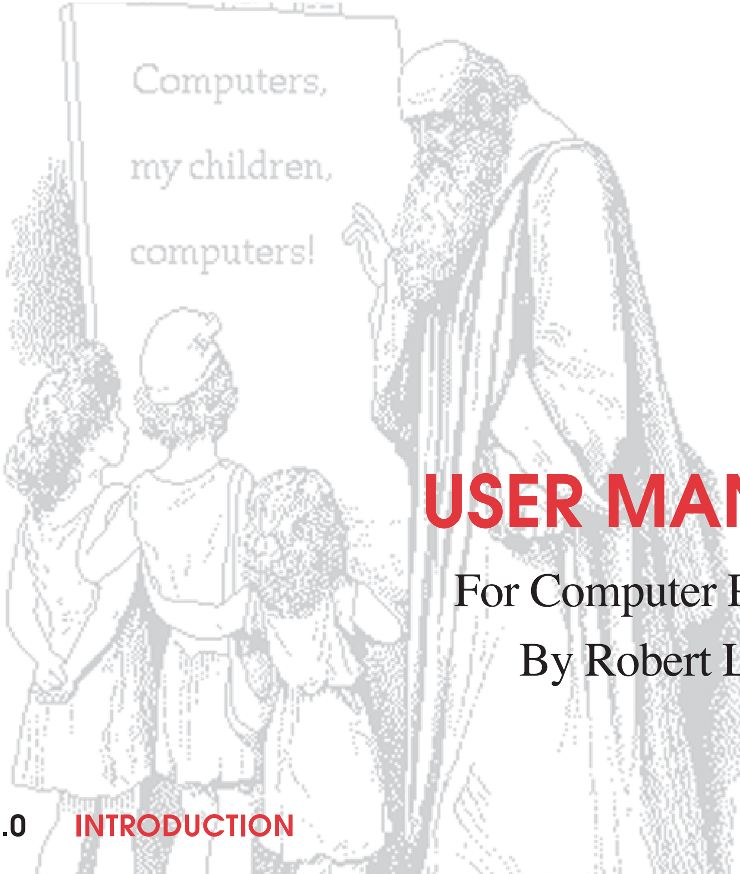


USER MANUAL

For Computer Programs

By Robert L. Norton

A.0 INTRODUCTION

In addition to the textbook version of the commercial simulation program *Working Model*, and the linkage synthesis program SYMECH, there are seven custom computer programs provided on the DVD with this text: programs FOURBAR, FIVEBAR, SIXBAR, SLIDER, MATRIX, DYNACAM, and ENGINE. These are student editions of the programs for educational use only. For commercial applications, professional versions with extended capabilities are available at **http://www.designofmachinery.com/**. Programs FOURBAR, FIVEBAR, SIXBAR, and SLIDER are based on the mathematics derived in Chapters 4 to 7 and 10 to 11 and use the equations presented therein to solve for position, velocity, and acceleration in linkages of the variety described in the particular program's name. Program DYNACAM is a cam design program based on the mathematics derived in Chapters 8 and 15. Program ENGINE is based on the mathematics derived in Chapters 13 and 14. Program MATRIX is a general linear simultaneous equation solver. All have similar choices for display of output data in the form of tables and plots. All the programs are designed to be user friendly and reasonably "crashproof." The author encourages users to email reports of any "bugs" or problems encountered in their use to him at norton@wpi.edu.

Learning Tools

All the custom programs provided with this text are designed to be learning tools to aid in the understanding of the relevant subject matter and *are specifically not intended to be used for commercial purposes in the design of hardware* **and should not be so used**.

It is quite possible to obtain inappropriate (but mathematically correct) results to any problem solved with these programs, due to incorrect or inappropriate input of data. In other words, the user is expected to understand the kinematic and dynamic theory underlying the program's structure and to also understand the mathematics on which the program's algorithms are based. This information on the underlying theory and mathematics is derived and described in the noted chapters of this text. Most equations used in the programs are derived or presented in this textbook.

Disclaimer

Commercial software for use in design or analysis needs to have built-in safeguards against the possibility of the user providing incorrect, inappropriate, or ridiculous values for input variables, in order to guard against erroneous results due to user ignorance or inexperience. **The student editions of the custom programs provided with this text are not commercial software and deliberately do not contain such safeguards against improper input data**, on the premise that to do so would "short circuit" the student's learning process. We learn most from our failures. These programs provide a consequence-free environment to explore failure of your designs "on paper" and in the process come to a more thorough and complete understanding of the subject matter. **The author and publisher are not responsible for any damages which may result from the use or misuse of these programs.**

Brute Force and Ignorance (BFI)

The very rapid computation speed of these programs allows the student to explore a much larger number and variety of potential solutions to more realistic and comprehensive problems than could be accomplished using only hand calculator solutions of these complicated systems of equations. This is both an advantage and a danger. The advantage is that the student can use the programs like a "flight simulator" to "fly" potential design solutions through their paces with no consequences from a "crash" of the design not yet built. If the student diligently attempts to interpret the program's results and relate them to the relevant theory, a more thorough understanding of the kinematics and dynamics can result. On the other hand, there is a great temptation to use these programs with "brute force and ignorance" (BFI) to somewhat randomly try solutions without regard to what the theory and equations are telling you and hope that somehow a usable solution will "pop out." The student who succumbs to this temptation will not obtain much benefit from the exercise and will probably have a poor design result. This situation is probably best summed up in the following comment from a student who had suffered through the course in kinematics using these programs to design solutions to three project problems like those listed at the end of Chapter 3.

> . . . The computer, with its immense benefits for the engineer, can also be a hindrance if one does not first develop a thorough understanding of the theory upon which a particular program is based. An over-reliance on the computer can leave one "computer smart" and "engineering stupid." The BFI approach becomes increasingly tempting when it can be employed with such ease. . . . *Brian Kimball*

Smart student! Use these computer programs wisely. Avoid ***B****rute* ***F****orce* and ***I****gnorance!* **Engineer** your solutions and understand the theory behind them.

A.1 GENERAL INFORMATION

Hardware/System Requirements

These programs require Windows 98/2000/NT/XP. A DVD drive is needed, as is a hard disk drive. A Pentium III (or faster) equivalent processor is recommended with at least 64MB of RAM.

Installing the Software

The DVD contains the executable program files plus all necessary Dynamic Link Library (DLL) and other ancillary files needed to run the programs. Run the SETUP file from the individual program's folder on the DVD to automatically decompress and install all of its files on your hard drive. The program name will appear in the list under the *Start* menu's *Program* menu after installation and can be run from there.

How to Use This Manual

This manual is intended to be used while running the programs. To see a screen referred to, bring it up within the program to follow its discussion.

A.2 GENERAL PROGRAM OPERATION

All seven programs in the set have similar features and operate in a consistent way. For example, all printing and plotting functions are selected from identical screens common to all programs. Opening and saving files are done identically in all programs. These common operations will be discussed in this section independent of the particular program. Later sections will address the unique features and operations of each program.

Note that *student editions* of these programs are supplied with this book at no charge and carry a limited-term license restricted to educational use in course work for up to 1 year. If you wish to use the program for the benefit of a company or for any commercial purpose, then you must obtain the professional edition of the same program. **The student editions are not to be used commercially**. The professional editions typically offer more features and better accuracy than the student editions.

Running the Programs (All Programs)

At start-up, a splash screen appears which identifies the program version, revision number, and revision date. Click the button labeled *Start* or press the *Enter* key to run the program. A *Disclaimer* screen next appears which defines the registered owner and allows the printing of a registration form if the software is as yet unregistered. A registration form can be accessed and printed from this screen.

The next screen, the *Title* screen, allows the input of any user and/or project identification desired. This information must be provided to proceed and is used to identify all plots and printouts from this program session. The second box on the *Title* screen allows any desired file name to be supplied for storing data to disk. This name defaults to

Model1 and may be changed at this screen and/or when later writing the data to disk. The third box allows the typing of a starting design number for the first design. This design number defaults to 1 and is automatically incremented each time you change the basic design during this program session. It is used only to identify plots, data files, and printouts so they can be grouped, if necessary, at a later date. When the *Next* button on the *Title* screen is clicked, the *Home* screen appears.

The *Home* Screen (All Programs)

All program actions start and end at the *Home* screen which has several pull-down menus and buttons, some of which commands (*File*, *New*, *Open*, *Save*, *Save As*, *Units*, *About*, *Plot*, *Print*, *Quit*) are common to all programs. These will be described below.

