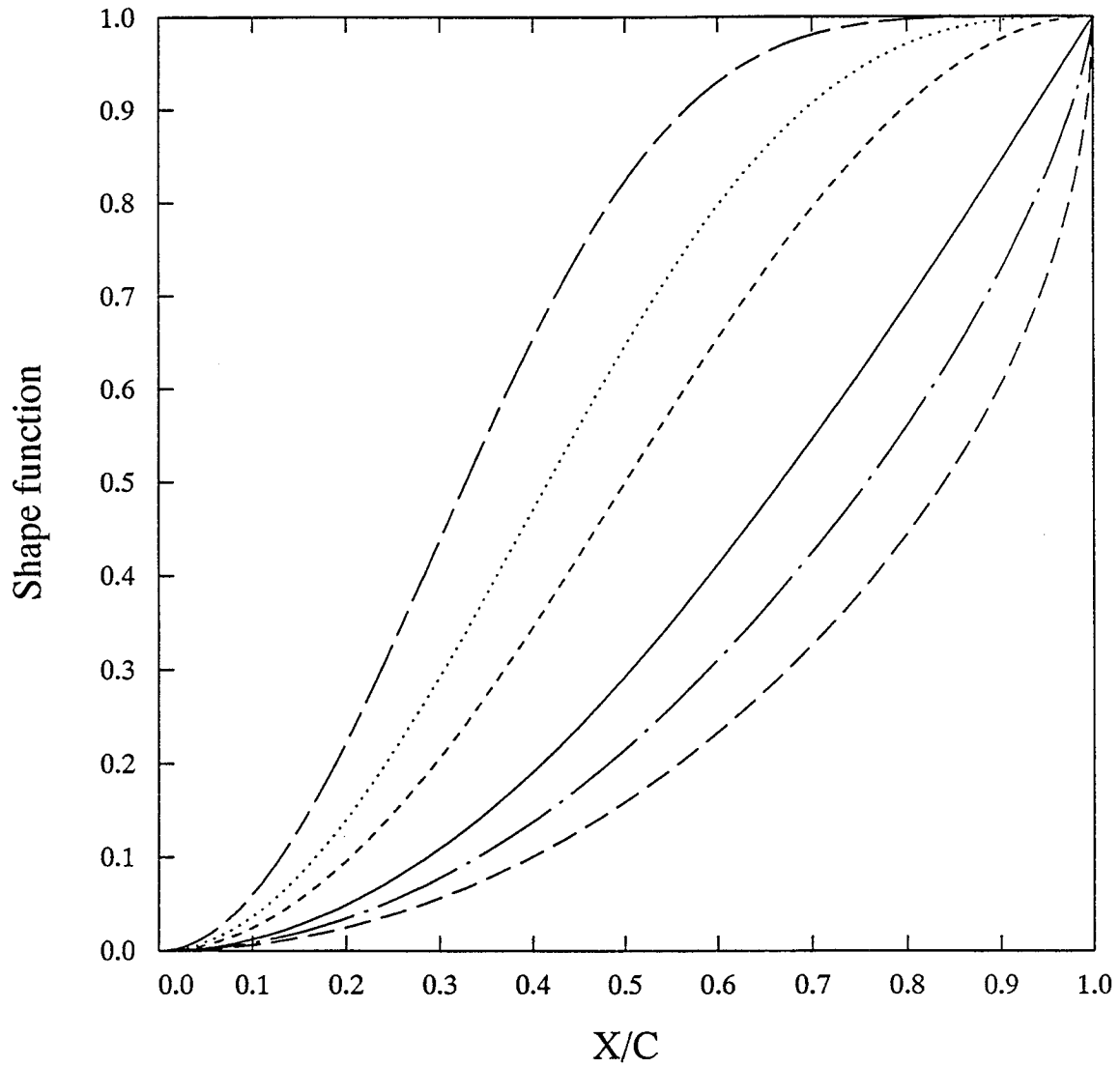
- | | | | |
|-------|-------------|-------|-------------|
| — | POWER 1.000 | — — | POWER 5.000 |
| - - - | POWER 2.000 | — · — | POWER 0.700 |
| ····· | POWER 3.000 | - - - | POWER 0.500 |



RCOS

(1 - 1/4 cosine, peak at right) POWER

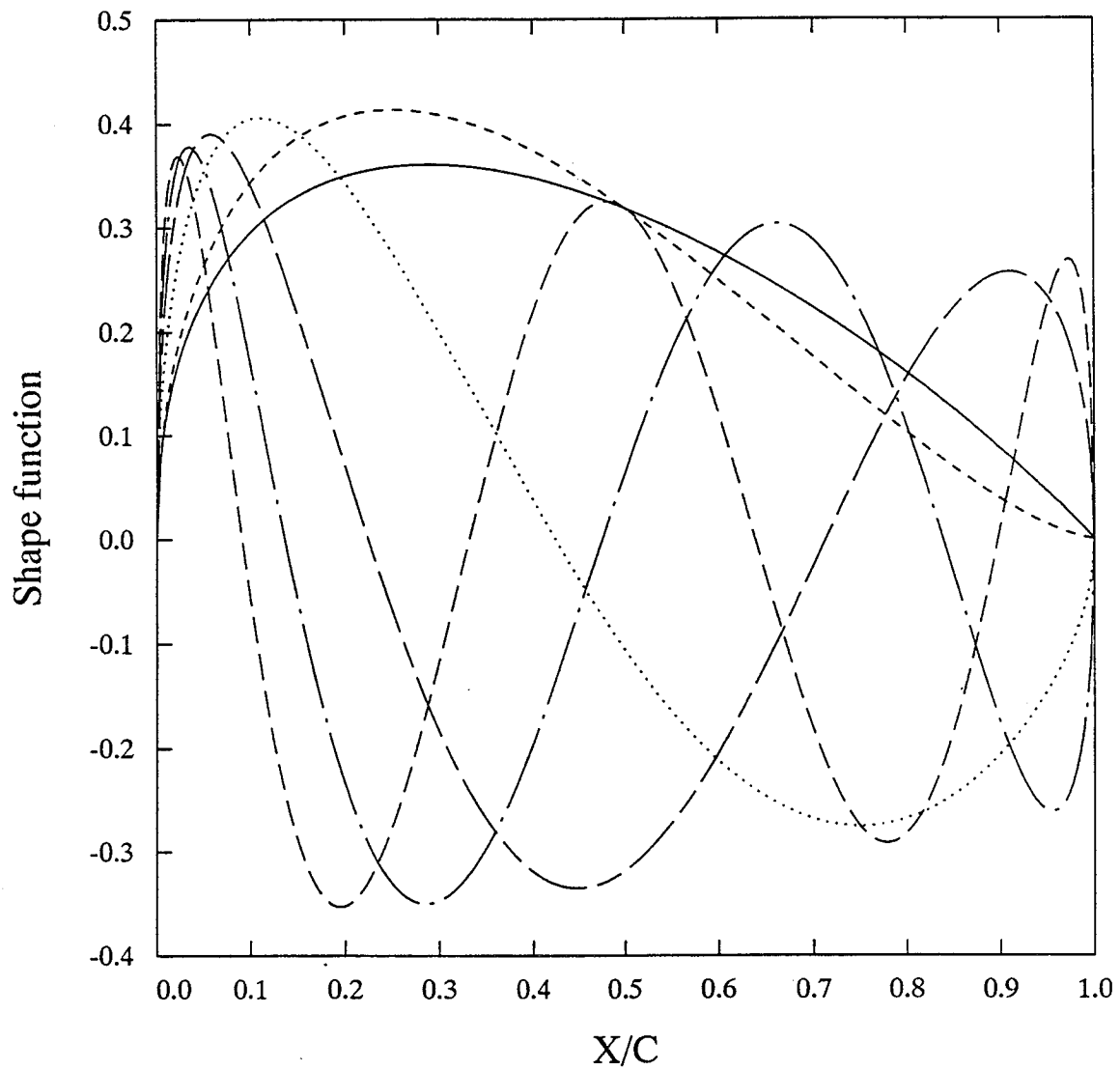
- | | | | |
|-----------|-------------|-----------|-------------|
| ———— | POWER 1.000 | — — — | POWER 5.000 |
| - - - - - | POWER 2.000 | — · — | POWER 0.700 |
| ····· | POWER 3.000 | - - - - - | POWER 0.500 |



WAGNER

$$\left(\frac{\sin(Nt)}{N} + \frac{\sin((N-1)t)}{N-1} \right) / \pi; \quad t = 2 \sin^{-1} \sqrt{x} \quad (N > 1)$$

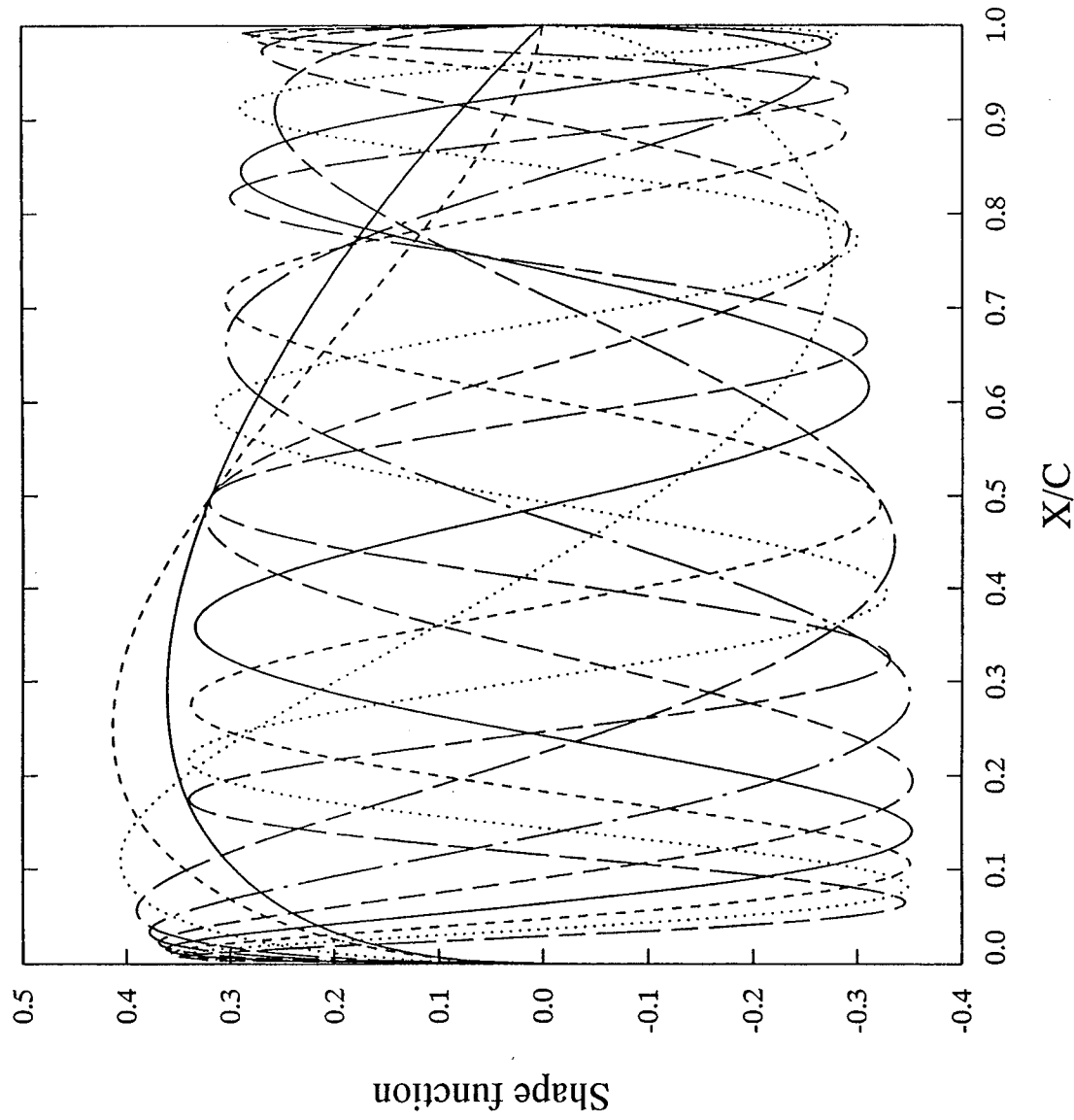
- | | | | |
|-------|-------|-------|-------|
| — | N = 1 | — — | N = 4 |
| - - - | N = 2 | — · — | N = 5 |
| ····· | N = 3 | - - - | N = 6 |



WAGNER

$$\left(\frac{\sin(Nt)}{N} + \frac{\sin((N-1)t)}{N-1} \right) / \pi; \quad t = 2 \sin^{-1} \sqrt{x} \quad (N > 1)$$

- | | | | |
|-------|-------|-------|--------|
| — | N = 1 | --- | N = 6 |
| - - - | N = 2 | — | N = 7 |
| ..... | N = 3 | - - - | N = 8 |
| — | N = 4 | ..... | N = 9 |
| — | N = 5 | — | N = 10 |



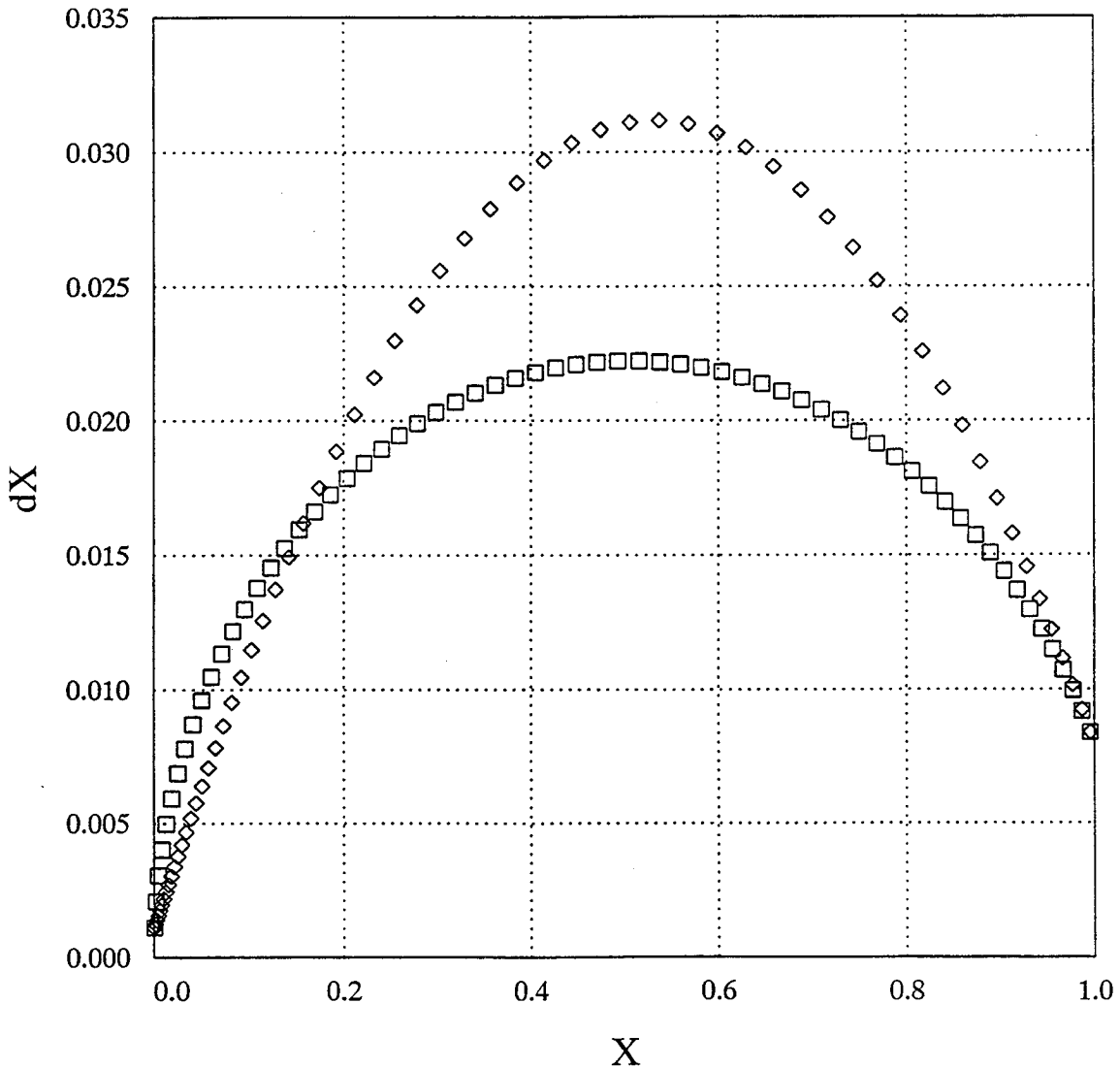
APPENDIX D: Coordinate Redistribution Illustrations

The following plots illustrate the behavior of various options available with PROFILE's REDISTRIBUTE mode for generating new coordinate distributions. The redistributions may be applied in terms of x or along the arc (either as a single curve or as two distinct curves). The composite Linear/Quadratic/Sine/Cosine and Vinokur distributions are generally preferable to any of the simpler sinusoidal distributions.

REDISTRIBUTE Options (1)

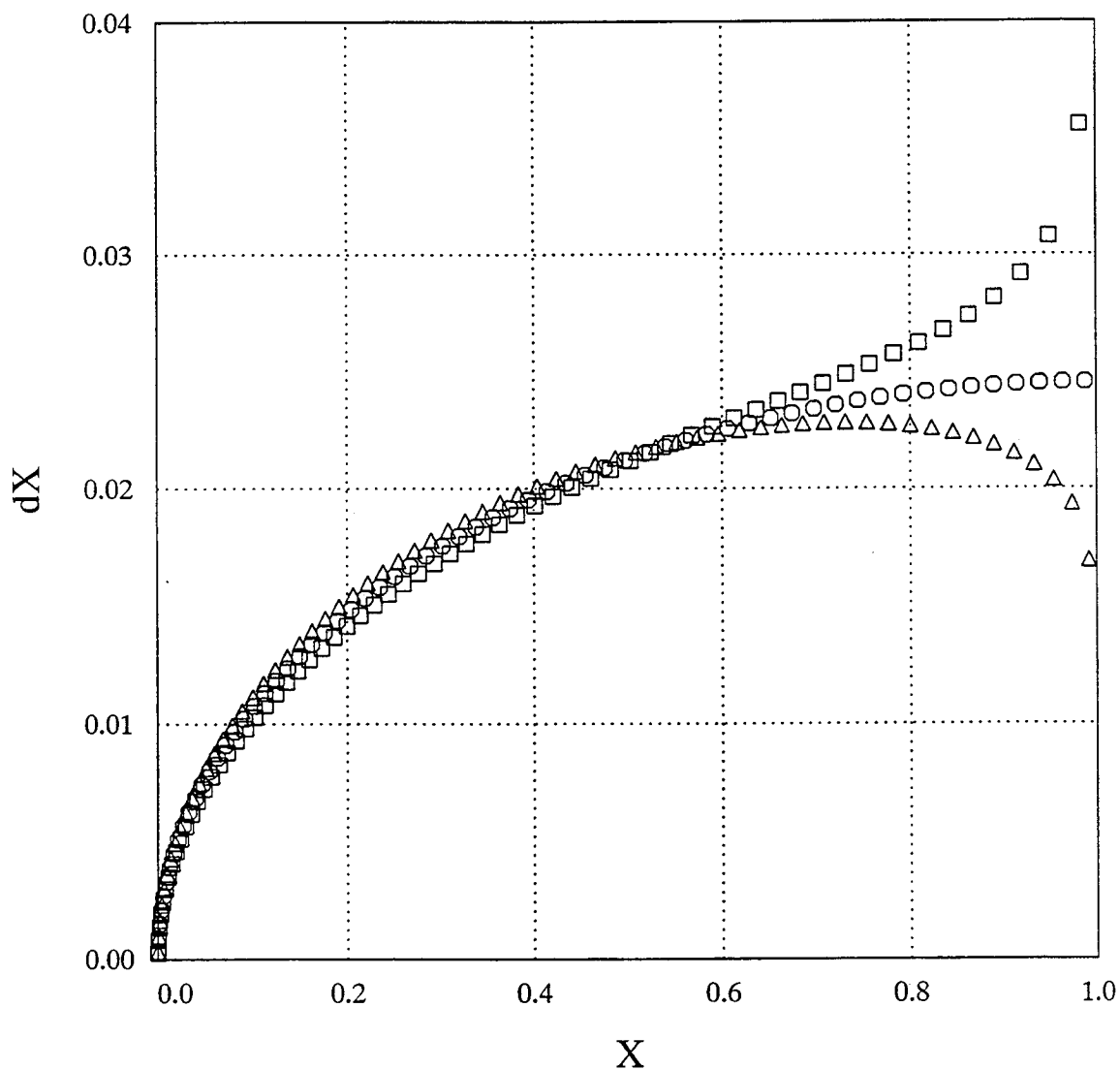
Suggested Linear/Quadratic/Sine/Cosine vs. Equivalent Vinokur Distribution (HTDIS2)

- FOILGRD: L/Q/S/C weights: 0.04, 0.00, 0.30, 0.66 Gmax: 1.88 at pt. 2 of 65
- ◇ HTDIS2: dX(1) = 0.001112856 dX(N-1) = 0.008384824 Gmax: 1.12 at pt. 2 of 65



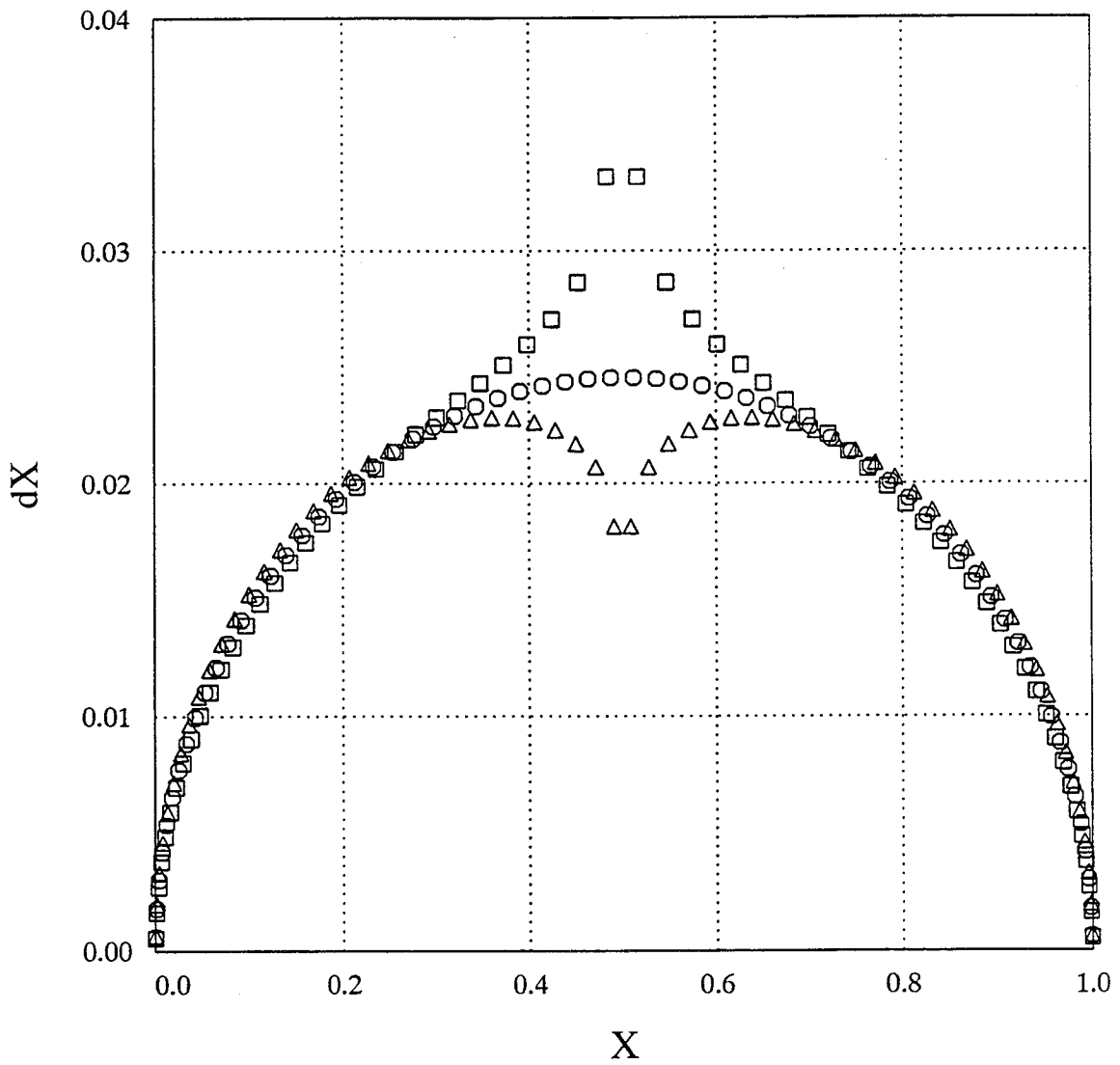
REDISTRIBUTE Options (2) One-sided sinusoidal bunching

- DSTRIB Mode = 1 Power = 0.900 Gmax: 3.00 at pt. 2 of 65
- DSTRIB Mode = 1 Power = 1.000 Gmax: 3.00 at pt. 2 of 65
- △ DSTRIB Mode = 1 Power = 1.100 Gmax: 3.00 at pt. 2 of 65



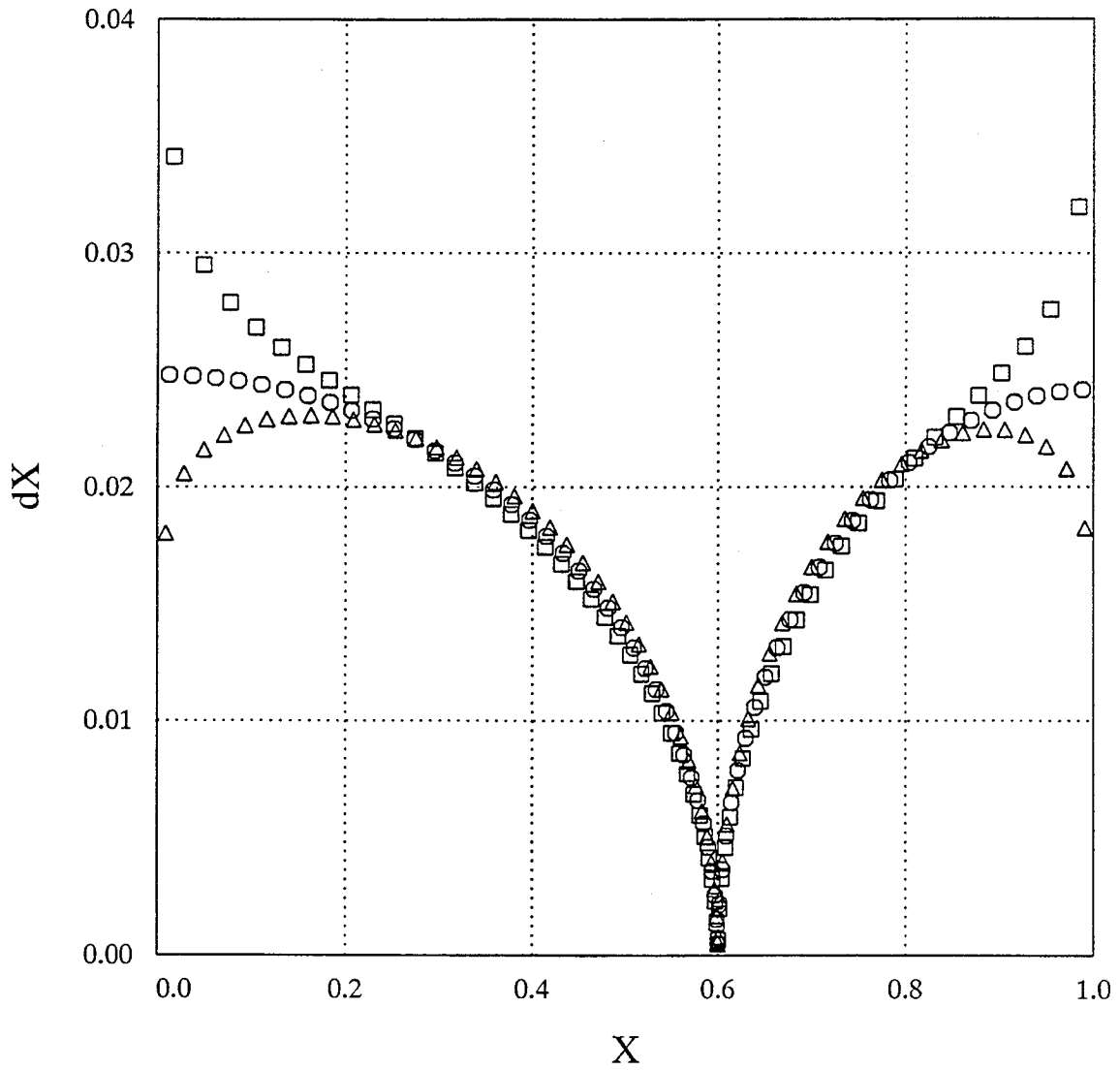
REDISTRIBUTE Options (3) Two-sided sinusoidal bunching

- DSTRIB Mode = 2 Power = 0.900 Gmax: -3.00 at pt. 64 of 65
- DSTRIB Mode = 2 Power = 1.000 Gmax: -3.00 at pt. 64 of 65
- △ DSTRIB Mode = 2 Power = 1.100 Gmax: -3.00 at pt. 64 of 65



REDISTRIBUTE Options (4) Sinusoidal bunching around an internal point

- DSTRIB Mode = 0 Power = 0.900 Gmax: -3.00 at pt. 38 of 65
- DSTRIB Mode = 0 Power = 1.000 Gmax: -3.00 at pt. 38 of 65
- △ DSTRIB Mode = 0 Power = 1.100 Gmax: -3.00 at pt. 38 of 65



APPENDIX E: Sample PROFILE Sessions and/or Results

Mode 0: Plots/tabulations (NACA 0012 airfoil)

Terminal session:

```
$ profile
```

```
Welcome to PROFILE from the Aerodynamics Division, NASA Ames.
```

```

0 = DISPLAY (plot/tabulate only or alter format/precision)
1 = RECTIFY leading edge definition; allows vertical shift
2 = NORMALIZE or denormalize coordinates
3 = REDISTRIBUTE the abscissas
4 = MODIFY either surface or both (apply shape functions)
5 = REFINE thickness/curvature
6 = OPTIMIZE one surface ("bumps" + target curvatures)
7 = TRANSFORM YU/YL to/from camber/thickness, or decamber
8 = ROTATE coordinates, with option to renormalize
9 = COMBINE option (add or subtract profiles)
10 = LOFT linearly between primary and secondary profiles
11 = NOSE-JOB option: round or sharpen the leading edge
12 = SMOOTH YU and/or YL: Wagner fn. fits or [im|ex]plicit

```

Select operating mode.

```
? = menu; CTRL Z = quit; <CR> = DISPLAY:
```

```
Input airfoil file? <CR>=naca0012.dat:
```

```
Input control file? <CR>=profile.inp or none:
```

```
No control file found - proceeding ...
```

```
Identifier for output files? <CR>="profile": mode0
```

```
Plot title line? <CR> uses "PROFILE" for the title:
```

```
NACA 0012 Airfoil
```

```
Plot subtitle line? <CR> means none:
```

```
Do you really want Cp estimates? (Y/N; <CR>=No)
```

```

Maximum thickness/chord (current axes) . . 12.0034% at X/C = 0.30000
Maximum camber/chord . . . . . 0.0001% at X/C = 0.84000
Unnormalized area . . . . . 0.822060E-01
Moment of inertia about X axis . . . . . 0.680856E-04

```

```

Airfoil plot file:      mode0.plt
Tabulated results:     mode0.tab
Curvature QPLOT file: mode0.crv
2nd derivatives file:  mode0.ypp
Spreadsheet file:      mode0.spread

```


Printable results (mode0.tab file):

Program PROFILE (Applied Aerodynamics Branch, NASA Ames)

Operating mode: 0 - DISPLAY

Control file :

Geometry file : naca0012.dat

Output file id: mode0

Profiles found: 1

Control file was absent - all defaults taken.

<continued on next page>

NACA 0012

Upper surface

Number of points: 72

Derivatives and curvature calculated by nonparametric finite differencing.

| X | Y | Y' | Y'' | CURVATURE |
|--------------|--------------|---------------|---------------|---------------|
| 0.000000E+00 | 0.000000E+00 | 0.134163E+02 | -0.223133E+05 | -0.916334E+01 |
| 0.200000E-03 | 0.223700E-02 | 0.895367E+01 | -0.223133E+05 | -0.305131E+02 |
| 0.500000E-03 | 0.391900E-02 | 0.473342E+01 | -0.582166E+04 | -0.514136E+02 |
| 0.100000E-02 | 0.555800E-02 | 0.280086E+01 | -0.190857E+04 | -0.725563E+02 |
| 0.120000E-02 | 0.608000E-02 | 0.250867E+01 | -0.101334E+04 | -0.514467E+02 |
| 0.150000E-02 | 0.678700E-02 | 0.224392E+01 | -0.751671E+03 | -0.506984E+02 |
| 0.200000E-02 | 0.781500E-02 | 0.194167E+01 | -0.457331E+03 | -0.438979E+02 |
| 0.300000E-02 | 0.952800E-02 | 0.157250E+01 | -0.281001E+03 | -0.434206E+02 |
| 0.400000E-02 | 0.109600E-01 | 0.134250E+01 | -0.178999E+03 | -0.381572E+02 |
| 0.500000E-02 | 0.122130E-01 | 0.118900E+01 | -0.128002E+03 | -0.341338E+02 |
| 0.600000E-02 | 0.133380E-01 | 0.107600E+01 | -0.979993E+02 | -0.309182E+02 |
| 0.700000E-02 | 0.143650E-01 | 0.989000E+00 | -0.759996E+02 | -0.273169E+02 |
| 0.800000E-02 | 0.153160E-01 | 0.918001E+00 | -0.659992E+02 | -0.263844E+02 |
| 0.900000E-02 | 0.162010E-01 | 0.860500E+00 | -0.490014E+02 | -0.213409E+02 |
| 0.100000E-01 | 0.170370E-01 | 0.814666E+00 | -0.426670E+02 | -0.198832E+02 |
| 0.120000E-01 | 0.185810E-01 | 0.738266E+00 | -0.337329E+02 | -0.175649E+02 |
| 0.150000E-01 | 0.206440E-01 | 0.651342E+00 | -0.242167E+02 | -0.142475E+02 |
| 0.200000E-01 | 0.235980E-01 | 0.553967E+00 | -0.147333E+02 | -0.986162E+01 |
| 0.300000E-01 | 0.284010E-01 | 0.433950E+00 | -0.927001E+01 | -0.715623E+01 |
| 0.400000E-01 | 0.322770E-01 | 0.357300E+00 | -0.605999E+01 | -0.506061E+01 |
| 0.500000E-01 | 0.355470E-01 | 0.304950E+00 | -0.440999E+01 | -0.385932E+01 |
| 0.600000E-01 | 0.383760E-01 | 0.266867E+00 | -0.320667E+01 | -0.289226E+01 |
| 0.800000E-01 | 0.430720E-01 | 0.211300E+00 | -0.235000E+01 | -0.220096E+01 |
| 0.100000E+00 | 0.468280E-01 | 0.169875E+00 | -0.179250E+01 | -0.171762E+01 |
| 0.120000E+00 | 0.498670E-01 | 0.138650E+00 | -0.133000E+01 | -0.129255E+01 |
| 0.140000E+00 | 0.523740E-01 | 0.113700E+00 | -0.116501E+01 | -0.114278E+01 |
| 0.160000E+00 | 0.544150E-01 | 0.920500E-01 | -0.999992E+00 | -0.987416E+00 |
| 0.180000E+00 | 0.560560E-01 | 0.740000E-01 | -0.805004E+00 | -0.798437E+00 |
| 0.200000E+00 | 0.573750E-01 | 0.580750E-01 | -0.787499E+00 | -0.783532E+00 |
| 0.220000E+00 | 0.583790E-01 | 0.438251E-01 | -0.637491E+00 | -0.635659E+00 |
| 0.240000E+00 | 0.591280E-01 | 0.313751E-01 | -0.607511E+00 | -0.606615E+00 |
| 0.260000E+00 | 0.596340E-01 | 0.198000E-01 | -0.549993E+00 | -0.549670E+00 |
| 0.280000E+00 | 0.599200E-01 | 0.957502E-02 | -0.472506E+00 | -0.472441E+00 |
| 0.300000E+00 | 0.600170E-01 | 0.749645E-04 | -0.477499E+00 | -0.477499E+00 |
| 0.320000E+00 | 0.599230E-01 | -0.867499E-02 | -0.397497E+00 | -0.397453E+00 |
| 0.340000E+00 | 0.596700E-01 | -0.165250E-01 | -0.387504E+00 | -0.387346E+00 |
| 0.360000E+00 | 0.592620E-01 | -0.240251E-01 | -0.362501E+00 | -0.362187E+00 |
| 0.380000E+00 | 0.587090E-01 | -0.308000E-01 | -0.314990E+00 | -0.314542E+00 |
| 0.400000E+00 | 0.580300E-01 | -0.371500E-01 | -0.320015E+00 | -0.319353E+00 |
| 0.420000E+00 | 0.572230E-01 | -0.431251E-01 | -0.277494E+00 | -0.276721E+00 |
| 0.440000E+00 | 0.563050E-01 | -0.485500E-01 | -0.264998E+00 | -0.264064E+00 |
| 0.460000E+00 | 0.552810E-01 | -0.537500E-01 | -0.255000E+00 | -0.253899E+00 |
| 0.480000E+00 | 0.541550E-01 | -0.585250E-01 | -0.222498E+00 | -0.221360E+00 |
| 0.500000E+00 | 0.529400E-01 | -0.630500E-01 | -0.230004E+00 | -0.228639E+00 |
| 0.520000E+00 | 0.516330E-01 | -0.673499E-01 | -0.199991E+00 | -0.198638E+00 |
| 0.540000E+00 | 0.502460E-01 | -0.713000E-01 | -0.195011E+00 | -0.193533E+00 |
| 0.560000E+00 | 0.487810E-01 | -0.751251E-01 | -0.187504E+00 | -0.185928E+00 |
| 0.580000E+00 | 0.472410E-01 | -0.786749E-01 | -0.167477E+00 | -0.165934E+00 |
| 0.600000E+00 | 0.456340E-01 | -0.821249E-01 | -0.177522E+00 | -0.175741E+00 |