General User Actions Possible Within a Program (All Programs)

The programs are constructed to allow operation from the keyboard or the mouse or with any combination of both input devices. Selections can be made either with the mouse or, if a button is highlighted (showing a dotted square within the button), the *Enter* key will activate the button as if it had been clicked with the mouse. Text boxes are provided where you need to type in data. These have a yellow background. In general, what you type in any text box is not accepted until you hit the *Enter* key or move off that box with the *Tab* key or the mouse. This allows you to retype or erase with no effect until you leave the text box. You can move between available input fields with the *Tab* key (and backup with *Shift-Tab*) on most screens. If you are in doubt as to the order in which to input the data on any screen, try using the *Tab* key as it will take you to each needed entry field in a sensible order. You can then type or mouse click to input the desired data in that field. Remember that a yellow background means typed input data is expected. Boxes with a cyan background provide information back to you but cannot be typed in.

Other information required from you is selected from drop-down menus or lists. These have a white background. Some lists allow you to type in a value different than any provided in the available list of selections. If you type an inappropriate response, it will simply ignore you or choose the closest value to your request. Typing the first few letters of a listed selection will sometimes cause it to be selected. Double clicking on a selectable item in a list will often provide a shortcut.

Help (All Programs)

The *Help* menus on some screens provide online access to this manual as well as specific instructions for various functions within the programs. A number of instructional videos are also accessible from the help menus. These download from a website and run automatically in Windows Media player or any similar program. These videos provide tutorial instruction in program use. You must be connected to the internet to access the online help and videos.

Units (All Programs)

The *Units* menu defines several units systems to choose from. It is your responsibility to ensure that the data as input are in some consistent units system. Units conversion is done within the program. The *Units* menu selection that you make will convert any data that may already be present from the current unit system to the selected one. Five unit systems are supported: ips, fps, SI, and two mixed unit versions of SI, cm-kg-N-s and mm-kg-N-s. These last two are really SI for dynamic calculation purposes but the length units are displayed in cm or mm and converted to m before calculating any parameters that involve kinematic or dynamic equations.

Examples (Most Programs)

Most of the programs have an *Examples* pull-down menu on the *Home* screen which provides some number of example mechanisms that will demonstrate the program's capability. Selecting an example from this menu will cause calculation of the mechanism and open a screen to allow viewing the results. In some cases you may need to hit a button marked *Calculate*, *Run*, or *Animate* on the presented screen to see the results. Some programs also provide access to examples from various screens.

Creating New, Saving, and Opening Files (*File* - All Programs)

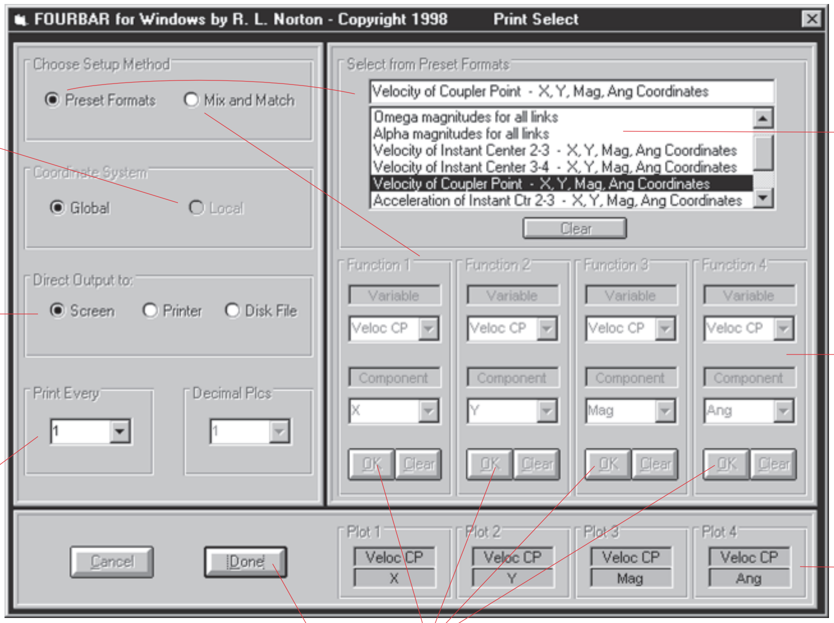
The standard *Windows* functions for creating new files, saving your work to disk, and opening a previously saved file are all accessible from the pull-down menu labeled *File* on each program's *Home* screen. Selecting *New* from this menu will zero any data you may have already created within the program, but before doing so will give warning and prompt you to save the data to disk.

The *Save* and *Save As* selections on the *File* menu prompt you to provide a file name and disk location to save your current model data to disk. The data are saved in a custom format and with a three-character suffix unique to the particular program. You should use the recommended suffix on these files as that will allow the program to see them on the disk when you want to open them later. If you forget to add the suffix when saving a file, you can still recover the file.

Selecting *Open* from the *File* menu prompts you to pick a file from those available in the disk directory that you choose. If you do not see any files with the program's suffix, use the pull-down menu within the *Open File* dialog box to choose S*how All Files* and you will then see them. They will read into the program properly with or without the suffix in their name as long as they were saved from the same program.

Copying Screens to Clipboard or Printer (*Copy* - All Programs)

Any screen can be copied as a graphic to the clipboard by using the standard *Windows* keyboard combo of *Alt-PrintScrn*. It will then be available for pasting into any compatible *Windows* program such as *Word* or *Powerpoint* that is running concurrently in *Windows*. Some screens also provide a button to dump the screen image to an attached laser printer. However, the quality of that printed image may be less than could be obtained by copying and pasting the image into any program that accepts graphic input such as *Word*, *Powerpoint,* or *Paint Shop Pro* and then printing it from that program. It seems that *Visual Basic* does not print graphics as well as some other *Windows* applications. NOTE: *In some cases the plotted functions may not print properly. If so, copy the screen to clipboard, paste into Word, and print from Word.*



FOURBAR for Windows by R. L. Norton - Copyright 1998 Print Select

Choose Setup Method: ● Preset Formats ○ Mix and Match

Coordinate System: ● Global ○ Local

Direct Output to: ● Screen ○ Printer ○ Disk File

Print Every: 1

Decimal Plcs: 1

Select from Preset Formats: Velocity of Coupler Point - X, Y, Mag, Ang Coordinates

- Omega magnitudes for all links
- Alpha magnitudes for all links
- Velocity of Instant Center 2-3 - X, Y, Mag, Ang Coordinates
- Velocity of Instant Center 3-4 - X, Y, Mag, Ang Coordinates
- Velocity of Coupler Point - X, Y, Mag, Ang Coordinates
- Acceleration of Instant Ctr 2-3 - X, Y, Mag, Ang Coordinates

	Function 1	Function 2	Function 3	Function 4
Variable	Veloc CP	Veloc CP	Veloc CP	Veloc CP
Component	X	Y	Mag	Ang

Plot 1	Plot 2	Plot 3	Plot 4
Veloc CP X	Veloc CP Y	Veloc CP Mag	Veloc CP Ang

Local coord. system only is available for some variables

Sends data to screen, printer, or a disk file for import to a spreadsheet

Skips over data to shorten output

Double click on any item in this list

– or –

Choose any four items and their components from these dropdown lists

These boxes show what will be printed

Click here to see the plots

Click here to select a variable for plot

FIGURE A-1

The *Print Select* screen is common to all programs (not all programs allow component selection)

Printing to Screen, Printer, and Exporting Disk Files (*Print* Button)

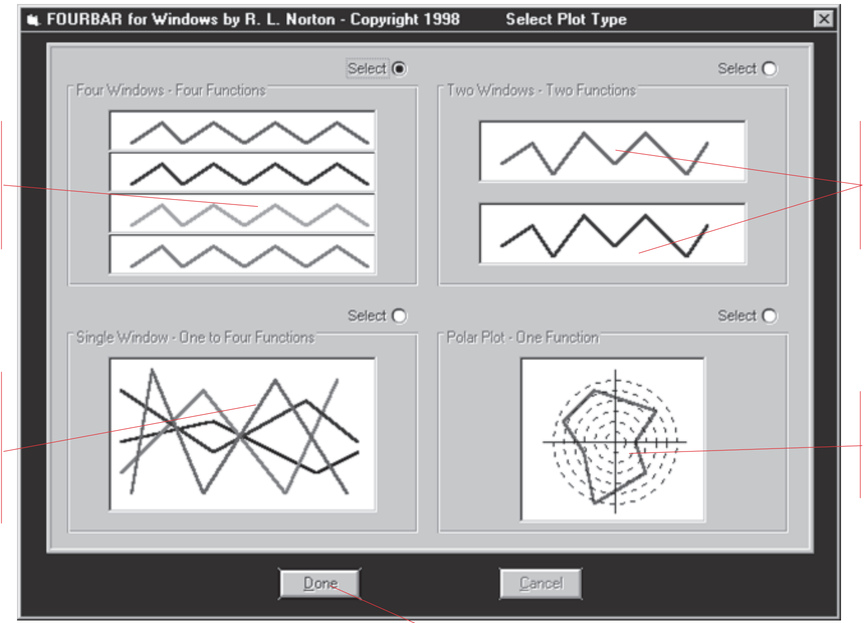
Selecting the *Print* button from the *Home* screen will open the *Print Select* screen (see Figure A-1) containing lists of variables that may be printed. Buttons on the left of this screen can be clicked to direct the printed output to one of *Screen*, *Printer*, or *Disk*. This choice defaults to *Screen* and so must be clicked each time the screen is opened to obtain either of the other options. The output is different with each of these selections.