| | | | | |
|--------------|--------------|---------------|---------------|---------------|
| 0.620000E+00 | 0.439560E-01 | -0.854251E-01 | -0.152495E+00 | -0.150841E+00 |
| 0.640000E+00 | 0.422170E-01 | -0.885000E-01 | -0.154996E+00 | -0.153193E+00 |
| 0.660000E+00 | 0.404160E-01 | -0.915500E-01 | -0.150003E+00 | -0.148137E+00 |
| 0.680000E+00 | 0.385550E-01 | -0.944250E-01 | -0.137501E+00 | -0.135682E+00 |
| 0.700000E+00 | 0.366390E-01 | -0.972749E-01 | -0.147488E+00 | -0.145419E+00 |
| 0.720000E+00 | 0.346640E-01 | -0.100050E+00 | -0.130018E+00 | -0.128090E+00 |
| 0.740000E+00 | 0.326370E-01 | -0.102725E+00 | -0.137496E+00 | -0.135348E+00 |
| 0.760000E+00 | 0.305550E-01 | -0.105475E+00 | -0.137501E+00 | -0.135238E+00 |
| 0.780000E+00 | 0.284180E-01 | -0.108100E+00 | -0.124986E+00 | -0.122827E+00 |
| 0.800000E+00 | 0.262310E-01 | -0.110750E+00 | -0.140017E+00 | -0.137480E+00 |
| 0.820000E+00 | 0.239880E-01 | -0.113425E+00 | -0.127494E+00 | -0.125072E+00 |
| 0.840000E+00 | 0.216940E-01 | -0.116125E+00 | -0.142489E+00 | -0.139655E+00 |
| 0.860000E+00 | 0.193430E-01 | -0.118925E+00 | -0.137513E+00 | -0.134647E+00 |
| 0.880000E+00 | 0.169370E-01 | -0.121650E+00 | -0.135005E+00 | -0.132062E+00 |
| 0.900000E+00 | 0.144770E-01 | -0.124525E+00 | -0.152479E+00 | -0.149000E+00 |
| 0.920000E+00 | 0.119560E-01 | -0.127475E+00 | -0.142518E+00 | -0.139113E+00 |
| 0.940000E+00 | 0.937800E-02 | -0.130475E+00 | -0.157502E+00 | -0.153564E+00 |
| 0.960000E+00 | 0.673700E-02 | -0.133616E+00 | -0.156612E+00 | -0.152510E+00 |
| 0.970000E+00 | 0.539300E-02 | -0.135250E+00 | -0.170079E+00 | -0.165516E+00 |
| 0.980000E+00 | 0.403200E-02 | -0.136950E+00 | -0.170002E+00 | -0.165329E+00 |
| 0.990000E+00 | 0.265400E-02 | -0.138867E+00 | -0.213333E+00 | -0.207308E+00 |
| 0.995000E+00 | 0.195700E-02 | -0.139400E+00 | 0.000000E+00 | 0.000000E+00 |
| 0.100000E+01 | 0.126000E-02 | -0.139400E+00 | 0.000000E+00 | 0.000000E+00 |

NACA 0012

Lower surface

Number of points: 72

Derivatives and curvature calculated by nonparametric finite differencing.

| X | Y | Y' | Y'' | CURVATURE |
|--------------|---------------|---------------|--------------|--------------|
| 0.000000E+00 | 0.000000E+00 | -0.134163E+02 | 0.223133E+05 | 0.916334E+01 |
| 0.200000E-03 | -0.223700E-02 | -0.895367E+01 | 0.223133E+05 | 0.305131E+02 |
| 0.500000E-03 | -0.391900E-02 | -0.473342E+01 | 0.582166E+04 | 0.514136E+02 |
| 0.100000E-02 | -0.555800E-02 | -0.280086E+01 | 0.190857E+04 | 0.725563E+02 |
| 0.120000E-02 | -0.608000E-02 | -0.250867E+01 | 0.101334E+04 | 0.514467E+02 |
| 0.150000E-02 | -0.678700E-02 | -0.224392E+01 | 0.751671E+03 | 0.506984E+02 |
| 0.200000E-02 | -0.781500E-02 | -0.194167E+01 | 0.457331E+03 | 0.438979E+02 |
| 0.300000E-02 | -0.952800E-02 | -0.157250E+01 | 0.281001E+03 | 0.434206E+02 |
| 0.400000E-02 | -0.109600E-01 | -0.134250E+01 | 0.178999E+03 | 0.381572E+02 |
| 0.500000E-02 | -0.122130E-01 | -0.118900E+01 | 0.128002E+03 | 0.341338E+02 |
| 0.600000E-02 | -0.133380E-01 | -0.107600E+01 | 0.979993E+02 | 0.309182E+02 |
| 0.700000E-02 | -0.143650E-01 | -0.989000E+00 | 0.759996E+02 | 0.273169E+02 |
| 0.800000E-02 | -0.153160E-01 | -0.918001E+00 | 0.659992E+02 | 0.263844E+02 |
| 0.900000E-02 | -0.162010E-01 | -0.860500E+00 | 0.490014E+02 | 0.213409E+02 |
| 0.100000E-01 | -0.170370E-01 | -0.814666E+00 | 0.426670E+02 | 0.198832E+02 |
| 0.120000E-01 | -0.185810E-01 | -0.738266E+00 | 0.337329E+02 | 0.175649E+02 |
| 0.150000E-01 | -0.206440E-01 | -0.651342E+00 | 0.242167E+02 | 0.142475E+02 |
| 0.200000E-01 | -0.235980E-01 | -0.553967E+00 | 0.147333E+02 | 0.986162E+01 |
| 0.300000E-01 | -0.284010E-01 | -0.433950E+00 | 0.927001E+01 | 0.715623E+01 |
| 0.400000E-01 | -0.322770E-01 | -0.357300E+00 | 0.605999E+01 | 0.506061E+01 |
| 0.500000E-01 | -0.355470E-01 | -0.304950E+00 | 0.440999E+01 | 0.385932E+01 |
| 0.600000E-01 | -0.383760E-01 | -0.266867E+00 | 0.320667E+01 | 0.289226E+01 |
| 0.800000E-01 | -0.430720E-01 | -0.211300E+00 | 0.235000E+01 | 0.220096E+01 |
| 0.100000E+00 | -0.468280E-01 | -0.169875E+00 | 0.179250E+01 | 0.171762E+01 |
| 0.120000E+00 | -0.498670E-01 | -0.138650E+00 | 0.133000E+01 | 0.129255E+01 |
| 0.140000E+00 | -0.523740E-01 | -0.113700E+00 | 0.116501E+01 | 0.114278E+01 |
| 0.160000E+00 | -0.544150E-01 | -0.920500E-01 | 0.999992E+00 | 0.987416E+00 |
| 0.180000E+00 | -0.560560E-01 | -0.740000E-01 | 0.805004E+00 | 0.798437E+00 |
| 0.200000E+00 | -0.573750E-01 | -0.580750E-01 | 0.787499E+00 | 0.783532E+00 |
| 0.220000E+00 | -0.583790E-01 | -0.438251E-01 | 0.637491E+00 | 0.635659E+00 |
| 0.240000E+00 | -0.591280E-01 | -0.313751E-01 | 0.607511E+00 | 0.606615E+00 |
| 0.260000E+00 | -0.596340E-01 | -0.198000E-01 | 0.549993E+00 | 0.549670E+00 |
| 0.280000E+00 | -0.599200E-01 | -0.957502E-02 | 0.472506E+00 | 0.472441E+00 |
| 0.300000E+00 | -0.600170E-01 | -0.749645E-04 | 0.477499E+00 | 0.477499E+00 |
| 0.320000E+00 | -0.599230E-01 | 0.867499E-02 | 0.397497E+00 | 0.397453E+00 |
| 0.340000E+00 | -0.596700E-01 | 0.165250E-01 | 0.387504E+00 | 0.387346E+00 |
| 0.360000E+00 | -0.592620E-01 | 0.240251E-01 | 0.362501E+00 | 0.362187E+00 |
| 0.380000E+00 | -0.587090E-01 | 0.308000E-01 | 0.314990E+00 | 0.314542E+00 |
| 0.400000E+00 | -0.580300E-01 | 0.371500E-01 | 0.320015E+00 | 0.319353E+00 |
| 0.420000E+00 | -0.572230E-01 | 0.431251E-01 | 0.277494E+00 | 0.276721E+00 |
| 0.440000E+00 | -0.563050E-01 | 0.485500E-01 | 0.264998E+00 | 0.264064E+00 |
| 0.460000E+00 | -0.552810E-01 | 0.537500E-01 | 0.255000E+00 | 0.253899E+00 |
| 0.480000E+00 | -0.541550E-01 | 0.585250E-01 | 0.222498E+00 | 0.221360E+00 |
| 0.500000E+00 | -0.529400E-01 | 0.630500E-01 | 0.230004E+00 | 0.228639E+00 |
| 0.520000E+00 | -0.516330E-01 | 0.673499E-01 | 0.199991E+00 | 0.198638E+00 |
| 0.540000E+00 | -0.502460E-01 | 0.713000E-01 | 0.195011E+00 | 0.193533E+00 |
| 0.560000E+00 | -0.487810E-01 | 0.751251E-01 | 0.187504E+00 | 0.185928E+00 |
| 0.580000E+00 | -0.472410E-01 | 0.786749E-01 | 0.167477E+00 | 0.165934E+00 |
| 0.600000E+00 | -0.456340E-01 | 0.821249E-01 | 0.177522E+00 | 0.175741E+00 |

| | | | | |
|--------------|---------------|--------------|--------------|--------------|
| 0.620000E+00 | -0.439560E-01 | 0.854251E-01 | 0.152495E+00 | 0.150841E+00 |
| 0.640000E+00 | -0.422170E-01 | 0.885000E-01 | 0.154996E+00 | 0.153193E+00 |
| 0.660000E+00 | -0.404160E-01 | 0.915500E-01 | 0.150003E+00 | 0.148137E+00 |
| 0.680000E+00 | -0.385550E-01 | 0.944250E-01 | 0.137501E+00 | 0.135682E+00 |
| 0.700000E+00 | -0.366390E-01 | 0.972749E-01 | 0.147488E+00 | 0.145419E+00 |
| 0.720000E+00 | -0.346640E-01 | 0.100050E+00 | 0.130018E+00 | 0.128090E+00 |
| 0.740000E+00 | -0.326370E-01 | 0.102725E+00 | 0.137496E+00 | 0.135348E+00 |
| 0.760000E+00 | -0.305550E-01 | 0.105475E+00 | 0.137501E+00 | 0.135238E+00 |
| 0.780000E+00 | -0.284180E-01 | 0.108100E+00 | 0.124986E+00 | 0.122827E+00 |
| 0.800000E+00 | -0.262310E-01 | 0.110750E+00 | 0.140017E+00 | 0.137480E+00 |
| 0.820000E+00 | -0.239880E-01 | 0.113450E+00 | 0.129995E+00 | 0.127525E+00 |
| 0.840000E+00 | -0.216930E-01 | 0.116125E+00 | 0.137488E+00 | 0.134753E+00 |
| 0.860000E+00 | -0.193430E-01 | 0.118900E+00 | 0.140014E+00 | 0.137096E+00 |
| 0.880000E+00 | -0.169370E-01 | 0.121650E+00 | 0.135005E+00 | 0.132062E+00 |
| 0.900000E+00 | -0.144770E-01 | 0.124525E+00 | 0.152479E+00 | 0.149000E+00 |
| 0.920000E+00 | -0.119560E-01 | 0.127475E+00 | 0.142518E+00 | 0.139113E+00 |
| 0.940000E+00 | -0.937800E-02 | 0.130475E+00 | 0.157502E+00 | 0.153564E+00 |
| 0.960000E+00 | -0.673700E-02 | 0.133616E+00 | 0.156612E+00 | 0.152510E+00 |
| 0.970000E+00 | -0.539300E-02 | 0.135250E+00 | 0.170079E+00 | 0.165516E+00 |
| 0.980000E+00 | -0.403200E-02 | 0.136950E+00 | 0.170002E+00 | 0.165329E+00 |
| 0.990000E+00 | -0.265400E-02 | 0.138867E+00 | 0.213333E+00 | 0.207308E+00 |
| 0.995000E+00 | -0.195700E-02 | 0.139400E+00 | 0.000000E+00 | 0.000000E+00 |
| 0.100000E+01 | -0.126000E-02 | 0.139400E+00 | 0.000000E+00 | 0.000000E+00 |

Maximum thickness/chord (current axes) . . . 12.0034% at X/C = 0.30000
 Maximum camber/chord 0.0001% at X/C = 0.84000
 Unnormalized area 0.822060E-01
 Moment of inertia about X axis 0.680856E-04

L.E.: 0.000000E+00 0.000000E+00 Chord: 0.100000E+01
 Mean-line angle at T.E. (deg.) 0.00

Mode 1: Rectify leading edge (NACA 6-series airfoil)

The leading edge of the NACA 6-series airfoil used here is not the most forward point on the airfoil. Note the negative abscissas on the upper surface in the set of tabulated coordinates for the input profile. To avoid problems with spline fitting, estimating derivatives, and applying shape functions, the leading edge definition needs to be "rectified" so that both surfaces are monotonic.

Terminal session:

```
$ profile
```

```
Welcome to PROFILE from the Aerodynamics Division, NASA Ames.
```

```
0 = DISPLAY (plot/tabulate only or alter format/precision)
1 = RECTIFY leading edge definition; allows vertical shift
2 = NORMALIZE or denormalize coordinates
3 = REDISTRIBUTE the abscissas
4 = MODIFY either surface or both (apply shape functions)
5 = REFINE thickness/curvature
6 = OPTIMIZE one surface ("bumps" + target curvatures)
7 = TRANSFORM YU/YL to/from camber/thickness, or decamber
8 = ROTATE coordinates, with option to renormalize
9 = COMBINE option (add or subtract profiles)
10 = LOFT linearly between primary and secondary profiles
11 = NOSE-JOB option: round or sharpen the leading edge
12 = SMOOTH YU and/or YL: Wagner fn. fits or [im|ex]plicit
```

Select operating mode.

```
? = menu; CTRL Z = quit; <CR> = DISPLAY: rectify
Input airfoil file? <CR>=naca0012.dat: naca64412.dat
Input control file? <CR>=profile.inp or none:
No control file found - proceeding ...
Identifier for output files? <CR>="profile": model
Plot title line? <CR> uses "PROFILE" for the title:
NACA 64412 Airfoil
Plot subtitle line? <CR> means none:
```

```
Do you really want Cp estimates? (Y/N; <CR>=No)
```

```
You have an option to shift the airfoil vertically.
The current leading edge ordinate is 0.002297
Enter a new leading edge ordinate or <CR> to leave as is:
```

Revised

```
Maximum thickness/chord (current axes) . . . 11.9988% at X/C = 0.37914
Maximum camber/chord . . . . . 1.9764% at X/C = 0.50006
Unnormalized area . . . . . 0.759163E-01
Moment of inertia about X axis . . . . . 0.820044E-04
```

```
Cannot give spreadsheet file: upper/lower Xs differ.
Use REDISTRIBUTE mode first.
```

```
Modified airfoil:      model.dat
Airfoil plot file:    model.plt
Tabulated results:    model.tab
Curvature QPLOT file: model.crv
2nd derivatives file: model.ypp
```

Program PROFILE (Applied Aerodynamics Branch, NASA Ames)

Operating mode: 1 - RECTIFY
 Control file :
 Geometry file : naca64412.dat
 Output file id: model
 Profiles found: 1

Control file was absent - all defaults taken.

NACA 64412 Airfoil

Revised upper surface

Number of points: 175

Derivatives and curvature calculated by nonparametric finite differencing.

| X | Y | Y' | Y'' | CURVATURE |
|---------------|--------------|---------------|---------------|---------------|
| -0.125000E-03 | 0.229700E-02 | 0.952000E+01 | 0.000000E+00 | 0.000000E+00 |
| -0.250000E-04 | 0.324900E-02 | 0.796281E+01 | -0.311438E+05 | -0.602530E+02 |
| 0.105000E-03 | 0.402100E-02 | 0.508383E+01 | -0.131481E+05 | -0.945279E+02 |
| 0.259000E-03 | 0.464800E-02 | 0.371525E+01 | -0.462567E+04 | -0.812167E+02 |
| 0.425000E-03 | 0.520100E-02 | 0.320541E+01 | -0.151698E+04 | -0.400704E+02 |
| 0.595000E-03 | 0.572400E-02 | 0.287323E+01 | -0.239115E+04 | -0.849206E+02 |
| . | . | . | . | . |
| . | . | . | . | . |
| 0.950269E+00 | 0.919000E-02 | -0.179678E+00 | 0.976517E-01 | 0.931066E-01 |
| 0.960208E+00 | 0.740900E-02 | -0.178982E+00 | 0.423161E-01 | 0.403612E-01 |
| 0.970148E+00 | 0.563200E-02 | -0.178805E+00 | -0.656194E-02 | -0.625937E-02 |
| 0.980090E+00 | 0.385400E-02 | -0.180442E+00 | -0.322791E+00 | -0.307644E+00 |
| 0.990038E+00 | 0.204300E-02 | -0.193566E+00 | -0.231577E+01 | -0.219146E+01 |
| 0.999999E+00 | 0.000000E+00 | -0.205100E+00 | 0.000000E+00 | 0.000000E+00 |

NACA 64412 airfoil with rectified leading edge

Revised lower surface

Number of points: 177

| X | Y | Y' | Y'' | CURVATURE |
|---------------|---------------|---------------|---------------|---------------|
| -0.125000E-03 | 0.229700E-02 | -0.183760E+02 | 0.000000E+00 | 0.000000E+00 |
| 0.000000E+00 | 0.000000E+00 | -0.158864E+02 | 0.398336E+05 | 0.987636E+01 |
| 0.625000E-03 | -0.214900E-02 | -0.260249E+01 | 0.267493E+04 | 0.123434E+03 |
| 0.102500E-02 | -0.297600E-02 | -0.191169E+01 | 0.779046E+03 | 0.775792E+02 |
| 0.139500E-02 | -0.363000E-02 | -0.162333E+01 | 0.779684E+03 | 0.112494E+03 |
| 0.174100E-02 | -0.414500E-02 | -0.140749E+01 | 0.467941E+03 | 0.909169E+02 |
| . | . | . | . | . |
| . | . | . | . | . |
| 0.949730E+00 | 0.344800E-02 | -0.919361E-02 | -0.143251E+01 | -0.143233E+01 |
| 0.959791E+00 | 0.328300E-02 | -0.249499E-01 | -0.169962E+01 | -0.169803E+01 |
| 0.969851E+00 | 0.294600E-02 | -0.444898E-01 | -0.218504E+01 | -0.217857E+01 |
| 0.979909E+00 | 0.238800E-02 | -0.708196E-01 | -0.305057E+01 | -0.302776E+01 |
| 0.989961E+00 | 0.152200E-02 | -0.118911E+00 | -0.651794E+01 | -0.638210E+01 |
| 0.999999E+00 | 0.000000E+00 | -0.151624E+00 | 0.000000E+00 | 0.000000E+00 |

Current % thickness: 11.99884
 Corresponding abscissa: 0.3790650

Mode 2: Normalize/denormalize (NACA 6-series airfoil)

The 6-series airfoil of the previous example is normalized here. Points to note:

- mode is selected by a sufficiently-unique name ("norm")
- the *.tab file is automatically suppressed because the upper and lower surfaces have dissimilar abscissas
- *denormalizing* would be invoked with a negative chord value

\$ profile

Welcome to PROFILE from the Aerodynamics Division, NASA Ames.

```

0 = DISPLAY (plot/tabulate only or alter format/precision)
1 = RECTIFY leading edge definition; allows vertical shift
2 = NORMALIZE or denormalize coordinates
3 = REDISTRIBUTE the abscissas
4 = MODIFY either surface or both (apply shape functions)
5 = REFINE thickness/curvature
6 = OPTIMIZE one surface ("bumps" + target curvatures)
7 = TRANSFORM YU/YL to/from camber/thickness, or decamber
8 = ROTATE coordinates, with option to renormalize
9 = COMBINE option (add or subtract profiles)
10 = LOFT linearly between primary and secondary profiles
11 = NOSE-JOB option: round or sharpen the leading edge
12 = SMOOTH YU and/or YL: Wagner fn. fits or [im|explicit

```

Select operating mode.

```

? = menu; CTRL Z = quit; <CR> = DISPLAY: norm
Input airfoil file? <CR>=naca0012.dat: naca64412.dat
Input control file? <CR>=profile.inp or none:
No control file found - proceeding ...
Identifier for output files? <CR>="profile": mode2
Plot title line? <CR> uses "PROFILE" for the title:
Normalize rectified NACA 64412 airfoil
Plot subtitle line? <CR> means none:

```

```

Do you really want Cp estimates? (Y/N; <CR>=No)
Current chord: 1.00012
Enter <CR> to normalize by this chord, or enter a
different chord; (a negative value de-normalizes):

```

Revised

```

Maximum thickness/chord (current axes) . . . 11.9988% at X/C = 0.37914
Maximum camber/chord . . . . . 1.9764% at X/C = 0.50006
Unnormalized area . . . . . 0.758975E-01
Moment of inertia about X axis . . . . . 0.819638E-04

```

Cannot give spreadsheet file: upper/lower Xs differ.
Use REDISTRIBUTE mode first.

```

Modified airfoil:      mode2.dat
Airfoil plot file:    mode2.plt
Tabulated results:    mode2.tab
Curvature QPLOT file: mode2.crv
2nd derivatives file: mode2.ypp

```


Mode 3: Redistribute coordinates (NACA 6-series airfoil)

Here, REDISTRIBUTE mode is used to reduce the number of points on the airfoil from 176 to 75 per surface. Points to note:

- distribution along the arc is chosen (although sometimes working with x may be preferred, particularly if abscissas common to both surfaces are desired)
- the composite Linear + Quadratic + Sine + Cosine distribution chosen, with the default weights of 0.04, 0.0, 0.3, and 0.66, is generally a good choice

\$ profile

Welcome to PROFILE from the Aerodynamics Division, NASA Ames.

```

0 = DISPLAY (plot/tabulate only or alter format/precision)
1 = RECTIFY leading edge definition; allows vertical shift
2 = NORMALIZE or denormalize coordinates
3 = REDISTRIBUTE the abscissas
4 = MODIFY either surface or both (apply shape functions)
5 = REFINE thickness/curvature
6 = OPTIMIZE one surface ("bumps" + target curvatures)
7 = TRANSFORM YU/YL to/from camber/thickness, or decamber
8 = ROTATE coordinates, with option to renormalize
9 = COMBINE option (add or subtract profiles)
10 = LOFT linearly between primary and secondary profiles
11 = NOSE-JOB option: round or sharpen the leading edge
12 = SMOOTH YU and/or YL: Wagner fn. fits or [im]explicit

```

Select operating mode.

```

? = menu; CTRL Z = quit; <CR> = DISPLAY: redis
Input airfoil file? <CR>=naca0012.dat: naca64412.dat
Input control file? <CR>=profile.inp or none:
No control file found - proceeding ...
Identifier for output files? <CR>="profile": mode3
Plot title line? <CR> uses "PROFILE" for the title:
Reduce the number of points per surface
Plot subtitle line? <CR> means none:

```

Do you really want Cp estimates? (Y/N; <CR>=No)

PROFILE treats the airfoil as one curve if the leading edge is rounded. In this case, if the trailing edge is also rounded, the curve is closed smoothly. Otherwise, the trailing edge is sharp or open (no continuity).

```

Is the LEADING edge rounded? (Y/N; <CR> means Y(es)):
Is the TRAILING edge rounded? (Y/N; <CR> means NO):
Distribute along the chord or the arc? (X/S; <CR> = X): s
Do you want to redistribute the UPPER surface? (<CR>=Y):

```

<continued>

Options (5 with indicated defaults is suggested for airfoils):

- 1: Xs or Ts are to be read from a file, not generated
- 0: Uniform distribution
- 1: Sinusoidal bunching towards the lower end
- 2: Symmetric sinusoidal bunching towards both ends
- 3: Sinusoidal bunching around an internal point
- 4: Vinokur distribution (1st & last increment specified)
- 5: Linear + Quadratic + Sine + Cosine combination

Enter distribution choice. <CR> = 5; ^Z (or ^D) = quit: 5

How many points? <CR> gives 100: 75

Defaults for L, Q, S, C terms are 0.04, 0.0, 0.3, 0.66.

Take the defaults? (Y/N; <CR>=Y):

Do you want to redistribute the LOWER surface? (<CR>=Y):

Options (5 with indicated defaults is suggested for airfoils):

- 1: Xs or Ts are to be read from a file, not generated
- 0: Uniform distribution
- 1: Sinusoidal bunching towards the lower end
- 2: Symmetric sinusoidal bunching towards both ends
- 3: Sinusoidal bunching around an internal point
- 4: Vinokur distribution (1st & last increment specified)
- 5: Linear + Quadratic + Sine + Cosine combination

Enter distribution choice. <CR> = 5; ^Z (or ^D) = quit: 5

How many points? <CR> gives 100: 75

Defaults for L, Q, S, C terms are 0.04, 0.0, 0.3, 0.66.

Take the defaults? (Y/N; <CR>=Y):

Revised

| | | |
|--|--------------|------------------|
| Maximum thickness/chord (current axes) . . . | 12.0001% | at X/C = 0.37339 |
| Maximum camber/chord | 1.9763% | at X/C = 0.50958 |
| Unnormalized area | 0.759160E-01 | |
| Moment of inertia about X axis | 0.820041E-04 | |

Cannot give spreadsheet file: upper/lower Xs differ.

Use REDISTRIBUTE mode first.

| | |
|-----------------------|-----------|
| Modified airfoil: | mode3.dat |
| Airfoil plot file: | mode3.plt |
| Tabulated results: | mode3.tab |
| Curvature QPLOT file: | mode3.crv |
| 2nd derivatives file: | mode3.ypp |

Mode 4: Add shape functions (NACA 0012 airfoil)

In this example, two shape functions are added to the airfoil. An exponential bump is added to the upper surface to blunt the leading edge, and the trailing function is added to both surfaces with a negative multiplier to deflect the trailing edge. The resulting plots of airfoil coordinates and surface pressures are shown.

```
$ profile
```

```
Welcome to PROFILE from the Aerodynamics Division, NASA Ames.
```

```
0 = DISPLAY (plot/tabulate only or alter format/precision)
1 = RECTIFY leading edge definition; allows vertical shift
2 = NORMALIZE or denormalize coordinates
3 = REDISTRIBUTE the abscissas
4 = MODIFY either surface or both (apply shape functions)
5 = REFINE thickness/curvature
6 = OPTIMIZE one surface ("bumps" + target curvatures)
7 = TRANSFORM YU/YL to/from camber/thickness, or decamber
8 = ROTATE coordinates, with option to renormalize
9 = COMBINE option (add or subtract profiles)
10 = LOFT linearly between primary and secondary profiles
11 = NOSE-JOB option: round or sharpen the leading edge
12 = SMOOTH YU and/or YL: Wagner fn. fits or [im]explicit
```

Select operating mode.

```
? = menu; CTRL Z = quit; <CR> = DISPLAY: mod
Input airfoil file? <CR>=naca0012.dat:
Input control file? <CR>=profile.inp or none: cps.inp
Identifier for output files? <CR>="profile": mode4
Plot title line? <CR> uses "PROFILE" for the title:
Blunt the leading edge; deflect the trailing edge
Plot subtitle line? <CR> means none:
```

```
Do you really want Cp estimates? (Y/N; <CR>=No) y
Enter Alpha, else <CR> gives 0.:
Enter free stream Mach number, else <CR> gives 0.: .3
```

```
0. Done.
1. SCALE: Y <- Y * P1
2. RAMP: Y <- X * P1
3. FLAP: Y <- Y - (X - P1) * TAN (P2 deg.) for X > P1
4. SLAT: Y <- Y - (P1 - X) * TAN (P2 deg.) for X < P1
5. TRAIL: X ** P1
6. DROOP: (1 - X) * EXP (-P1 * X)
7. LEAD: (1 - X) ** P1
8. EXPO: (X^P (1-X) EXP (-P2 X)) / (P1^P (1-P) EXP (-P2 P))
9. SINE: SIN ** P2 of pi * X ** (LOG (0.5) / LOG (P1))
10. SINF: Flipped form of 9 [SINE] - left & right swapped
11. SIN1: Symmetric form of 9 [SINE] - left half
12. SIN2: Symmetric form of 9 [SINE] - right half
13. COSL: 1/4 cosine, peak at left; power P1
14. COSR: 1/4 cosine, peak at left; power P1
15. LCOS: 1/4 cosine, peak at left; power P1
16. RCOS: 1/4 cosine, peak at left; power P1
17. WAGNER: Wagner function; P1 = order of term N
```

First shape function to add to the UPPER surface?

? = menu; CTRL Z = quit; <CR> = **DONE**: expo
Shape function EXPO: Enter CENTER : .05
Shape function EXPO: Enter WIDTH : 10
Shape function EXPO: Enter MULTIPLIER: .01

Next shape function for the UPPER surface?

? = menu; CTRL Z = quit; <CR> = **DONE**: trail
Shape function TRAIL: Enter POWER : 5
Shape function TRAIL: Enter MULTIPLIER: -.01

Next shape function for the UPPER surface?

? = menu; CTRL Z = quit; <CR> = **DONE**:

First shape function to add to the LOWER surface?

? = menu; CTRL Z = quit; <CR> = **DONE**: trail
Shape function TRAIL: Enter POWER : 5
Shape function TRAIL: Enter MULTIPLIER: -.01

Next shape function for the LOWER surface?

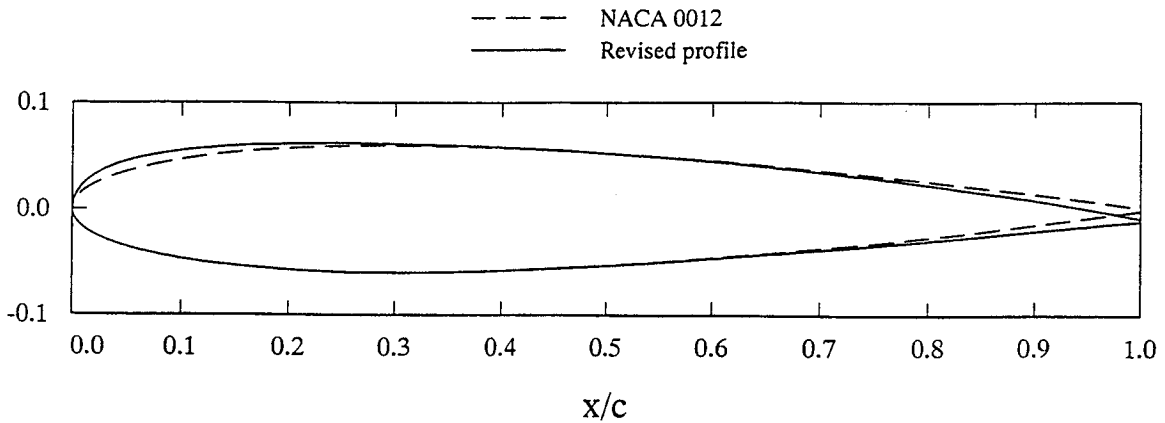
? = menu; CTRL Z = quit; <CR> = **DONE**:

Revised

| | | |
|--|--------------|------------------|
| Maximum thickness/chord (current axes) . . | 12.1809% | at X/C = 0.28000 |
| Maximum camber/chord | -1.0000% | at X/C = 1.00000 |
| Unnormalized area | 0.841178E-01 | |
| Moment of inertia about X axis | 0.731306E-04 | |
| Original C1: 0.000 | Cm: 0.000 | |
| Revised C1: 0.190 | Cm: -0.022 | |

Modified airfoil: mode4.dat
Airfoil plot file: mode4.plt
Tabulated results: mode4.tab
Curvature QPLOT file: mode4.crv
Cp distributions file: mode4.cps

Blunt the leading edge; deflect the trailing edge



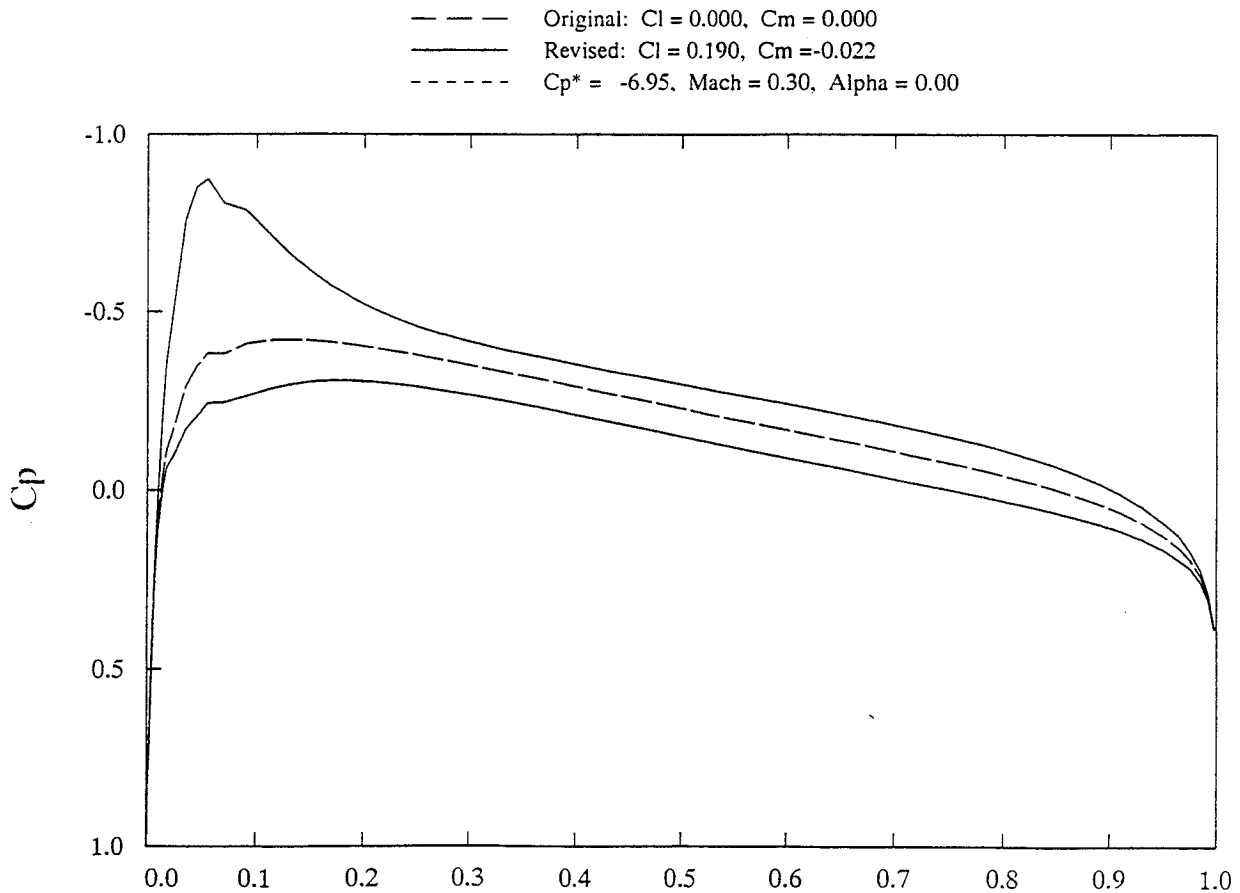
EXPONENTIAL (upper surface)

CENTER 0.050000
 WIDTH 10.000000
 MULTIPLIER 0.010000

TRAILING (both surfaces)

POWER 5.000000
 MULTIPLIER -0.010000

Blunt the leading edge; deflect the trailing edge



Mode 5: Refine thickness/curvature (Ames-01 airfoil)

In this example, the Ames-01 rotor section is smoothed using target second derivatives, and the thickness is refined to 10%. The target y'' values were derived by hand-editing the .ypp file from a preliminary run of PROFILE on ames01.dat using MODE = 0. The plots of curvature from this MODE = 0 run guided the smoothing out of the second derivatives by hand, where some trial-and-error is suggested till the user develops a feel for cause and effect.

The .tab file shows details of the iteration necessary to achieve the requested thickness ratio. The resulting plots of the airfoil and curvature are also shown.

Remember that REFINE mode has an option suited to knocking out spikes in the curvature, or to flattening the curvature plots in some single range of abscissas. This does not require an input table of y'' values. The option is not illustrated.

```
$ profile
```

```
Welcome to PROFILE from the Aerodynamics Division, NASA Ames.
```

```
0 = DISPLAY (plot/tabulate only or alter format/precision)
1 = RECTIFY leading edge definition; allows vertical shift
2 = NORMALIZE or denormalize coordinates
3 = REDISTRIBUTE the abscissas
4 = MODIFY either surface or both (apply shape functions)
5 = REFINE thickness/curvature
6 = OPTIMIZE one surface ("bumps" + target curvatures)
...
...
```

Select operating mode.

```
? = menu; CTRL Z = quit; <CR> = DISPLAY: refine
Input airfoil file? <CR>=naca0012.dat: ames01.dat
Input control file? <CR>=profile.inp or none:
Identifier for output files? <CR>="profile": mode5
Plot title line? <CR> uses "PROFILE" for the title:
REFINE mode used on Ames-01 Rotor Section
Plot subtitle line? <CR> means none:
Curvature smoothed via target  $y''$  distribution; new T/C=10%
Do you really want Cp estimates? (Y/N; <CR>=No)
Do you want an explanation of the prompts to follow? (Y/N; <CR>=No): y
```

```
REFINE works with 2N equations in N unknowns (the ys):
```

```
    N of the form       $y(\text{new}) = \text{scale} * y(\text{old})$ 
and N of the form     $wt * y''(\text{new}) = wt * y''(\text{desired})$ 
```

where wt represents weighting of the second derivative equations to equilibrate the two halves of the system.