Selecting *Screen* will result in a scrollable screen window full of the requested data. Scrolling will allow you to view all data requested serially. This data screen can be copied to the clipboard or dumped to a printer as described above, but this clip or dump will typically show only a portion of the available data, i.e., one screenful.

Selecting *Printer* as the output device will cause the entire selection of data to print to an available printer. Only some of the sidebar information shown on the screen display will be included in this printout.

Selecting *Disk* as the output device will cause your selections to be sent to the file of your choice in an ASCII text format (tab delimited) that can be opened in a spreadsheet program such as *Excel*. You can then do further calculations or plotting of data within the spreadsheet program.

The *Print Select* screen has two modes for data selection, *Preset Formats* and *Mix and Match*. The former provides preselected sets of four variables for printing. Selecting *Mix and Match* allows you to pick any four of the available variables for printing. You must print four variables at a time in either mode. Depending on the program, you



Double click here to get four cartesian plots in four aligned windows

Double click here to get two cartesian plots in two aligned windows

Double click here to get from one to four superposed cartesian plots in one window

Double click here to get one polar plot in one window

Click here to select variables for plots

FIGURE A-2

The *PlotType* screen is common to all programs that allow plotting

may be able to select other ancillary parameters such as the number of decimal places or the frequency of data to be printed.

Plotting Data (*Plot* Button)

The *Plot* button on the *Home* screen brings up the *PlotType* screen (see Figure A-2) which is the same in all programs. Variables in these programs can be plotted in one of several formats, three cartesian (see below) and one polar (see below). This screen allows a choice among these four "flavors" of plots shown as plot-style icons. The first icon (upper left) provides four functions plotted on cartesian axes in four separate windows. The second icon (upper right) plots two functions on cartesian axes in separate windows. The third icon (lower left) allows one to four functions to be plotted on common cartesian axes in a single window. This choice is of value to show a single function full screen or to overlay multiple functions. (Be advised, however, that multiple functions will scale to the largest function of the set, so if there are large differences in magnitude between the members of the set, it may be difficult to see and interpret the smaller ones.) The fourth icon (lower right) provides a polar plot of one selected function. You may select any of these four plot styles by clicking on its icon or on the *Select* button above it and then clicking *Next*. Shortcut: Double clicking on a plot icon will bring up the next screen immediately.

CARTESIAN PLOTS depict a dependent variable versus an independent variable on cartesian (x, y) axes. In these programs, the independent variable shown on the x axis may be either time or angle, depending on the calculation choice made in the particular program. The variable for the *y* axis is selected from the plot menu. Angular velocities and torques are vectors but are directed along the *z* axis in a two-dimensional system. So their magnitudes can be plotted on cartesian axes and compared because their directions are constant, known, and the same.

POLAR PLOTS Plots of linear velocities, linear accelerations, and forces require a different treatment than the cartesian plots used for the angular vector parameters. Their directions are not the same and vary with time or input angle. One way to represent these linear vectors is to make two cartesian plots, one for magnitude and one for angle of the vector at each time or angle step. Alternatively, the x and y components of the vector at each time or angle step can be presented as a pair of cartesian plots. Either of these approaches requires two plots per vector and has the disadvantage of being difficult to interpret. A better method for vectors that act on a moving point (such as a force on a moving pin) can be to make a polar plot with respect to a local, nonrotating axis coordinate system (LNCS) x, y attached at the moving point. This local, nonrotating x, y axis system translates with the point as it moves but remains always parallel to the global X, Y axis system. By plotting the vectors on this moving axis system we can see both their magnitude and direction at each time or angle step, since we are attaching the roots of all the vectors to the moving point at which they act.

In some of the programs, polar plots can be paused between the plotting of each vector. Without a pause, the plotting may occur too quickly for the eye to detect the order in which they are drawn. When a mouse click is required between the drawing of each vector, their order is easily seen. With each pause, the current value of the independent variable (time or angle) as well as the magnitude and angle of the vector are displayed.

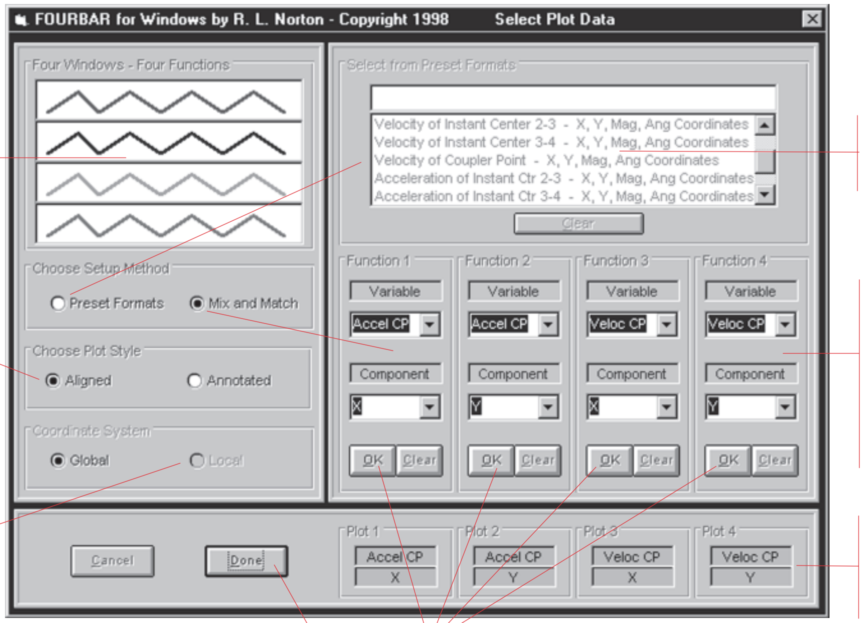
The programs also allow alternate presentations of polar plots, showing just the vectors, just the envelope of the path of the vector tips, or both. A plot that connects the tips of the vectors with a line (its envelope) is called a **hodograph**.

SELECTING PLOT VARIABLES Choosing any one of the four plot types from the *Plot Type* screen brings up a *Plot Select* screen which is essentially the same in all programs. (See Figure A-3.) As with the *Print Select* screen, two arrangements for selecting the functions to be plotted are provided, *Preset Formats* and *Mix and Match*. The former provides preselected collections of functions, and the latter allows you to select up to four functions from those available on the pull-down menus. In some cases you will also have to select the component of the function desired, i.e., *x*, *y*, *mag,* or *angle*.

PLOT ALIGNMENT Some of the *Plot Select* screens offer a choice of two further plot style variants labeled *Aligned* and *Annotated.* The aligned style places multiple plots in exact phase relationship, one above the other. The annotated style does not align the plots but allows more variety in their display such as fills and grids. The data displayed is the same in each case.

COORDINATE SYSTEMS For particular variables in some programs, a choice of coordinate system is provided for display of vector information in plots. The *Coordinate System* panel on the *Plot Select* screen will become active when one of these variables is selected. Then either the *Global* or *Local* button can be clicked. (It defaults to *Global*.)

GLOBAL COORDINATES The *Global* choice in the *Coordinate System* panel refers all angles to the *XY* axes of Figure A-6 (p. 781). For polar plots the vectors shown with the *Global* choice actually are drawn in a local, nonrotating coordinate system (LNCS)


FOURBAR for Windows by R. L. Norton - Copyright 1998   Select Plot Data

Four Windows - Four Functions

Select from Preset Formats

Velocity of Instant Center 2-3 - X, Y, Mag, Ang Coordinates
Velocity of Instant Center 3-4 - X, Y, Mag, Ang Coordinates
Velocity of Coupler Point - X, Y, Mag, Ang Coordinates
Acceleration of Instant Ctr 2-3 - X, Y, Mag, Ang Coordinates
Acceleration of Instant Ctr 3-4 - X, Y, Mag, Ang Coordinates

Choose Setup Method: ○ Preset Formats ● Mix and Match

Choose Plot Style: ● Aligned ○ Annotated

Coordinate System: ● Global ○ Local

	Function 1	Function 2	Function 3	Function 4
Variable	Accel CP	Accel CP	Veloc CP	Veloc CP
Component	X	Y	X	Y

Plot 1	Plot 2	Plot 3	Plot 4
Accel CP	Accel CP	Veloc CP	Veloc CP
X	Y	X	Y

Plot type icon

Aligned puts plots in proper phase - annotated does not

Local coord. system only is available for some variables

Double click on any item in this list

– or –

Choose any four items and their components from these drop-down lists

These boxes show what will be plotted

Click here to see the plots

Click here to select a variable for plot

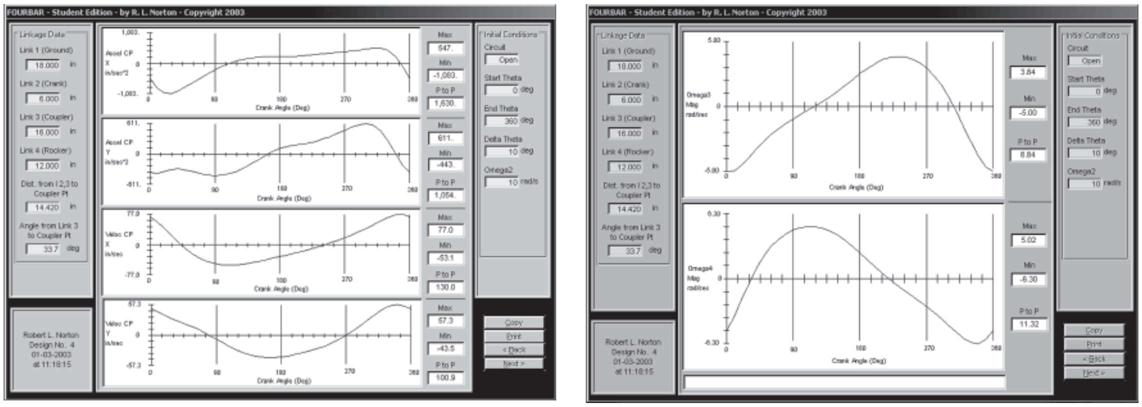
FIGURE A-3

The *PlotSelect* screens are common to all programs. This shows one of four styles of *PlotSelect* screens

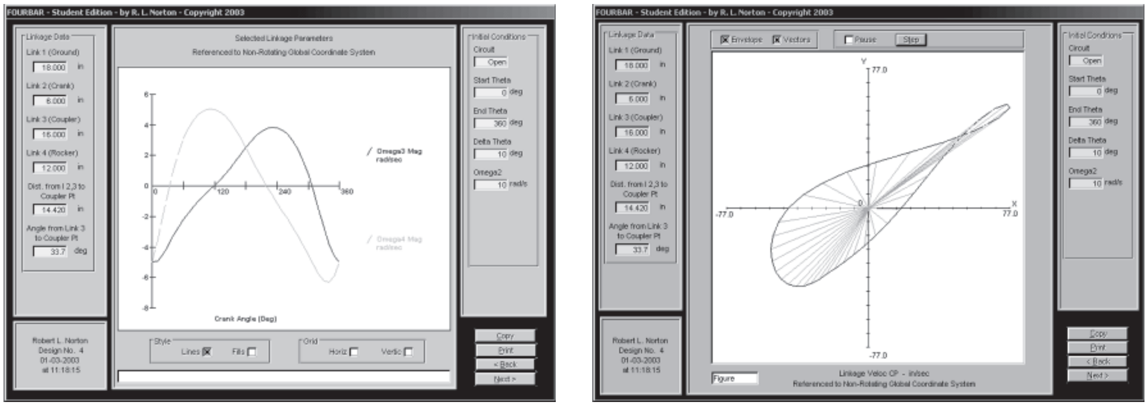
that remains parallel to the global system such as x_1, y_1 at point A and x_2, y_2 at point B in Figure A-1 (p. 774). The LNCS x_2, y_2 at point B behaves in the same way as the LNCS x_1, y_1 at point A; that is, it travels with point B but remains parallel to the world coordinate system X,Y at all times.

LOCAL COORDINATES The coordinate system x',y' also travels with point B as its origin, but is embedded in link 4 and rotates with that link, continuously changing its orientation with respect to the global coordinate system X,Y making it an LRCS. Each link has such an LRCS but not all are shown in Figure A-3. The *Local* choice in the *Coordinate System* panel uses the LRCS for each link to allow the plotting and printing of the tangential and radial components of acceleration or force on a link. This is of value if, for example, a bending stress analysis of the link is wanted. The dynamic force components perpendicular to the link due to the product of the link mass and tangential acceleration will create a bending moment in the link. The radial component will create tension or compression.

PLOTTING Once your selections are made and are shown in the cyan boxes at the lower right of the *Plot Select* screen, the *Next* button will become available. Clicking it will bring up the plots that you selected. Figure A-4 (p. 778) shows examples of the four plot types available. From this *Plot* screen you may copy to the clipboard for pasting into another application or dump the *Plot* screen to a printer. The *Back* button returns you to the previous *Plot Select* screen. *Next* returns you to the *Home* screen.



(*a*) Four aligned plots in separate windows (*b*) Two aligned plots in separate windows



(*c*) One to four plots superposed in one window (*d*) Single polar plot

FIGURE A-4

The four styles of plots available in all programs. Sidebar information is different in each program

The *About* Menu (All Programs)

The *About* pull-down menu on the *Home* screen will display a splash screen containing information on the edition and revision of your copy of the program. The *Disclaimer* and *Registration* form can also be accessed from this menu.

Exiting a Program (All Programs)

Choosing either the *Quit* button or *Quit* on the *File* pull-down menu on the *Home* screen will exit the program. If the current data has not been saved since it was last changed, it will prompt you to save the model using an appropriate suffix. In all cases, it will ask you to confirm that you want to quit. If you choose yes, the program will terminate and any unsaved data will be gone at that point.

Support (All Programs)

Please notify the author of any bugs via email to norton@wpi.edu.

A.3 PROGRAM FOURBAR

FOURBAR is a linkage design and analysis program intended for use by students, engineers and other professionals who are knowledgeable in or are learning the art and science of linkage design. It is assumed that the user knows how to determine whether a linkage design is good or bad and whether it is suitable for the application for which it is intended. The program will calculate the kinematic and dynamic data associated with any linkage design, but cannot substitute for the engineering judgment of the user. The linkage theory and mathematics on which this program is based are documented in Chapters 4 to 7, 10, and 11 of this textbook. Please consult them for explanations of the theory and mathematics involved.

The FOURBAR *Home Screen*

Initially, only the *Input* and *Quit* buttons are active on the *Home* screen. Typically, you will start a linkage design with the *Input* button, but for a quick look at a linkage as drawn by the program, one of the examples under the *Example* pull-down menu can be selected and it will draw a linkage. If you activate one of these examples, when you return from the *Animati*on screen you will find all the other buttons on the *Home* screen to be active. We will address each of these buttons in due course below.

Input Data (FOURBAR *Input* Screen)

Figure A-5 defines the input parameters, link numbering, and the axis system used in program FOURBAR. The link lengths needed are ground link 1, input link 2, coupler link 3, and output link 4, defined by their pin-to-pin distances and labeled *a, b, c, d* in the figure.