The first half enables thickness to be changed, while the second half enables the second derivatives (and hence the curvature distribution) to be smoothed. The scaling and the weighting use "sine" shape functions which must be

controlled by you the user - hence the series of prompts to be discussed next.

<Hit RETURN for more.>

Thickness ratio refinement:

The nonlinear y scaling is intended to preserve as much as possible the curvature near the leading and trailing edges. The sine function is centered at the point of maximum thickness. Higher powers of the sine tend to preserve the leading/trailing-edge properties better.

Curvature smoothing:

Typical weighting of the y" equations varies from 0.004 at the leading and trailing edges to 0.04 at the center of the region of interest (where most of the smoothing is sought). Use a power of 3. or 4. to smooth out some NARROW region of noisy curvature, else a lesser power (1., 1.5, or 2.) if BROAD smoothing is sought (probably in conjunction with a table of target 2nd derivatives).

Original % thickness: 10.27440
 Enter desired % thickness, or <CR> to keep same: 10.0
 Enter power of sine to use for y scaling (<CR> = 2.):
 Enter file name for target 2nd derivatives; <CR> if none:
 amesltarg.ypp
 Is the upper surface to be left unchanged? (Y/N; <CR>=No):

Smoothing of upper surface is controlled by the following:
 Center of smoothed region? <CR> gives x/c=0.5:
 Power of sine for y" weights? <CR> gives 3.0:
 Weight at x/c=0,1 for y"? <CR> gives .004:
 Peak weight for y"? <CR> gives .040:

Is the lower surface to be left unchanged? (Y/N; <CR>=No):

Smoothing of lower surface is controlled by the following:
 Center of smoothed region? <CR> gives x/c=0.5:
 Power of sine for y" weights? <CR> gives 3.0:
 Weight at x/c=0,1 for y"? <CR> gives .004:
 Peak weight for y"? <CR> gives .040:

| | | | | |
|---------|----------------------|-----------|--------------------|---------|
| Itn.: 0 | Current % thickness: | 10.05261 | Corresponding x/c: | 0.35000 |
| Itn.: 1 | Current % thickness: | 10.01084, | Corresponding x/c: | 0.35000 |
| Itn.: 2 | Current % thickness: | 9.94346 | Corresponding x/c: | 0.35000 |
| Itn.: 3 | Current % thickness: | 10.00000 | Corresponding x/c: | 0.35000 |

Revised

Maximum thickness/chord (current axes) . . . 10.0000% at X/C = 0.35000
 Maximum camber/chord 1.3457% at X/C = 0.20000
 Unnormalized area 0.722792E-01
 Moment of inertia about X axis 0.524195E-04

Modified airfoil: mode5.dat
 Airfoil plot file: mode5.plt
 Tabulated results: mode5.tab
 Curvature QPLOT file: mode5.crv
 2nd derivatives file: mode5.ypp

Ames-01 y" values, smoothed as targets for REFINE mode

39 ! Upper 2nd Derivatives

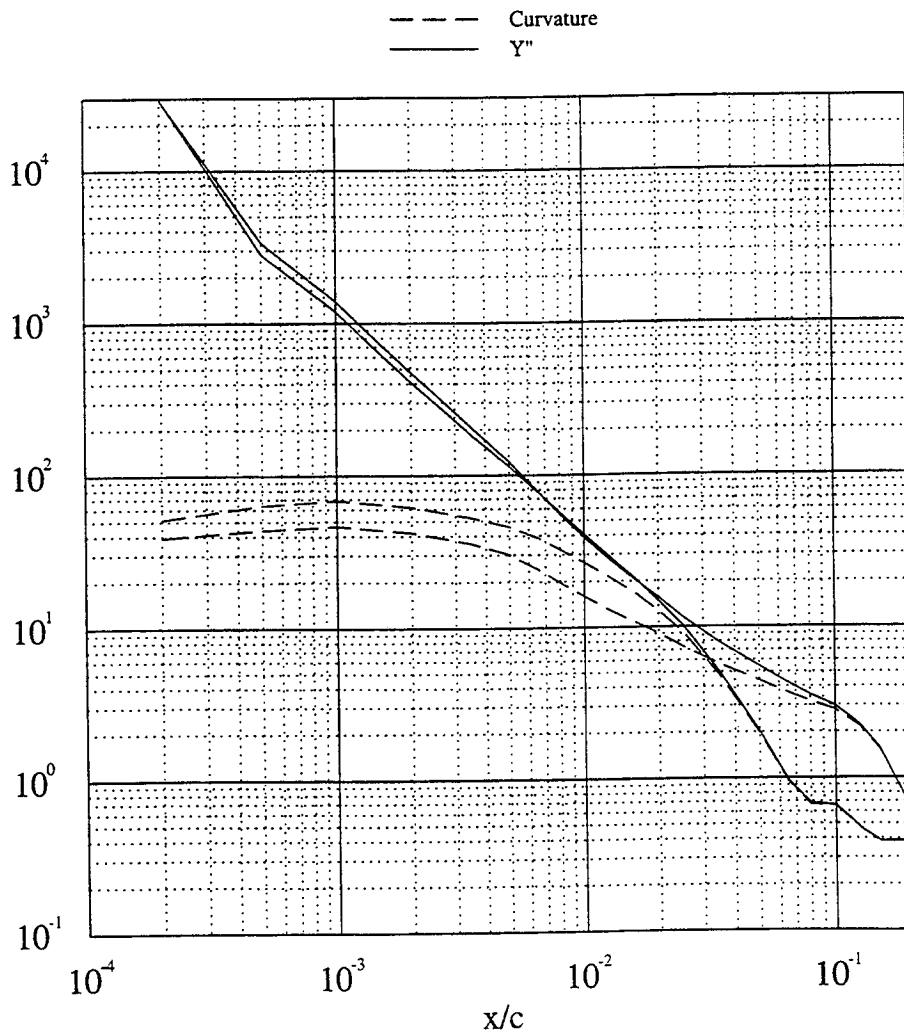
| | |
|-------------|--------------|
| 0.20000E-03 | -29020. |
| 0.50000E-03 | -3385.0 |
| 0.10000E-02 | -1392.0 |
| 0.20000E-02 | -472.53 |
| 0.35000E-02 | -207.11 |
| 0.50000E-02 | -123.11 |
| 0.65000E-02 | -79.111 |
| 0.80000E-02 | -55.333 |
| 0.10000E-01 | -38.978 |
| 0.12500E-01 | -28.171 |
| 0.16000E-01 | -20.543 |
| 0.20000E-01 | -15.611 |
| 0.25000E-01 | -11.533 |
| 0.35000E-01 | -7.8 |
| 0.50000E-01 | -5.9 |
| 0.65000E-01 | -4.4 |
| 0.80000E-01 | -3.4 |
| 0.10000 | -2.5 |
| 0.12500 | -1.7 |
| 0.15000 | -1.1 |
| 0.20000 | -0.6 |
| 0.25000 | -0.3 |
| 0.30000 | -0.22 |
| 0.35000 | -0.22 |
| 0.40000 | -0.25 |
| 0.45000 | -0.27 |
| 0.50000 | -0.27840 |
| 0.55000 | -0.29800 |
| 0.60000 | -0.32600 |
| 0.65000 | -0.36000 |
| 0.70000 | -0.39800 |
| 0.75000 | -0.37600 |
| 0.80000 | -0.22640 |
| 0.85000 | -0.32004E-01 |
| 0.90000 | 0.44374 |
| 0.92500 | 0.9 |
| 0.95000 | 1.3 |
| 0.97500 | 1.7 |
| 0.99000 | 1.9733 |

39 ! Lower 2nd Derivatives

| | |
|-------------|---------|
| 0.20000E-03 | 29267. |
| 0.50000E-03 | 2838.3 |
| 0.10000E-02 | 1193.3 |
| 0.20000E-02 | 408.27 |
| 0.35000E-02 | 184.44 |
| 0.50000E-02 | 114.67 |
| 0.65000E-02 | 78.667 |
| 0.80000E-02 | 56.857 |
| 0.10000E-01 | 40.756 |
| 0.12500E-01 | 29.600 |
| 0.16000E-01 | 21.000 |
| 0.20000E-01 | 14.811 |
| 0.25000E-01 | 10.160 |
| 0.35000E-01 | 4.9547 |
| 0.50000E-01 | 2.0222 |
| 0.65000E-01 | 0.96444 |
| 0.80000E-01 | 0.68096 |
| 0.10000 | 0.58 |

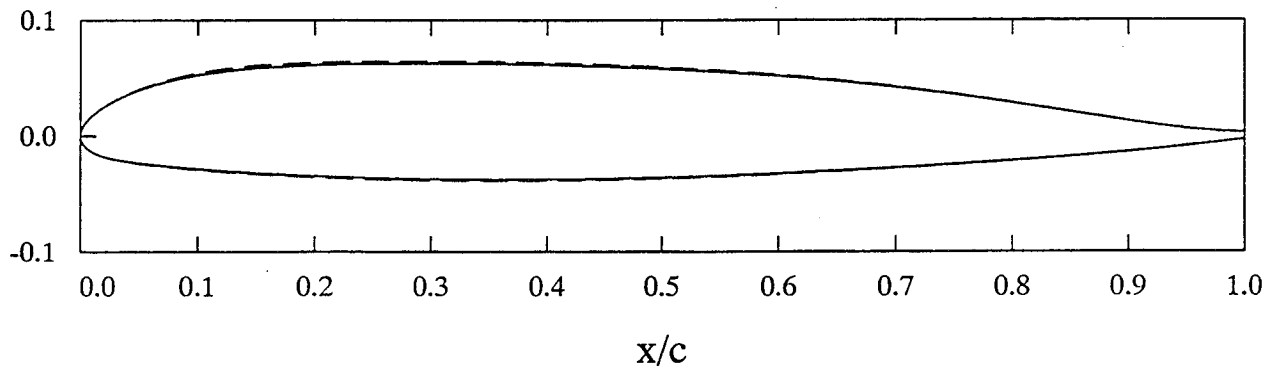
| | |
|---------|---------|
| 0.12500 | 0.46880 |
| 0.15000 | 0.38400 |
| 0.20000 | 0.34 |
| 0.25000 | 0.30240 |
| 0.30000 | 0.25560 |
| 0.35000 | 0.21840 |
| 0.40000 | 0.19480 |
| 0.45000 | 0.19 |
| 0.50000 | 0.18760 |
| 0.55000 | 0.16400 |
| 0.60000 | 0.14360 |
| 0.65000 | 0.12040 |
| 0.70000 | 0.11400 |
| 0.75000 | 0.13200 |
| 0.80000 | 0.14160 |
| 0.85000 | 0.17640 |
| 0.90000 | 0.26 |
| 0.92500 | 0.30 |
| 0.95000 | 0.33 |
| 0.97500 | 0.30 |
| 0.99000 | 0.26 |

Ames-01 Section Y'' and Curvature (negative signs suppressed)
 Log-log scaling can facilitate working with the leading edge



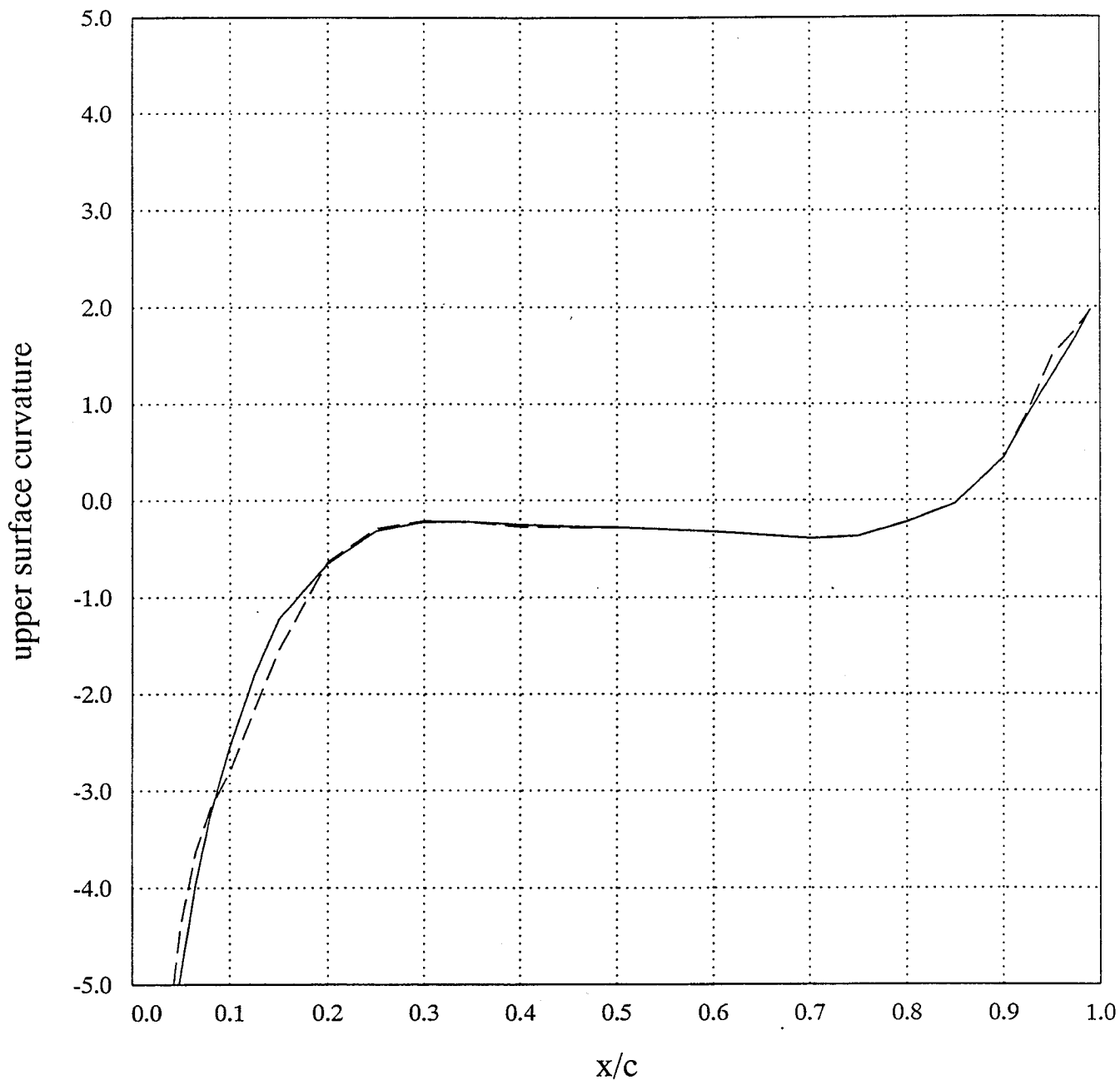
REFINE mode used on Ames-01 Rotor Section
Curvature smoothed via target y'' distribution; new T/C=10%

--- Original Ames 01
— Revised profile



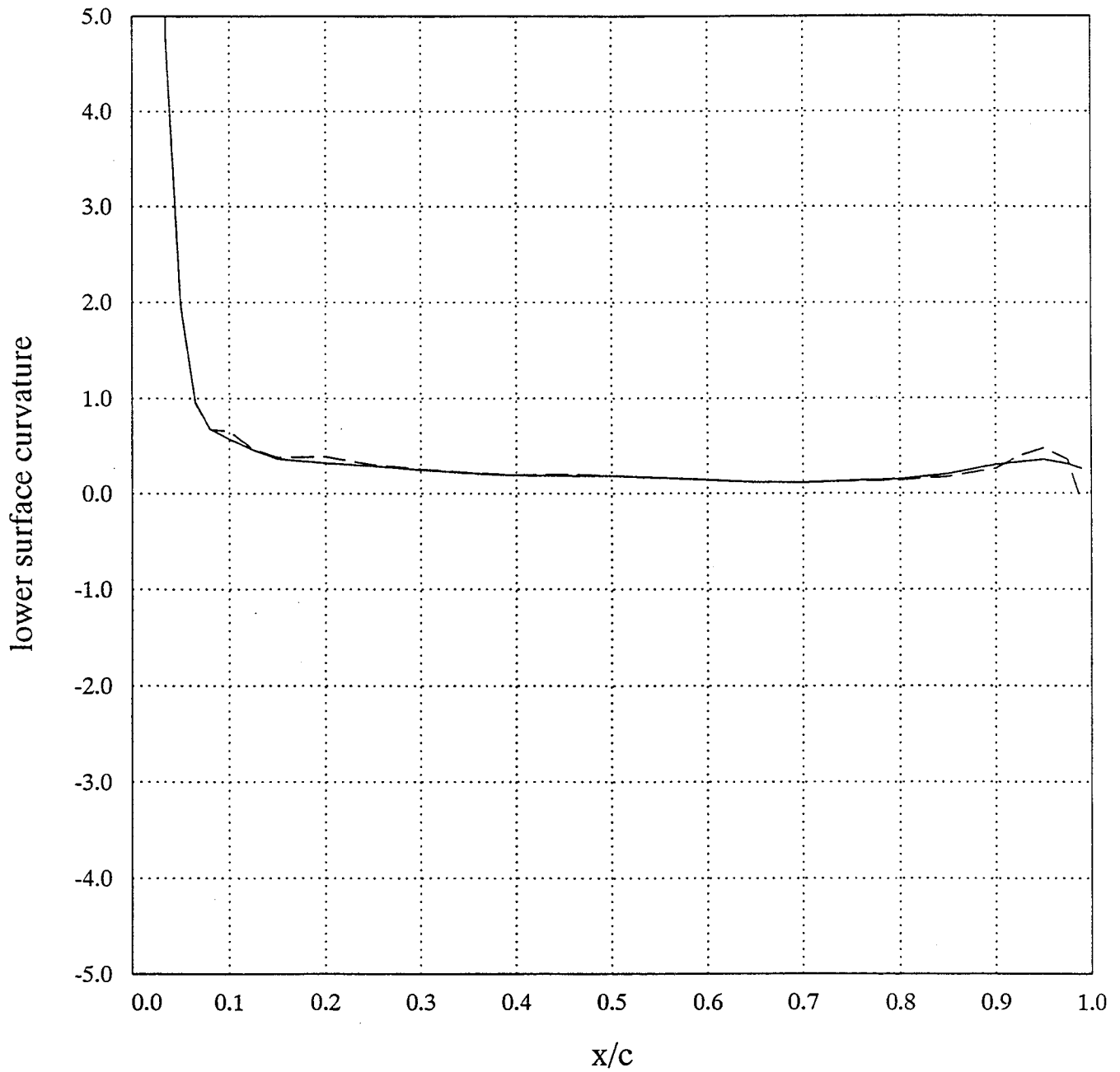
REFINE mode used on Ames-01 Rotor Section
Curvature smoothed via target y'' distribution; new T/C=10%

--- Original
— Revised



REFINE mode used on Ames-01 Rotor Section
Curvature smoothed via target y'' distribution; new T/C=10%

--- Original
— Revised



Mode 6: Optimize curvature (Ames-01 airfoil)

The following example of OPTIMIZE mode starts with the result from the previous example—a REFINEd Ames-01 rotor section. This may not be very representative in that the result achieved here, or something very like it, could have been achieved more efficiently using REFINE instead. As indicated in the body of the text, OPTIMIZE is an experimental scheme at the time of writing. It has worked well on problems constructed with known solution. The present example is more realistic in that the true minimum is not known.