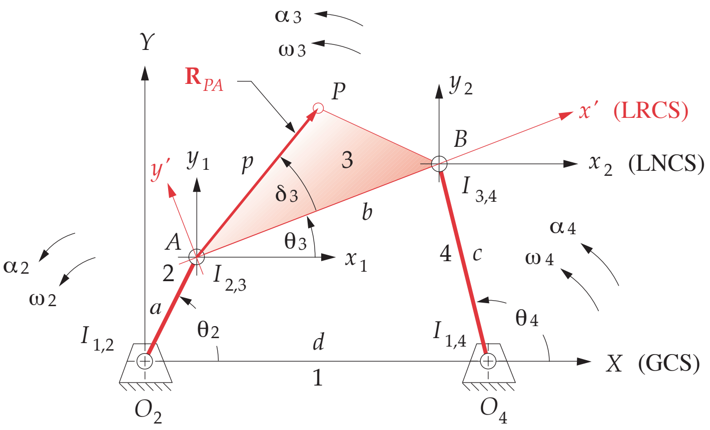
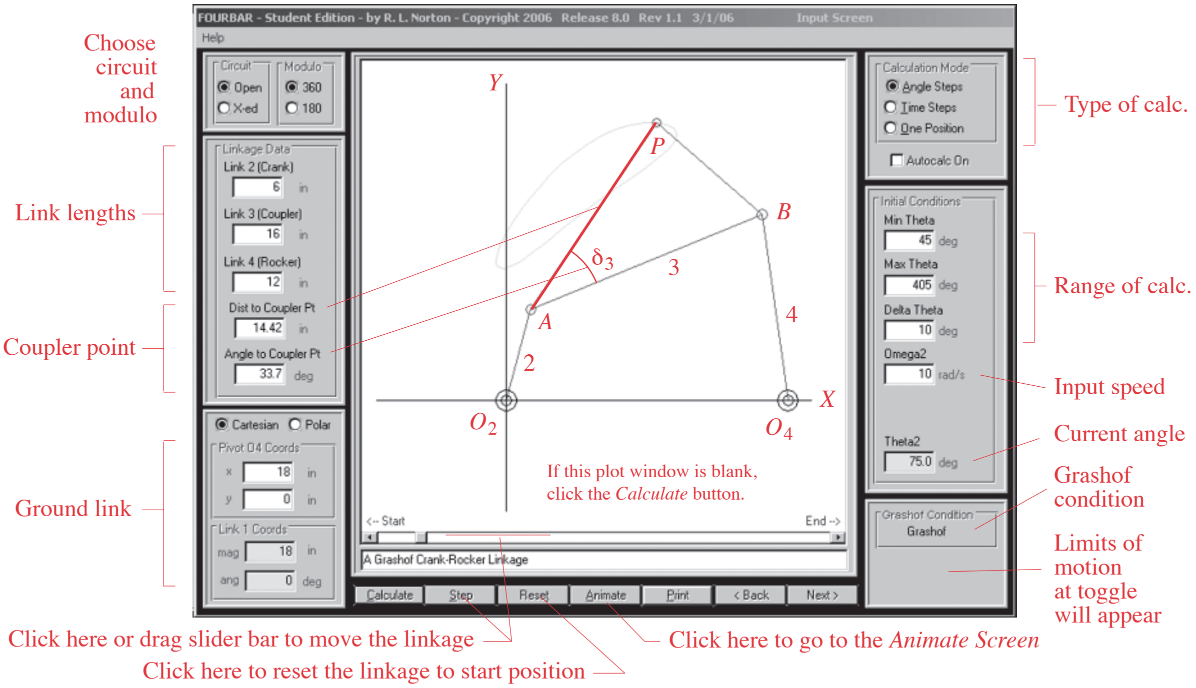


FIGURE A-5

Linkage data for program FOURBAR. (Open the file F_A-05.4br in FOURBAR to see this linkage)

The global *X* axis is horizontal, shown in the figure along link 1, defined by the instant centers $I_{1,2}$ and $I_{1,4}$ which are also labeled, respectively, O_2 and O_4 in the figure. Instant center $I_{1,2}$, the driver crank pivot, is the origin of the global coordinate system. You can define the angle of link 1 with respect to the global X axis with polar or cartesian coordinates for the location of pivot O_4 as shown in Figure A-6.

In addition to the link lengths, you must supply the location of one coupler point on link 3 to find that point's coupler curve positions, velocities, and accelerations. This point is located by a position vector rooted at $I_{2,3}$ (point *A*) and directed to the coupler point *P* of interest which can be anywhere on link 3. The program requires that you input the polar coordinates of this vector which are labeled *p* and δ_3 in Figure A-5. The program asks for the distance from $I_{2,3}$ to the coupler point, which is *p*, and the angle the coupler point makes with link 3 which is δ_3. Note that angle δ_3 is not referenced to either the global coordinate system (GCS) *X, Y* or to the local nonrotating coordinate system (LNCS) *x, y* at point *A*. Rather, it is referenced to the line *AB* which is the pin-to-pin edge of link 3 (LRCS). Angle δ_3 is a property of link 3 and is embedded in it. The angle which locates vector $\mathbf{R}_{PA}$ in the *x, y* coordinate system is the sum of angle δ_3 and angle θ_3. This addition is done in the program, after θ_3 is calculated for each position of the input crank. Also see Section 4.5 (p. 171). The coordinate system, dimensions, angles, and nomenclature in Figure A-5 are consistent with those of Figure 4-6 (p. 172) that were used in the derivation of the equations solved in program FOURBAR.



FOURBAR - Student Edition - by R. L. Norton - Copyright 2006 Release 8.0 Rev 1.1 3/1/06 Input Screen

Circuit: ● Open ○ X-ed

Modulo: ● 360 ○ 180

Linkage Data

Link 2 (Crank) 6 in

Link 3 (Coupler) 16 in

Link 4 (Rocker) 12 in

Dist to Coupler Pt 14.42 in

Angle to Coupler Pt 33.7 deg

● Cartesian ○ Polar

Pivot 04 Coords

x 18 in

y 0 in

Link 1 Coords

mag 18 in

ang 0 deg

If this plot window is blank, click the *Calculate* button.

A Grashof Crank-Rocker Linkage

Calculation Mode

● Angle Steps

○ Time Steps

○ One Position

☐ Autocalc On

Initial Conditions

Min Theta 45 deg

Max Theta 405 deg

Delta Theta 10 deg

Omega2 10 rad/s

Theta2 75.0 deg

Grashof Condition

Grashof

Choose circuit and modulo

Link lengths

Coupler point

Ground link

Type of calc.

Range of calc.

Input speed

Current angle

Grashof condition

Limits of motion at toggle will appear

Click here or drag slider bar to move the linkage

Click here to go to the *Animate Screen*

Click here to reset the linkage to start position

FIGURE A-6

Input Data screen for program FOURBAR. Corresponding screens in FIVEBAR, SIXBAR, and SLIDER are similar

Calculation (FOURBAR, FIVEBAR, SIXBAR, and SLIDER *Input* Screens)

Basic data for a linkage design is defined on the *Input* screen shown in Figure A-6, which is activated by selecting the *Input* button on the *Home* screen. When you open this screen for the first time, it will have default data for all parameters. The linkage geometry is defined in the *Linkage Data* panel on the left side of the screen. You may change these by typing over the data in the yellow text boxes.

The open or crossed circuit of the linkage is selected in a panel at the upper left of the screen in Figure A-6. Select the type of calculation desired, one of *Angle Steps, Time Steps*, or *One Position* from the *Calculation Mode* in the upper-right panel. The start, finish, and delta step information is different for each of these calculation methods, and the input text box labels in the *Initial Conditions* panel will change based on your choice. Type the desired initial, delta, and final conditions as desired.

ONE POSITION will calculate position, velocity, and acceleration for any one specified input position θ_2, input angular velocity ω_2, and angular acceleration α_2.

ANGLE STEPS assumes that the angular acceleration α_2 of input link 2 is zero, making ω_2 constant. The values of initial and final crank angle θ_2, angle step $\Delta\theta_2$, and the constant input crank velocity ω_2 are requested. The program will compute all linkage parameters for each angle step. This is a steady-state analysis and is suitable for either Grashof or non-Grashof linkages provided that the total linkage excursion is limited in the latter case.

TIME STEPS requires input of a start time, finish time, and a time step, all in seconds. The value for α_2 (which must be either a constant or zero) and the initial position θ_2 and initial velocity ω_2 of link 2 at time zero must also be supplied. The program will then calculate all linkage parameters for each time step by applying the specified acceleration, which of course will change the angular velocity of the driver link with time. This is a transient analysis. The linkage will make as many revolutions of the driver crank as is necessary to run for the specified time. This choice is more appropriate for Grashof linkages, unless very short time durations are specified, as a non-Grashof linkage will quickly reach its toggle positions.

Note that a combination of successive **Time Step**, **Crank Angle,** and **Time Step** analyses can be used to simulate the start-up, steady-state, and deceleration phases, respectively, of a system for a complete analysis.

CALCULATE The *Calculate* button will compute all data for your linkage and show it in an arbitrary position in the linkage window on the *Input* screen. If at any time the white linkage window is blank, the *Calculate* button will bring back the image. The *Step* button will move the linkage through its range in calculation steps. The slider bar drags it through its motion.

After calculation, the *Animate* and *Next* buttons on the *Input* screen will become available. The *Animate* or *Next* button takes you to the *Animation* screen where you can run the linkage through any range of motion to observe its behavior. You can also change any of the linkage parameters on the *Animation* screen and then recalculate the results there with the *Recalc* button. The *Next* button on the *Animation* screen returns you to the *Home* screen. The *Plot* and *Print* buttons will now be available as well as the *Animate* button which will send you back to the *Animation* screen.