Limited experimentation with different scalings suggests the minimum is poorly defined in this example, and that some solutions found by QNMDIF are not acceptable judging by the waviness of the curvature plots. The rerun of this example for the purposes of updating the user guide was on a different system (DEC Alpha, rather than a VAX), and did not achieve a confirmed optimum, although the reduction of the objective from 1.59972 to 0.176186 is still worthwhile. Use of 32-bit arithmetic is marginal here—64 bits are preferable for optimization.

Keep in mind that the choice of 10 Wagner functions is quite arbitrary, as is the target curvature distribution, which is an edited form of the .crv file output from the previous REFINE example. Note also that this smoothed version of Ames-01 was used as the starting guess rather than the original Ames-01 because successful application of smooth shape functions essentially demands a smooth base profile if the result is also to be smooth.

Note that only one surface may be OPTIMIZED at a time.

\$ profile

Welcome to PROFILE from the Aerodynamics Division, NASA Ames.

```

0 = DISPLAY (plot/tabulate only or alter format/precision)
1 = RECTIFY leading edge definition; allows vertical shift
2 = NORMALIZE or denormalize coordinates
3 = REDISTRIBUTE the abscissas
4 = MODIFY either surface or both (apply shape functions)
5 = REFINE thickness/curvature
6 = OPTIMIZE one surface ("bumps" + target curvatures)
...
...

```

Select operating mode.

```

? = menu; CTRL Z = quit; <CR> = DISPLAY: optim
Input airfoil file? <CR>=naca0012.dat: sample5.dat
Input control file? <CR>=profile.inp or none: lines.inp
Identifier for output files? <CR>="profile": mode6
Plot title line? <CR> uses "PROFILE" for the title:
OPTIMIZE mode on REFINEd Ames-01 Section
Plot subtitle line? <CR> means none:
Target curvature distribution; no constraint on thickness
Do you really want Cp estimates? (Y/N; <CR>=No)

```

Enter U(pper) or L(ower) to indicate the surface being optimized: U
 Original thickness: 10.00000
 Enter desired % thickness (<CR> means keep same or don't care):
 Enter thickness penalty parameter (<CR> means no constraint):
 Enter N to use Wagner functions 1:N, or <CR> to use an input file:
 10
 Enter seed for scale factors. <CR> gives 1000.
 Enter target curvature distribution file name:
 ames1targ.crv
 Do you want full optimization printout? (Y/N; <CR>=No):

Initial function value: 1.59972
 Final function value: 0.176186
 Modified % thickness: 10.3951
 Corresponding abscissa: 0.300000

Revised

Maximum thickness/chord (current axes) . . . 10.3951% at X/C = 0.30000
 Maximum camber/chord 1.5295% at X/C = 0.20000
 Unnormalized area 0.740618E-01
 Moment of inertia about X axis 0.586708E-04

Modified airfoil: mode6.dat
 Airfoil plot file: mode6.plt
 Tabulated results: mode6.tab
 Curvature QPLOT file: mode6.crv

Corresponding mode6.tab file:

Program PROFILE (Applied Aerodynamics Branch, NASA Ames)

Operating mode: 6 - OPTIMIZE
 Control file : lines.inp
 Geometry file : mode5.dat
 Output file id: mode6
 Profiles found: 1

Control file contents:

PLTLINES: LONG SOLID
 XAXIS: 6.
 NOFILE: YPP CPS

Case: OPTIMIZE mode on REFINED Ames-01 Section

Original thickness: 10.0000
 Corresponding x/c: 0.350000
 Target thickness : 10.0000
 Penalty parameter : 0.000000E+00

Shape Function Description

Function 1: Name: WAGNER

| Parameter | Value | Scale | Active? |
|-----------|------------|---------|---------|
| N | 1.00000000 | 1.00000 | F |
| MULTIP | 0.00000000 | 1.00000 | T |

Function 2: Name: WAGNER

| Parameter | Value | Scale | Active? |
|-----------|------------|---------|---------|
| N | 2.00000000 | 1.00000 | F |
| MULTIP | 0.00000000 | 1.00000 | T |

Function 3: Name: WAGNER

| Parameter | Value | Scale | Active? |
|-----------|------------|---------|---------|
| N | 3.00000000 | 1.00000 | F |
| MULTIP | 0.00000000 | 1.00000 | T |

Function 4: Name: WAGNER

| Parameter | Value | Scale | Active? |
|-----------|------------|---------|---------|
| N | 4.00000000 | 1.00000 | F |
| MULTIP | 0.00000000 | 1.00000 | T |

Function 5: Name: WAGNER

| Parameter | Value | Scale | Active? |
|-----------|------------|---------|---------|
| N | 5.00000000 | 1.00000 | F |
| MULTIP | 0.00000000 | 1.00000 | T |

Function 6: Name: WAGNER

| Parameter | Value | Scale | Active? |
|-----------|------------|---------|---------|
| N | 6.00000000 | 1.00000 | F |
| MULTIP | 0.00000000 | 3.00000 | T |

Function 7: Name: WAGNER

| Parameter | Value | Scale | Active? |
|-----------|------------|---------|---------|
| N | 7.00000000 | 1.00000 | F |
| MULTIP | 0.00000000 | 3.00000 | T |

Function 8: Name: WAGNER

| Parameter | Value | Scale | Active? |
|-----------|------------|---------|---------|
| N | 8.00000000 | 1.00000 | F |
| MULTIP | 0.00000000 | 3.00000 | T |

Function 9: Name: WAGNER

| Parameter | Value | Scale | Active? |
|-----------|------------|---------|---------|
| N | 9.00000000 | 1.00000 | F |
| MULTIP | 0.00000000 | 3.00000 | T |

Function 10: Name: WAGNER

| Parameter | Value | Scale | Active? |
|-----------|-------------|---------|---------|
| N | 10.00000000 | 1.00000 | F |
| MULTIP | 0.00000000 | 3.00000 | T |

Total number of active parameters: 10

Target curvature distribution found:

Target curvature distribution for OPTIMIZing REFINEd Ames-01 section

| | |
|---------------|------------|
| 2.0000001E-03 | -41.97514 |
| 3.5000001E-03 | -35.54548 |
| 4.9999999E-03 | -30.08586 |
| 6.5000001E-03 | -24.19976 |
| 8.0000004E-03 | -19.68576 |
| 9.9999998E-03 | -15.97039 |
| 1.2500000E-02 | -13.07197 |
| 1.6000001E-02 | -10.78795 |
| 2.0000000E-02 | -9.075468 |
| 2.5000000E-02 | -7.347409 |
| 3.5000000E-02 | -5.611370 |
| 5.0000001E-02 | -4.386199 |
| 6.4999998E-02 | -3.75 |
| 7.9999998E-02 | -3.2 |
| 0.1000000 | -2.5 |
| 0.1250000 | -1.85 |
| 0.1500000 | -1.4 |
| 0.2000000 | -0.85 |
| 0.2500000 | -0.50 |
| 0.3000000 | -0.40 |
| 0.3500000 | -0.32 |
| 0.4000000 | -0.27 |
| 0.4500000 | -0.27 |
| 0.5000000 | -0.28 |
| 0.5500000 | -0.2959736 |
| 0.6000000 | -0.3226536 |
| 0.6500000 | -0.3546374 |
| 0.7000000 | -0.3896636 |
| 0.7500000 | -0.3654254 |
| 0.8000000 | -0.2186162 |
| 0.8500000 | 0.0 |
| 0.9000000 | 0.44 |
| 0.9250000 | 0.93 |
| 0.9500000 | 1.3 |
| 0.9750000 | 1.7 |
| 0.9900000 | 2.0 |

Initial function value: 1.59972

CENDIF: Begin gradient calculation.

| I | V | Gradient | Diag of Hessian | Old H | New H | No Fun |
|----|--------------------|--------------------|--------------------|--------------------|--------------------|--------|
| 1 | 0.000000000000E+00 | -.755872924805E+03 | 0.461301906250E+06 | -.100000004750E-02 | 0.658449334878E-05 | 8 0 |
| 2 | 0.000000000000E+00 | -.910333679199E+03 | 0.626639187500E+06 | -.100000004750E-02 | 0.564945048609E-05 | 8 0 |
| 3 | 0.000000000000E+00 | -.120349267578E+04 | 0.142698325000E+07 | -.100000004750E-02 | 0.374373894374E-05 | 8 0 |
| 4 | 0.000000000000E+00 | -.117385205078E+04 | 0.278857525000E+07 | -.100000004750E-02 | 0.267808150056E-05 | 8 0 |
| 5 | 0.000000000000E+00 | -.102510314941E+04 | 0.489271300000E+07 | -.100000004750E-02 | 0.202180899578E-05 | 8 0 |
| 6 | 0.000000000000E+00 | -.127974838257E+03 | 0.911137062500E+06 | -.100000004750E-02 | 0.468514599561E-05 | 8 0 |
| 7 | 0.000000000000E+00 | 0.336355171204E+02 | 0.143178687500E+07 | -.100000004750E-02 | 0.373745342586E-05 | 8 0 |
| 8 | 0.000000000000E+00 | 0.386606445313E+03 | 0.218920825000E+07 | -.100000004750E-02 | 0.302253579321E-05 | 8 0 |
| 9 | 0.000000000000E+00 | 0.646069641113E+03 | 0.321423750000E+07 | -.100000004750E-02 | 0.249445679401E-05 | 8 0 |
| 10 | 0.000000000000E+00 | 0.117063940430E+04 | 0.449075900000E+07 | -.100000004750E-02 | 0.211035307984E-05 | 8 0 |

QNMDIF HAS FAILED TO SATISFY THE CONVERGENCE TEST

FINAL ITERATION 16 FUNCTION VALUE 0.176185816526413E+00

| | FINAL SOLUTION | GRADIENT |
|----|------------------------|------------------------|
| 1 | 0.305014615878463E-02 | 0.305061674118042E+01 |
| 2 | 0.408021593466401E-02 | 0.391688078641891E+00 |
| 3 | 0.863504654262215E-03 | 0.481614917516708E+00 |
| 4 | -0.139779422897846E-02 | -0.248437857627869E+01 |
| 5 | -0.163336121477187E-02 | 0.336818695068359E+01 |
| 6 | -0.252397009171546E-02 | -0.445589685440063E+01 |
| 7 | -0.102962967503117E-04 | -0.457506227493286E+01 |
| 8 | 0.166770094074309E-02 | 0.387006551027298E+00 |
| 9 | 0.349189416738227E-03 | -0.146057212352753E+01 |
| 10 | -0.278906867606565E-03 | -0.164626750946045E+02 |

NUMBER OF FUNCTION EVALUATIONS 360

CHOLESKY FACTORS OF APPROXIMATE HESSIAN

| ELEMENTS OF DIAGONAL MATRIX | | | | | |
|-----------------------------|-----------------------|------------------------|------------------------|------------------------|--|
| 0.75920637500000E+06 | 0.69883981250000E+06 | 0.18812326250000E+07 | 0.28949965000000E+07 | 0.30809932500000E+07 | |
| 0.82940050000000E+06 | 0.15846810000000E+07 | 0.33654459375000E+06 | 0.29743796875000E+06 | 0.93086212500000E+06 | |
| LOWER TRIANGULAR FACTOR | | | | | |
| 0.399245321750641E+00 | 0.368354409933090E+00 | 0.931292176246643E-01 | | | |
| 0.686931908130646E+00 | 0.866292099952698E+00 | 0.444542318582535E+00 | -0.534809172153473E+00 | | |
| 0.918694615364075E+00 | 0.124433600902557E+01 | -0.145138893276453E-01 | 0.104163914918900E+00 | -0.300390213727951E+00 | |
| 0.143369174003601E+01 | 0.400722295045853E+00 | 0.233337759971619E+00 | -0.641300082206726E-01 | 0.190635591745377E+00 | |
| 0.423312425613403E+00 | 0.27794602513333E+00 | | | | |
| 0.477122426033020E+00 | 0.229310914874077E+00 | -0.439356490969658E-01 | 0.550142586231232E+00 | 0.951968580484390E-01 | |
| -0.226820275187492E+00 | -0.55597013235092E+00 | | | | |
| 0.245663806796074E+00 | 0.468529134988785E+00 | 0.449284791946411E+00 | -0.428719103336334E+00 | 0.500615060329437E+00 | |
| 0.825645923614502E+00 | 0.703093588352203E+00 | 0.735792398452759E+00 | | | |
| -0.268849059939384E-01 | 0.396191179752350E-01 | -0.341518968343735E+00 | 0.553645312786102E+00 | -0.421670049428940E+00 | |
| -0.322754681110382E-01 | 0.225044041872025E-02 | 0.224667739868164E+01 | -0.319160878658295E+00 | | |
| -0.209290280938148E+00 | | | | | |
| 0.123313713073730E+01 | | | | | |

LOWER BOUND ON CONDITION NUMBER OF HESSIAN 0.103584394454956E+02

NORM OF GRADIENT 0.184742355346680E+02

Repeat of best function evaluation: 0.176186

Modified % thickness: 10.3951
Corresponding abscissa: 0.300000

.....
.....

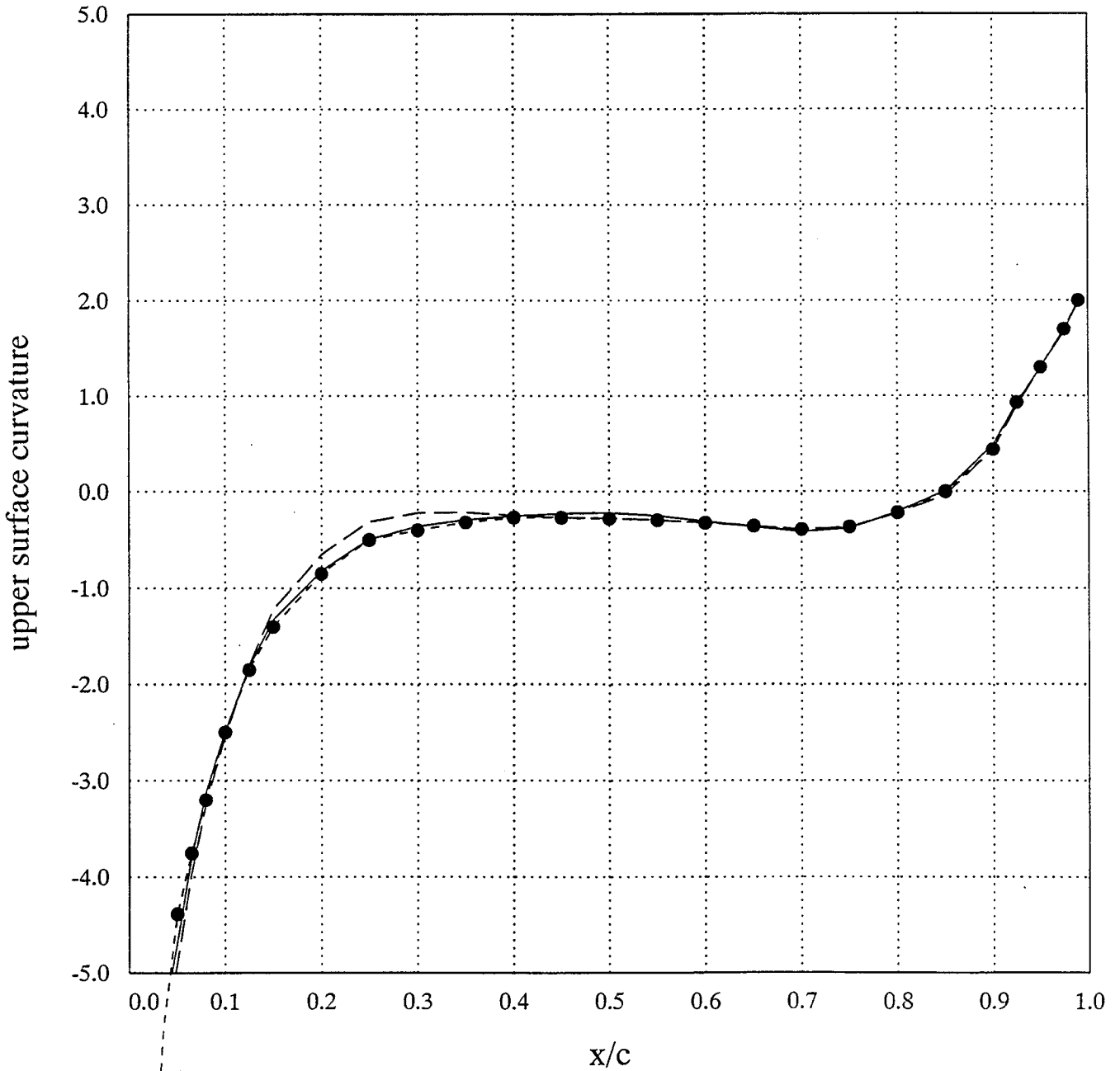
Revised

Maximum thickness/chord (current axes) . . 10.3951% at X/C = 0.30000
Maximum camber/chord 1.5295% at X/C = 0.20000
Unnormalized area 0.740618E-01
Moment of inertia about X axis 0.586708E-04

L.E.: 0.000000E+00 0.000000E+00 Chord: 0.100000E+01
Mean-line angle at T.E. (deg.) 2.68

OPTIMIZE mode on REFINEd Ames-01 Section
Target curvature distribution; no constraint on thickness

- Original
- Target
- Revised



Mode 7: Transform ordinates (Ames-01 airfoil)

In this example, the Ames-01 airfoil is transformed from upper/lower surface coordinates to the camber/semi-thickness representation. The result is shown as a scale plot, from the .plt file.