CALCULATION ERRORS If a position is encountered which cannot be reached by the links (in either the angle step or time step calculations), the mathematical result will be an attempt to take the square root of a negative number. The program will then show a dialog box with the message *Links do not connect for Theta2=xx* and present three choices: Abort, Retry, or Ignore. **Abort** will terminate the calculation at this step and return you to the *Input* screen. **Retry** will set the calculated parameters to zero at the current position and attempt to continue the computation at the next step, reporting successive problems as they occur. **Ignore** will continue the calculation for the entire excursion, setting the calculated parameters to zero at any subsequent positions with problems but will not present any further error messages. If a linkage is non-Grashof and you request calculation for angles that it cannot reach, then you will trip this error sequence. Choosing **Ignore** will force the calculation to completion, and you can then observe the possible motions of the linkage in the linkage window of the *Input* screen with the *Step* button.

GRASHOF CONDITION Once the calculation is done, the linkage's Grashof condition is displayed in a panel at the lower right of the screen. If the linkage is non-Grashof, the angles at which it reaches toggle positions are displayed in a second panel at lower right (not shown in the figure). This information can be used to reset the initial conditions to avoid tripping the "links cannot connect" error.

Animation (FOURBAR, FIVEBAR, SIXBAR, and SLIDER)

The *Animate* button on the *Home* screen brings up the *Animatio*n screen as shown in Figure A-7. Its *Run* button activates the linkage and runs it through the range of motion defined in its most recent calculation. The Grashof condition is reported at the upper right of the screen. The number of cycles for animation can be typed in the *Cycles* box at lower left.

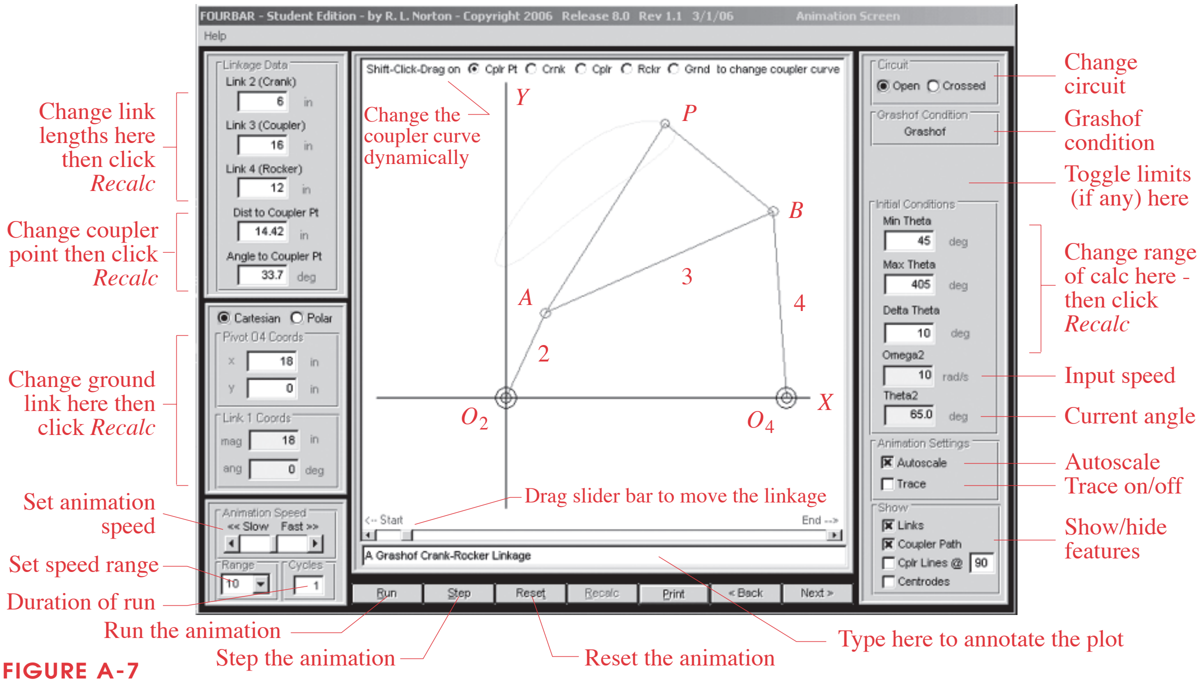
Animation speed can be adjusted with a slider at lower left. This feature is provided to accommodate variations in speed among computers. The *Fast* setting always gives the maximum computer speed. If your computer is very fast, the animation may occur too rapidly to be seen. The drop down box labeled *Range*, lets you change the range of the speed control. Larger range values will give slower animations at the *Slow* setting. The *Step* button moves the linkage one increment of the independent variable at a time.

Text boxes in the *Linkage Data* panel allow the linkage geometry to be changed without returning to the *Input* screen. The initial conditions can be redefined in the panel on the right of this screen. The *Open-Crossed* selection can be switched, but the *Calculation Type* can only be changed on the *Input* screen. Use the *Back* button. After any such change, the linkage must be recalculated with the *Recalc* button and then rerun.

Two panels at the lower right of the *Animatio*n screen provide switches to change the animation display. In the *Show Curves* panel, displays of *Links*, *Coupler Path*, and *Centrodes* can be turned on and off in subsequent animations.

CENTRODES Only the FOURBAR program calculates and draws the fixed and moving centrodes (the loci of the instant centers as defined in Section 6.5 and shown in Figure 6-15a). Different colors are used to distinguish the fixed from the moving centrode. The centrodes are drawn with their point of common tangency located at the first position calculated. Thus, you can orient them anywhere by your choice of start angle for the calculation.

AUTOSCALE can be turned on or off in the *Animation Settings* panel. The linkage animation plot is normally autoscaled to fit the screen based on the size of the linkage



Linkage Data
Link 2 (Crank) 6 in
Link 3 (Coupler) 16 in
Link 4 (Rocker) 12 in
Dist to Coupler Pt 14.42 in
Angle to Coupler Pt 33.7 deg
● Cartesian ○ Polar
Pivot 04 Coords
x 18 in
y 0 in
Link 1 Coords
mag 18 in
ang 0 deg
Animation Speed << Slow Fast >>
Range 10
Cycles 1
Shift-Click-Drag on ● Cplr Pt ○ Crnk ○ Cplr ○ Rckr ○ Grnd to change coupler curve
A Grashof Crank-Rocker Linkage
Circuit ● Open ○ Crossed
Grashof Condition Grashof
Initial Conditions
Min Theta 45 deg
Max Theta 405 deg
Delta Theta 10 deg
Omega2 10 rad/s
Theta2 65.0 deg
Animation Settings
☒ Autoscale
☐ Trace
Show
☒ Links
☒ Coupler Path
☐ Cplr Lines @ 90
☐ Centrodes

Change link lengths here then click *Recalc*
Change coupler point then click *Recalc*
Change ground link here then click *Recalc*
Set animation speed
Set speed range
Duration of run
Run the animation
Step the animation
Change the coupler curve dynamically
Drag slider bar to move the linkage
Reset the animation
Type here to annotate the plot
Change circuit
Grashof condition
Toggle limits (if any) here
Change range of calc here - then click *Recalc*
Input speed
Current angle
Autoscale
Trace on/off
Show/hide features

FIGURE A-7

FOURBAR *Animate Screen*. Programs FIVEBAR, SIXBAR, and SLIDER have similar animation screens