The TRANSFORM option can reverse this process, but no sample is shown.

```
$ profile
```

```
Welcome to PROFILE from the Aerodynamics Division, NASA Ames.
```

```

0 = DISPLAY (plot/tabulate only or alter format/precision)
1 = RECTIFY leading edge definition; allows vertical shift
2 = NORMALIZE or denormalize coordinates
3 = REDISTRIBUTE the abscissas
4 = MODIFY either surface or both (apply shape functions)
5 = REFINE thickness/curvature
6 = OPTIMIZE one surface ("bumps" + target curvatures)
7 = TRANSFORM YU/YL to/from camber/thickness, or decamber
8 = ROTATE coordinates, with option to renormalize
9 = COMBINE option (add or subtract profiles)
10 = LOFT linearly between primary and secondary profiles
11 = NOSE-JOB option: round or sharpen the leading edge
12 = SMOOTH YU and/or YL: Wagner fn. fits or [im|explicit]

```

Select operating mode.

```

? = menu; CTRL Z = quit; <CR> = DISPLAY: transform
Input airfoil file? <CR>=naca0012.dat: ames01.dat
Input control file? <CR>=profile.inp or none:
No control file found - proceeding ...
Identifier for output files? <CR>="profile": mode7
Plot title line? <CR> uses "PROFILE" for the title:
TRANSFORM mode used on Ames-01 Section
Plot subtitle line? <CR> means none:
Upper/lower y coordinates tranformed to camber/thickness

```

Options for TRANSFORM mode:

```

0 = Decamber upper/lower surface coordinates
1 = Upper/lower surfaces to camber/thickness distributions
2 = Camber/thickness distributions to upper/lower surfaces

```

```
Enter selection (<CR> = 1):
```

```

Maximum thickness/chord (current axes) . . . 10.2744% at X/C = 0.30000
Maximum camber/chord . . . . . 1.4105% at X/C = 0.15000
Unnormalized area . . . . . 0.738818E-01
Moment of inertia about X axis . . . . . 0.565657E-04

```

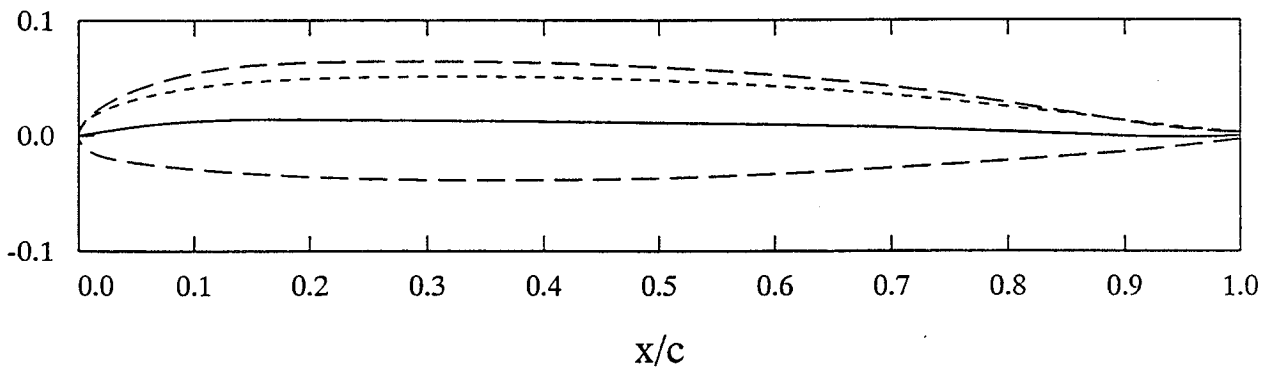
```

Modified airfoil:      mode7.dat
Airfoil plot file:    mode7.plt
Tabulated results:    mode7.tab
2nd derivatives file: mode7.ypp

```

TRANSFORM mode used on Ames-01 Section
Upper/lower y coordinates tranformed to camber/thickness

- Original Ames-01
- Semithickness
- Camber (mean line)



Mode 8: Rotate coordinates

\$ profile

Welcome to PROFILE from the Aerodynamics Division, NASA Ames.

- 0 = DISPLAY (plot/tabulate only or alter format/precision)
- 1 = RECTIFY leading edge definition; allows vertical shift
- 2 = NORMALIZE or denormalize coordinates
- 3 = REDISTRIBUTE the abscissas
- 4 = MODIFY either surface or both (apply shape functions)
- 5 = REFINE thickness/curvature
- 6 = OPTIMIZE one surface ("bumps" + target curvatures)
- 7 = TRANSFORM YU/YL to/from camber/thickness, or decamber
- 8 = ROTATE coordinates, with option to renormalize
- 9 = COMBINE option (add or subtract profiles)
- 10 = LOFT linearly between primary and secondary profiles
- 11 = NOSE-JOB option: round or sharpen the leading edge
- 12 = SMOOTH YU and/or YL: Wagner fn. fits or [im|ex]plicit

Select operating mode.

? = menu; CTRL Z = quit; <CR> = **DISPLAY**: rotate

Input airfoil file? <CR>=naca0012.dat:

Input control file? <CR>=profile.inp or none:

No control file found - proceeding ...

Identifier for output files? <CR>="profile": mode8

Plot title line? <CR> uses "PROFILE" for the title:

Rotate coordinates about 1/4 chord

Plot subtitle line? <CR> means none:

Do you really want Cp estimates? (Y/N; <CR>=No)

Options for applying twist:

- 1 = Rotate about leading edge
- 2 = Rotate about trailing edge
- 3 = Rotate about quarter-chord (on center-line)
- 4 = Rotate about specified point

Enter selection (<CR> = 1): 3

Enter twist (degrees; positive is anticlockwise): -8

Do you want the result renormalized? (Y/N; <CR> = Yes): n

*** WARNING: Leading edge point is no longer the true leading edge.
PROFILE's "rectify" option may be appropriate.

Revised

Maximum thickness/chord (current axes) . . .*****% at X/C = 1.00000

Maximum camber/chord*****% at X/C = 1.00000

Unnormalized area 0.821691E-01

Moment of inertia about X axis 0.200787E-03

Modified airfoil: mode8.dat

Airfoil plot file: mode8.plt

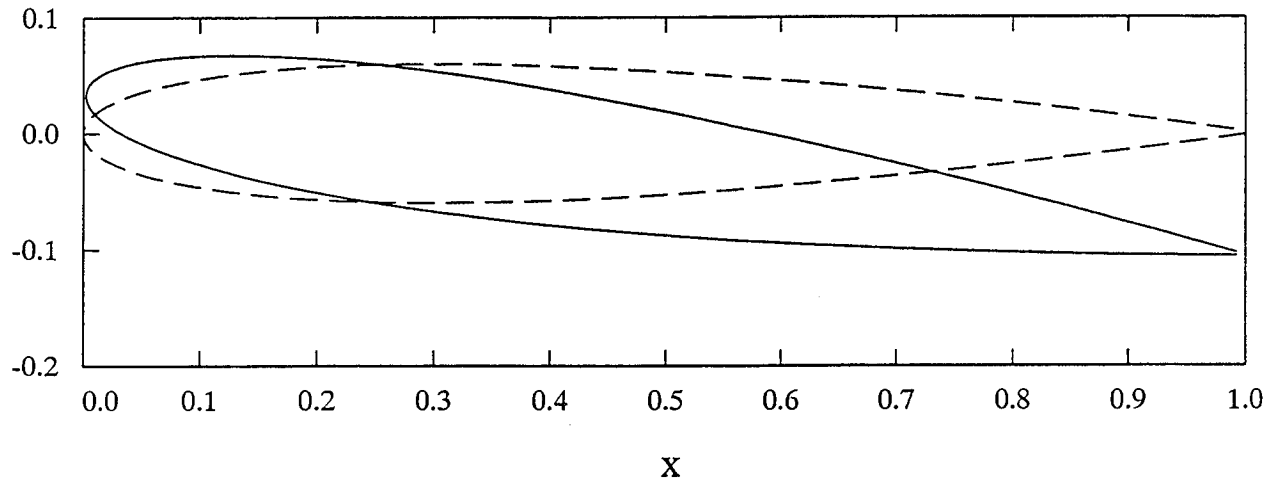
Tabulated results: mode8.tab

Curvature QPLOT file: mode8.crv

2nd derivatives file: mode8.ypp

Rotate coordinates about 1/4 chord

--- NACA 0012
— Revised profile



Mode 9: Combine profiles

In this example, displacement thickness results from program LBAUER are added to the original airfoil (presumably for analysis by an inviscid code).

Since COMBINE mode requires that the two profiles to be combined have the same abscissas, the computational-mesh boundary layer values from LBAUER required a preliminary pass through PROFILE using REDISTRIBUTE mode, which acquired the target abscissas from the original airfoil file. This intermediate step is not shown, but two points should be noted: first, PROFILE handled the boundary layer data in wraparound form—no problem; and second, the “sharp leading edge” option (treating the two surfaces as separate curves) is appropriate for the redistribution.

COMBINE mode can remove such a boundary layer similarly. It can also combine two airfoils in the algebraic sense of adding or subtracting. These options are not shown.

\$ profile

Welcome to PROFILE from the Aerodynamics Division, NASA Ames.

- 0 = DISPLAY (plot/tabulate only or alter format/precision)
- ...
- 9 = COMBINE option (add or subtract profiles)
- ...

Select operating mode.

? = menu; CTRL Z = quit; <CR> = **DISPLAY**: combine
 Input airfoil file? <CR>=naca0012.dat: l1011.dat
 Input control file? <CR>=profile.inp or none:
 No control file found - proceeding ...
 Identifier for output files? <CR>="profile": mode9
 Plot title line? <CR> uses "PROFILE" for the title:
 Combine airfoil and displacement thickness
 Plot subtitle line? <CR> means none:

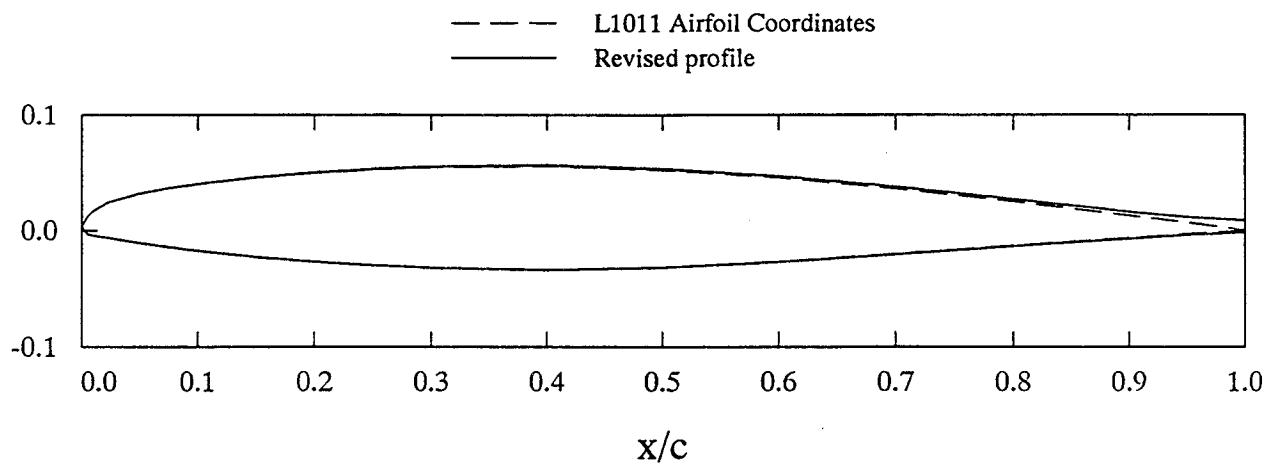
Do you really want Cp estimates? (Y/N; <CR>=No)
 Enter file name for secondary coordinates:
 blayer.dat
 Do secondary coordinates represent displacement thickness? <CR>=Y:
 Are they to be ADDED? <CR>=Y=added; N=subtracted:

Revised

Maximum thickness/chord (current axes) . . . 9.0634% at X/C = 0.40030
 Maximum camber/chord 0.8210% at X/C = 0.25011
 Unnormalized area 0.613745E-01
 Moment of inertia about X axis 0.348705E-04

Modified airfoil: mode9.dat
 Airfoil plot file: mode9.plt
 Tabulated results: mode9.tab
 Curvature QPLOT file: mode9.crv
 2nd derivatives file: mode9.ypp

Combine airfoil and displacement thickness



Mode 10: Loft between two profiles

\$ profile

Welcome to PROFILE from the Aerodynamics Division, NASA Ames.

- 0 = DISPLAY (plot/tabulate only or alter format/precision)
- 1 = RECTIFY leading edge definition; allows vertical shift
- 2 = NORMALIZE or denormalize coordinates
- 3 = REDISTRIBUTE the abscissas
- 4 = MODIFY either surface or both (apply shape functions)
- 5 = REFINE thickness/curvature
- 6 = OPTIMIZE one surface ("bumps" + target curvatures)
- 7 = TRANSFORM YU/YL to/from camber/thickness, or decamber
- 8 = ROTATE coordinates, with option to renormalize
- 9 = COMBINE option (add or subtract profiles)
- 10 = LOFT linearly between primary and secondary profiles
- 11 = NOSE-JOB option: round or sharpen the leading edge
- 12 = SMOOTH YU and/or YL: Wagner fn. fits or [im]explicit

Select operating mode.

? = menu; CTRL Z = quit; <CR> = **DISPLAY**: loft
 Input airfoil file? <CR>=naca0012.dat:
 Input control file? <CR>=profile.inp or none:
 No control file found - proceeding ...
 Identifier for output files? <CR>="profile": mode10
 Plot title line? <CR> uses "PROFILE" for the title:
 Loft between NACA 0012 and NACA 0012 sections
 Plot subtitle line? <CR> means none:

Do you really want Cp estimates? (Y/N; <CR>=No)
 Enter file name for secondary coordinates:
 naca0012.dat
 Enter primary section's unnormalized (Xle, Yle) and chord.
 (3 values; <CR> = leave normalized): 0 0 10
 Enter secondary section's unnormalized (Xle, Yle) and chord.
 (3 values; <CR> = leave normalized): 5 1 6

 Enter span stations of primary, secondary, and desired sections:
 0 15 8

Revised

Maximum thickness/chord (current axes) . . . 12.0034% at X/C = 0.30000
 Maximum camber/chord 0.0001% at X/C = 0.84000
 Unnormalized area 0.508727E+01
 Moment of inertia about X axis 0.170779E+01

Modified airfoil: mode10.dat
 Airfoil plot file: mode10.plt
 Tabulated results: mode10.tab
 Curvature QPLOT file: mode10.crv
 2nd derivatives file: mode10.ypp

Mode 11: Sharpen a rounded leading edge, and conversely

```
$ profile
```

```
Welcome to PROFILE from the Aerodynamics Division, NASA Ames.
```

```
0 = DISPLAY (plot/tabulate only or alter format/precision)
...
8 = ROTATE coordinates, with option to renormalize
9 = COMBINE option (add or subtract profiles)
10 = LOFT linearly between primary and secondary profiles
11 = NOSE-JOB option: round or sharpen the leading edge
12 = SMOOTH YU and/or YL: Wagner fn. fits or [im|ex]plicit
```

Select operating mode.

```
? = menu; CTRL Z = quit; <CR> = DISPLAY: nose
Input airfoil file? <CR>=naca0012.dat:
Input control file? <CR>=profile.inp or none:
No control file found - proceeding ...
Identifier for output files? <CR>="profile": model1
Plot title line? <CR> uses "PROFILE" for the title:
Sharpen leading edge of NACA 0012 section
Plot subtitle line? <CR> means none:
Result is reversible
Do you really want Cp estimates? (Y/N; <CR>=No)
```

```
PROFILE's "nose-job" options are:
```

- (1) Round off a sharp leading edge
- (2) Sharpen a rounded leading edge

```
What'll it be? 2
```

```
Index of first UPPER surface point to retain: 10
Index of first LOWER surface point to retain: 10
```

```
Estimate of leading edge by extrapolation:
X = -0.167262E-02   Y = 0.000000E+00
```

```
Different X? <CR> = above value:
Different Y? <CR> = above value:
```

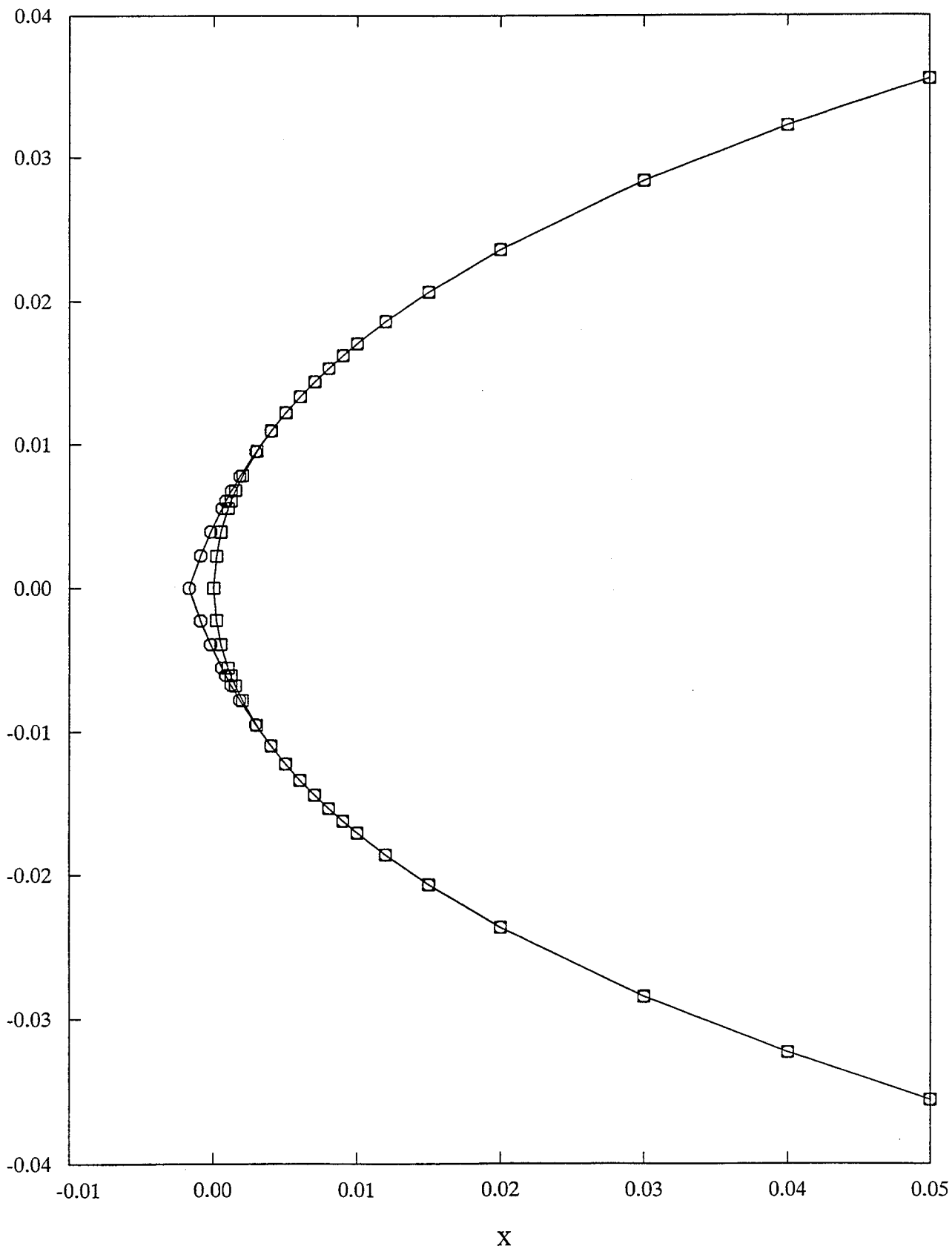
Revised

```
Maximum thickness/chord (current axes) . . . 11.9834% at X/C = 0.30117
Maximum camber/chord . . . . . 0.0000% at X/C = 0.84027
Unnormalized area . . . . . 0.822188E-01
Moment of inertia about X axis . . . . . 0.680857E-04
```

```
Modified airfoil:      model1.dat
Airfoil plot file:    model1.plt
Tabulated results:    model1.tab
Curvature QPLOT file: model1.crv
2nd derivatives file: model1.ypp
```

Sharpen leading edge of NACA 0012 section Result is reversible

—□— NACA 0012
—○— Revised profile



Mode 12: Smooth airfoil (implicit/explicit schemes or fitting of Wagner functions)

(a) Wagner function fitting

\$ profile

Welcome to PROFILE from the Aerodynamics Division, NASA Ames.

- 0 = DISPLAY (plot/tabulate only or alter format/precision)
- 1 = RECTIFY leading edge definition; allows vertical shift
- 2 = NORMALIZE or denormalize coordinates
- 3 = REDISTRIBUTE the abscissas
- 4 = MODIFY either surface or both (apply shape functions)
- 5 = REFINE thickness/curvature
- 6 = OPTIMIZE one surface ("bumps" + target curvatures)
- 7 = TRANSFORM YU/YL to/from camber/thickness, or decamber
- 8 = ROTATE coordinates, with option to renormalize
- 9 = COMBINE option (add or subtract profiles)
- 10 = LOFT linearly between primary and secondary profiles
- 11 = NOSE-JOB option: round or sharpen the leading edge
- 12 = SMOOTH YU and/or YL: Wagner fn. fits or [im|ex]plicit

Select operating mode.

? = menu; CTRL Z = quit; <CR> = **DISPLAY**: smooth
 Input airfoil file? <CR>=naca0012.dat: naca64412.dat
 Input control file? <CR>=profile.inp or none:
 No control file found - proceeding ...
 Identifier for output files? <CR>="profile": model2a
 Plot title line? <CR> uses "PROFILE" for the title:
 Smoothing via fitting of Wagner functions
 Plot subtitle line? <CR> means none:

Do you really want Cp estimates? (Y/N; <CR>=No)

Smoothing methods:

- 1: Least squares fitting of Wagner functions 1:N
 - 2: Implicit + explicit smoothing, variable along chord
- Pick one. Default = 1:

Enter # Wagner functions to use on the UPPER surface.

(<CR> = 10; 0 or EOF (^D) = leave surface alone):

pts. to fix (after smoothing) forward of the TE? (>=0; [3])

Wagner fns. for the LOWER surface? (<CR> = same as upper)

pts. to fix (after smoothing) forward of the TE? (>=0; [3])

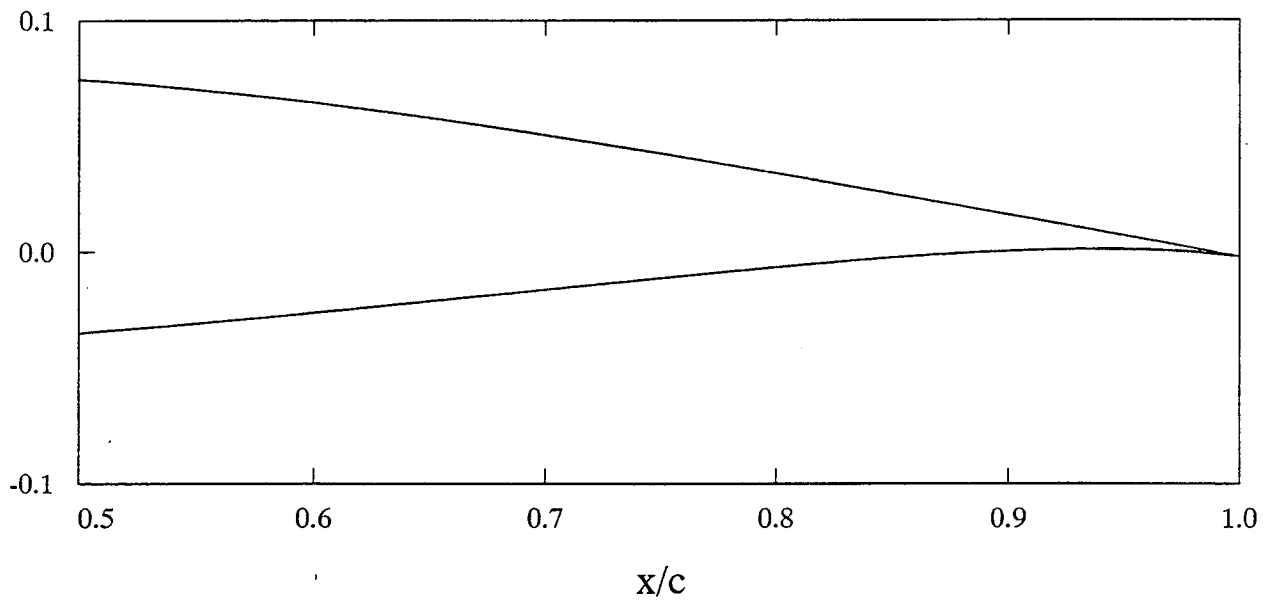
Revised

Maximum thickness/chord (current axes) . . . 11.9845% at X/C = 0.36906
 Maximum camber/chord 1.9752% at X/C = 0.51013
 Unnormalized area 0.759270E-01
 Moment of inertia about X axis 0.820018E-04

Modified airfoil: model2a.dat
 Airfoil plot file: model2a.plt
 Tabulated results: model2a.tab
 Curvature QPLOT file: model2a.crv
 2nd derivatives file: model2a.ypp

Smoothing via fitting of Wagner functions
 All defaults taken, including patch of 3 points forward of trailing edge

--- NACA 64412
 — Revised profile



(b) Implicit smoothing

\$ profile

Welcome to PROFILE from the Aerodynamics Division, NASA Ames.

0 = DISPLAY (plot/tabulate only or alter format/precision)

 10 = LOFT linearly between primary and secondary profiles
 11 = NOSE-JOB option: round or sharpen the leading edge
 12 = SMOOTH YU and/or YL: Wagner fn. fits or [im|ex]plicit

Select operating mode.

? = menu; CTRL Z = quit; <CR> = **DISPLAY**: smooth
 Input airfoil file? <CR>=naca0012.dat: naca64412.dat
 Input control file? <CR>=profile.inp or none:
 No control file found - proceeding ...
 Identifier for output files? <CR>="profile": model2b
 Plot title line? <CR> uses "PROFILE" for the title:
 Implicit smoothing of NACA 64412 section
 Plot subtitle line? <CR> means none:
 Eps = 0.01, s(norm) ** 5 weighting
 Do you really want Cp estimates? (Y/N; <CR>=No)

Smoothing methods:

1: Least squares fitting of Wagner functions 1:N
 2: Implicit + explicit smoothing, variable along chord
 Pick one. Default = 1: 2

Enter smoothing controls for the UPPER surface. (0. = leave it alone.)
 [Peak] IMPLICIT smoothing coefficient? (>=0.; [0.01])
 [Peak] EXPLICIT smoothing coefficient? (>=0.; [0.10*dS**2]) 0
 Uniform smoothing along the chord? (Y/N; [N])

0. Done.
 1. SCALE: $Y \leftarrow Y * P1$
 2. RAMP: $Y \leftarrow X * P1$
 3. FLAP: $Y \leftarrow Y - (X - P1) * \text{TAN}(P2 \text{ deg.})$ for $X > P1$
 4. SLAT: $Y \leftarrow Y - (P1 - X) * \text{TAN}(P2 \text{ deg.})$ for $X < P1$
 5. TRAIL: $X ** P1$
 6. DROOP: $(1 - X) * \text{EXP}(-P1 * X)$
 7. LEAD: $(1 - X) ** P1$
 8. EXPO: $(X^P (1-X) \text{EXP}(-P2 X)) / (P1^P (1-P) \text{EXP}(-P2 P))$
 9. SINE: $\text{SIN} ** P2$ of $\text{pi} * X ** (\text{LOG}(0.5) / \text{LOG}(P1))$
 10. SINF: Flipped form of 9 [SINE] - left & right swapped
 11. SIN1: Symmetric form of 9 [SINE] - left half
 12. SIN2: Symmetric form of 9 [SINE] - right half
 13. COSL: 1/4 cosine, peak at left; power P1
 14. COSR: 1/4 cosine, peak at left; power P1
 15. LCOS: 1 - 1/4 cosine, peak at left; power P1
 16. RCOS: 1 - 1/4 cosine, peak at left; power P1
 17. WAGNER: Wagner function; P1 = order of term N

Choose a weighting function.

? = menu; CTRL Z or <CR> = quit: trail
 Shape function TRAIL: Enter POWER : 5
 Smooth LOWER surface the same way? (Y/N; [Y])

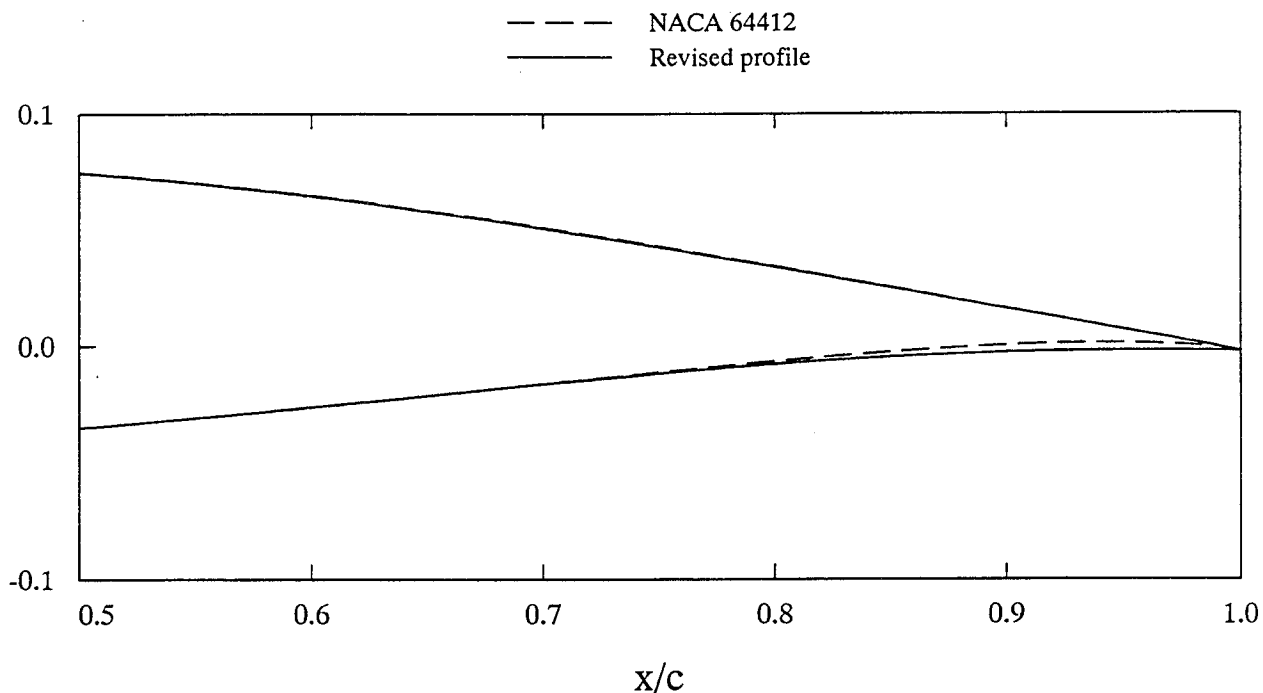
Revised

Maximum thickness/chord (current axes) . . . 11.9879% at X/C = 0.36906
 Maximum camber/chord 1.9719% at X/C = 0.50006
 Unnormalized area 0.762751E-01
 Moment of inertia about X axis 0.815168E-04

Modified airfoil: mode12b.dat
 Airfoil plot file: mode12b.plt
 Tabulated results: mode12b.tab
 Curvature QPLOT file: mode12b.crv
 2nd derivatives file: mode12b.ypp

Implicit smoothing of NACA 64412 section

Eps = 0.01, s(norm) ** 5 weighting



(c) Explicit smoothing

\$ profile

Welcome to PROFILE from the Aerodynamics Division, NASA Ames.

0 = DISPLAY (plot/tabulate only or alter format/precision)

.....

10 = LOFT linearly between primary and secondary profiles

11 = NOSE-JOB option: round or sharpen the leading edge

12 = SMOOTH YU and/or YL: Wagner fn. fits or [im|ex]plicit

Select operating mode.

? = menu; CTRL Z = quit; <CR> = **DISPLAY**: smooth

Input airfoil file? <CR>=naca0012.dat: naca64412.dat

Input control file? <CR>=profile.inp or none:

No control file found - proceeding ...

Identifier for output files? <CR>="profile": model2c

Plot title line? <CR> uses "PROFILE" for the title:

Explicit smoothing of NACA 64412 section

Plot subtitle line? <CR> means none:

Eps = 0.01, s(norm) ** 5 weighting

Do you really want Cp estimates? (Y/N; <CR>=No)

Smoothing methods:

1: Least squares fitting of Wagner functions 1:N

2: Implicit + explicit smoothing, variable along chord

Pick one. Default = 1: 2

Enter smoothing controls for the UPPER surface. (0. = leave it alone.)

[Peak] IMPLICIT smoothing coefficient? (>=0.; [0.01]) 0

[Peak] EXPLICIT smoothing coefficient? (>=0.; [0.10*dS**2])

explicit smoothing iterations? [1]

Uniform smoothing along the chord? (Y/N; [N])

0. Done.

1. SCALE: $Y \leftarrow Y * P1$

2. RAMP: $Y \leftarrow X * P1$

3. FLAP: $Y \leftarrow Y - (X - P1) * \text{TAN}(P2 \text{ deg.})$ for $X > P1$

4. SLAT: $Y \leftarrow Y - (P1 - X) * \text{TAN}(P2 \text{ deg.})$ for $X < P1$

5. TRAIL: $X ** P1$

6. DROOP: $(1 - X) * \text{EXP}(-P1 * X)$

7. LEAD: $(1 - X) ** P1$

8. EXPO: $(X^P (1-X) \text{EXP}(-P2 X)) / (P1^P (1-P) \text{EXP}(-P2 P))$

9. SINE: $\text{SIN} ** P2$ of $\text{pi} * X ** (\text{LOG}(0.5) / \text{LOG}(P1))$

10. SINP: Flipped form of 9 [SINE] - left & right swapped

11. SIN1: Symmetric form of 9 [SINE] - left half

12. SIN2: Symmetric form of 9 [SINE] - right half

13. COSL: 1/4 cosine, peak at left; power P1

14. COSR: 1/4 cosine, peak at left; power P1

15. LCOS: 1 - 1/4 cosine, peak at left; power P1

16. RCOS: 1 - 1/4 cosine, peak at left; power P1

17. WAGNER: Wagner function; P1 = order of term N

Choose a weighting function.

? = menu; CTRL Z or <CR> = quit: trail

Shape function TRAIL: Enter POWER : 5

Smooth LOWER surface the same way? (Y/N; [Y])

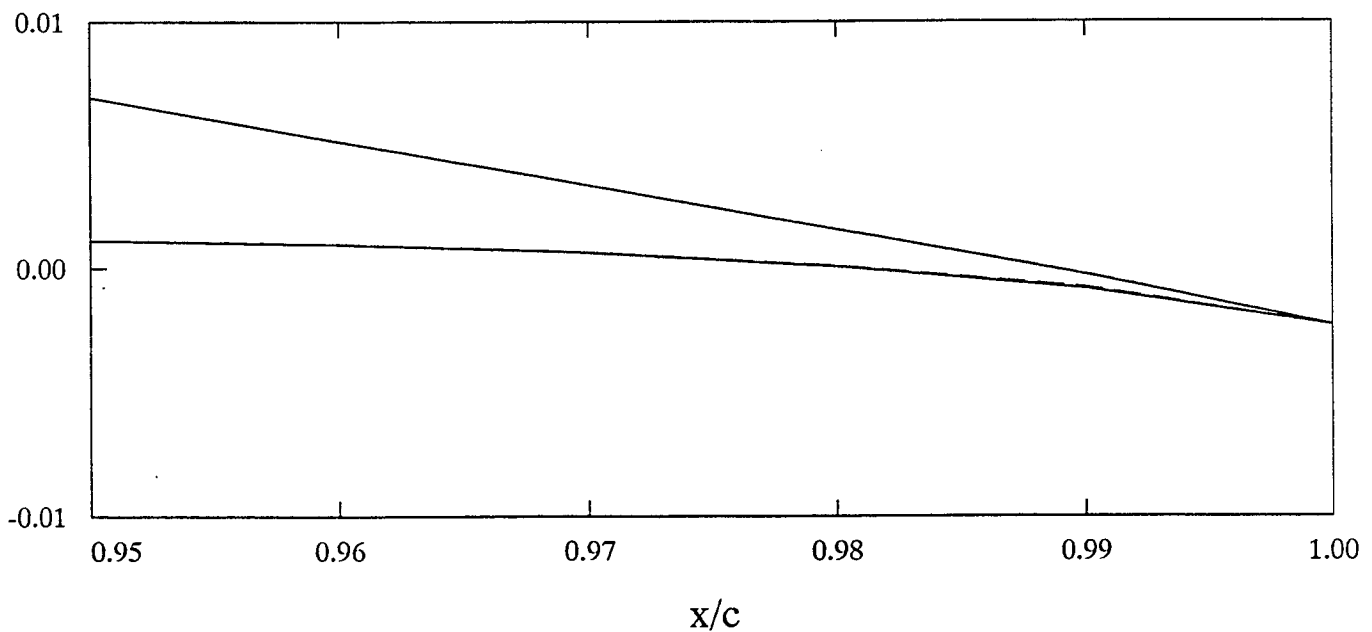
Revised

Maximum thickness/chord (current axes) . . . 11.9988% at X/C = 0.37914
Maximum camber/chord 1.9764% at X/C = 0.50006
Unnormalized area 0.759179E-01
Moment of inertia about X axis 0.820039E-04

Modified airfoil: model12c.dat
Airfoil plot file: model12c.plt
Tabulated results: model12c.tab
Curvature QPLOT file: model12c.crv
2nd derivatives file: model12c.ypp

Explicit smoothing of NACA 64412 section Eps = 0.1 (* ds ** 2); s(norm) ** 5 weighting; 1 iteration

--- NACA 64412 rectified
— Revised profile



REPORT DOCUMENTATION PAGE

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| 13. ABSTRACT (Maximum 200 words) This report provides user information for program PROFILE, an aerodynamics design utility for plotting, tabulating, and manipulating airfoil profiles. A dozen main functions are available. The theory and implementation details for two of the more complex options are also presented. These are the REFINER option, for smoothing curvature in selected regions while retaining or seeking some specified thickness ratio, and the OPTIMIZE option, which seeks a specified curvature distribution. Use of programs QPLOT and BPLOT is also described, since all of the plots provided by PROFILE (airfoil coordinates, curvature distributions, pressure distributions) are achieved via the general-purpose QPLOT utility. BPLOT illustrates (again, via QPLOT) the shape functions used by two of PROFILE's options. These three utilities should be distributed as one package. They were designed and implemented for the Applied Aerodynamics Branch at NASA Ames Research Center, Moffett Field, California. They are all written in FORTRAN 77 and run on DEC and SGI systems under OpenVMS and IRIX. | | | | |
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