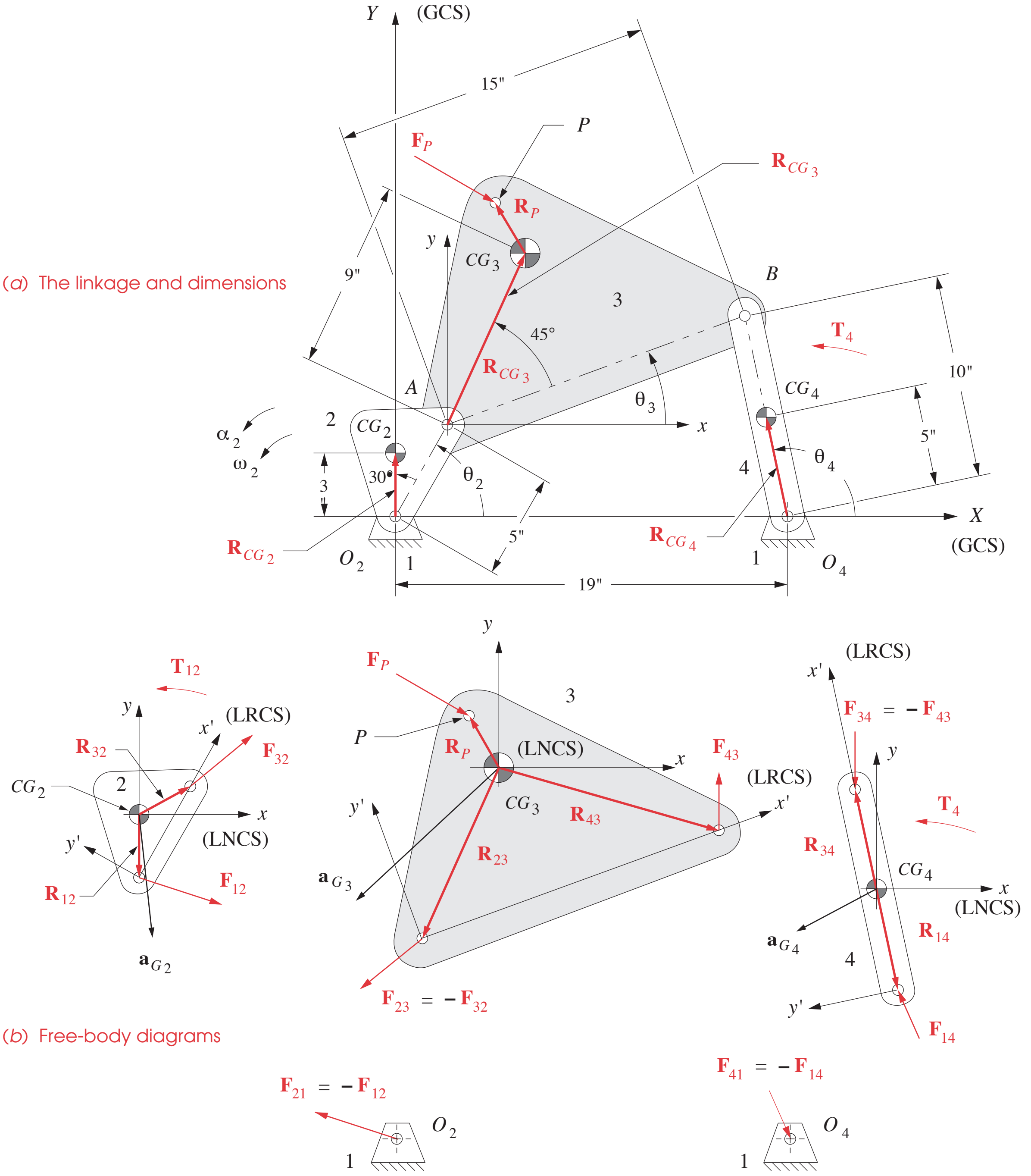
and its coupler curves (but not of the centrodes as they can go to infinity). You may want to turn off autoscaling when you wish to print two plots of different linkages at the same scale for later manual superposition. Turning off autoscaling will retain the most recent scale factor used. When on, it will rescale each plot to fit the screen.

TRACE Turning *Trace* on keeps all positions of the linkage visible on the screen so that the pattern of motion can be seen. Turning *Trace* off erases all prior positions, showing only the current position as it cycles the linkage through all positions giving a dynamic view of linkage behavior.

DYNAMIC MODIFICATION Select the link to be changed at the top of the window. then shift-click-drag the link with the mouse to change its dimension and watch the coupler curve and linkage parameters update dynamically.

Dynamics (FOURBAR, FIVEBAR, SIXBAR, and SLIDER *Dynamics* Screen)

The *Dynamics* button on the *Home* screen brings up a screen that allows input of data on link masses, mass moments of inertia, *CG* locations, and any external forces or torques acting on the links. The location of the *CG* of each moving link is defined in the same way as the coupler point, by a position vector whose root is at the low-numbered instant center of each link. That is, for link 2 it is $I_{1,2}$; for link 3, $I_{2,3}$; and for link 4, $I_{1,4}$. These vectors for a fourbar linkage are shown in Figure A-8a (p. 784) labeled $\mathbf{R}_{CGi}$ where *i* is the link number. Note that the angle of each *CG* vector is measured with respect to a *local rotating coordinate system* (LRCS) whose origin is at the aforementioned instant center and whose *x* axis lies along the line of centers of the link. For example, in

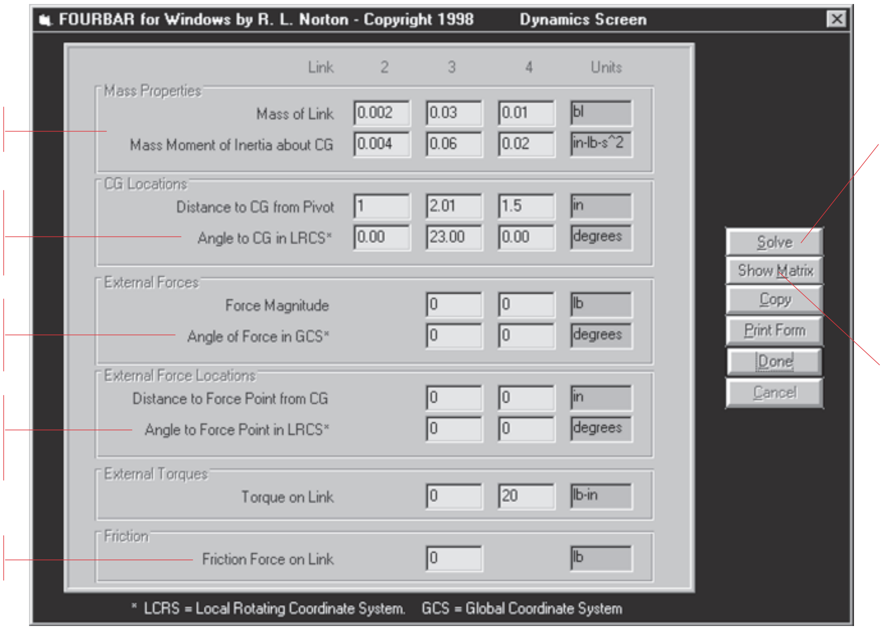


(*a*) The linkage and dimensions

(*b*) Free-body diagrams

FIGURE A-8

Definition of data needed for dynamics calculations in program FOURBAR



FOURBAR for Windows by R. L. Norton - Copyright 1998 Dynamics Screen

	Link	2	3	4	Units
Mass Properties	Mass of Link	0.002	0.03	0.01	bl
	Mass Moment of Inertia about CG	0.004	0.06	0.02	in-lb-s^2
CG Locations	Distance to CG from Pivot	1	2.01	1.5	in
	Angle to CG in LRCS*	0.00	23.00	0.00	degrees
External Forces	Force Magnitude		0	0	lb
	Angle of Force in GCS*		0	0	degrees
External Force Locations	Distance to Force Point from CG		0	0	in
	Angle to Force Point in LRCS*		0	0	degrees
External Torques	Torque on Link		0	20	lb-in
Friction	Friction Force on Link		0		lb

* LCRS = Local Rotating Coordinate System. GCS = Global Coordinate System

Be careful of your units here

Note the local, rotating coordinate system

Note the global coordinate system

Note the local, rotating coordinate system

This acts at coupler point

Calculates all forces and torques

Displays the matrix of dynamic parameters (eq. 11.9)

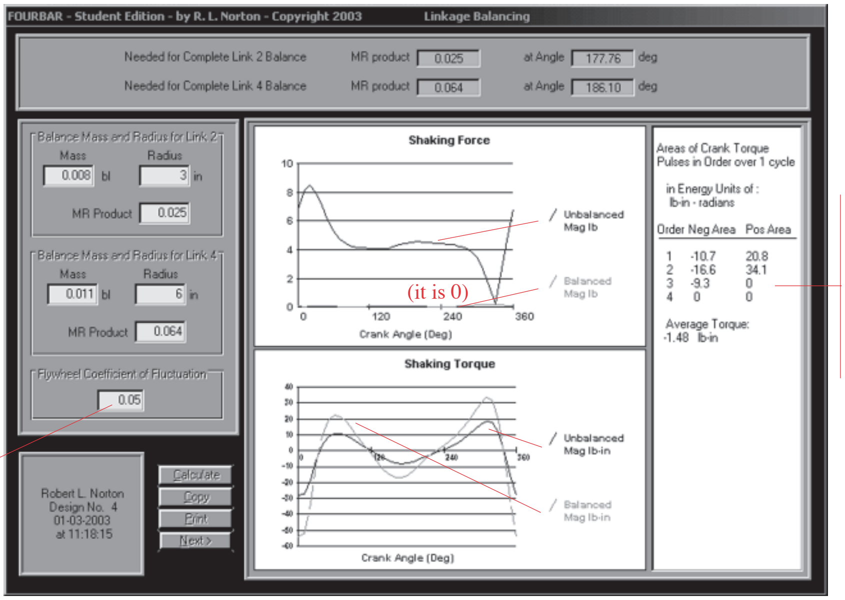
FIGURE A-9

Dynamic Data Input screen for program FOURBAR. Screens for programs FIVEBAR, SIXBAR, and SLIDER are similar

Figure A-8a (p. 784), link 2's *CG* vector is 3 in at 30°, link 3's is 9 in at 45°, and link 4's is 5 in at 0°. The program will automatically create the necessary position vectors $\mathbf{R}_{12}$, $\mathbf{R}_{32}$, $\mathbf{R}_{23}$, $\mathbf{R}_{43}$, $\mathbf{R}_{34}$, and $\mathbf{R}_{14}$ needed for the dynamic force equations as shown in the free-body diagrams in Figure A-8b. These position vectors are, of course, recalculated in the *nonrotating local coordinate systems* (LNCS) at the links' *CG*s for each new position of the linkage as the link angles change.

The masses and mass moments of inertia with respect to the *CG*s of the moving links are also required. Any external forces or torques which are applied to links 3 or 4 are typed in the appropriate boxes on the *Dynamics* screen as shown in Figure A-9 (p. 785). The direction angle of any external force must be measured with respect to the *global coordinate system* (GCS). The program will assume that this angle remains constant for all positions of the linkage analyzed. You must also supply the magnitude and direction of the position vector $\mathbf{R}_P$ which locates any point on the force vector $\mathbf{F}_P$. This $\mathbf{R}_P$ vector is measured in the *rotating, local coordinate system* (LRCS) embedded in the link, as were the *CG*s of the links. $\mathbf{R}_P$ is *not* measured in the global system. The program takes care of the resolution of these $\mathbf{R}_P$ vectors, for each position of the linkage, into coordinates in the nonrotating local coordinate system at the *CG*. Note that if you wish to account for the gravitational force on a heavy link, you may do so by applying that weight as an external force acting through the link's *CG* at 270° in the global system ($\mathbf{R}_P = 0$).

For other linkages such as the fivebar, sixbar, and fourbar slider-crank, the dynamic data input is similar. The only difference is the number of links for which mass property data and possible external forces and torques must be supplied.



FOURBAR - Student Edition - by R. L. Norton - Copyright 2003 Linkage Balancing

Needed for Complete Link 2 Balance MR product 0.025 at Angle 177.76 deg

Needed for Complete Link 4 Balance MR product 0.064 at Angle 186.10 deg

Balance Mass and Radius for Link 2: Mass 0.008 bl, Radius 3 in, MR Product 0.025

Balance Mass and Radius for Link 4: Mass 0.011 bl, Radius 6 in, MR Product 0.064

Flywheel Coefficient of Fluctuation: 0.05

Robert L. Norton
Design No. 4
01-03-2003
at 11:18:15

Areas of Crank Torque Pulses in Order over 1 cycle

in Energy Units of : lb-in - radians

Order	Neg Area	Pos Area
1	-10.7	20.8
2	-16.6	34.1
3	-9.3	0
4	0	0

Average Torque: -1.48 lb-in

Calculated with eq. 12.8

Input any values desired - are defaulted to above MR product values

Input a value between 0 and 1 - is used to generate flywheel torque curve

These are from a piecewise integration of the balanced torque curve at lower left - see Section 11.11

FIGURE A-10

Linkage Balancing screen in program FOURBAR only. Other programs do allow flywheel calculations

After solving (by clicking the *Solve* button), clicking the *Show Matrix* button will display the dynamics matrix for the linkage. The results of the dynamics calculations are automatically stored for later plotting and printing. The menus on the *Plot* and *Print* screens will expand to include forces and torques for all links.

Balancing (FOURBAR Only)*

The *Balance* button on the FOURBAR *Home* screen brings up the *Balance* screen shown in Figure A-10 (p. 786), which immediately displays the mass-radius products needed on links 2 and 4 to force balance it and reduce the shaking force to zero. If you place the total amounts of the calculated mass-radius products on the rotating links, the shaking force will become zero and the shaking torque will increase. A partial balance condition can be specified by reducing the balance masses and accepting some nonzero shaking force in return for a smaller increase in torque.

The FOURBAR *Balance* screen in Figure A-10 displays two mini-plots that superpose the shaking forces and shaking torques before and after balancing. Effects on the shaking force and torque from changes in the amount of balance mass-radius product placed on each link can be immediately seen in these plots. The energy in each pulse of the torque-time curve is also displayed in a sidebar on the right of this screen for use in a flywheel sizing calculation. See Section 11.11 (p. 586) for a discussion of the meaning and use of these data. The program calculates a smoothed torque function by multiplying the raw torque by the coefficient of fluctuation specified in the box at lower left.

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* Program ENGINE also allows balancing but its *Balance Screen* is completely different than in FOURBAR and so will be discussed separately in the section on the ENGINE program.

Cognates (FOURBAR Only)

The *Cognates* pull-down menu allows switching among the three cognates which create the same coupler curve. Switching among them requires recalculation of all kinematic and dynamic parameters via the *Input*, *Dynamics*, and *Balance* buttons. The previously used mass property data is retained but can be changed easily by selecting the *Dynamics* button. The *Cayley Diagram* menu pick under *Cognates* displays that diagram of all three cognates. See Chapter 3. Whenever linkage data are changed on the *Input Screen* and recalculated, the program automatically calculates the dimensions of that linkage's two cognates. These can be switched to, calculated, and investigated at any time.

Synthesis (FOURBAR Only)

This pull-down menu allows selection of two- or three-position synthesis of a linkage, each with a choice of two methods. See Chapter 5 for a discussion of these methods and derivations of the equations used. When the linkage is synthesized, its link geometry is automatically put into the input screen and recalculation is then required.

Other

See Section A.2, General Program Operation (p. 771) for information on *New, Open, Save, Save As, Plot, Print, Units*, and *Quit* functions.

A.4 PROGRAM FIVEBAR

FIVEBAR is a linkage design and analysis program intended for use by students, engineers, and other professionals who are knowledgeable in or are learning the art and science of linkage design. It is assumed that the user knows how to determine whether a linkage design is good or bad and whether it is suitable for the application for which it is intended. The program will calculate the kinematic and dynamic data associated with any geared fivebar linkage design, but cannot substitute for the engineering judgment of the user. The linkage theory and mathematics on which this program is based are documented in Chapters 4 to 7, and 11 of this textbook. Please consult them for explanations of the theory and mathematics involved.

The FIVEBAR *Home* Screen

Initially, only the *Input* and *Quit* buttons are active on the *Home* screen. Typically, you will start a linkage design with the *Input* button, but for a quick look at a linkage as drawn by the program, one of the examples under the *Example* pull-down menu can be selected and it will draw a linkage. If you activate one of these examples, when you return from the *Animati*on screen you will find all the other buttons on the *Home* screen to be active. We will address each of these buttons in due course below.

Input Data (The *Input* Screen)

Because this program deals with the geared fivebar mechanism (GFBM), it requires more input data than for the fourbar mechanism. Five link lengths must be supplied as shown in Figure A-11: driver crank (link 2), first coupler (link 3), second coupler (link

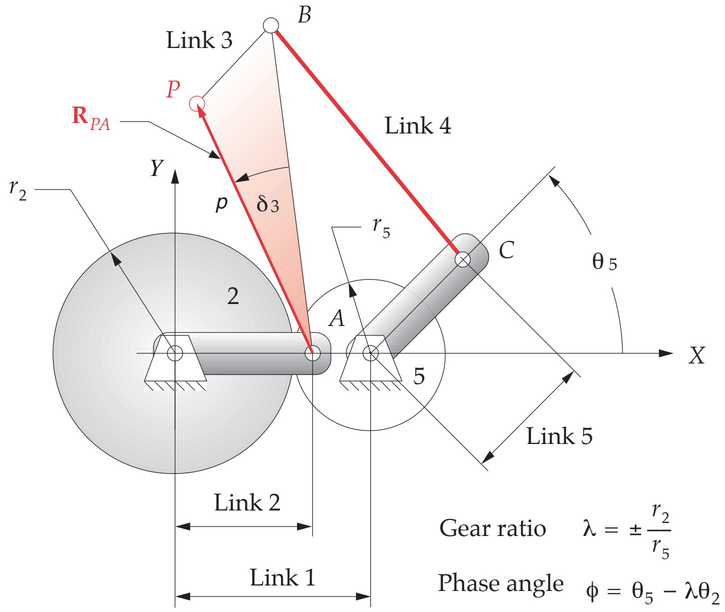

FIGURE A-11

Input data for program FIVEBAR. (Open the disk file F_A-11.5br in FIVEBAR to see this linkage)

4), driven crank (link 5), and ground (link 1). Two other linkage parameters must be defined as input, namely, the gear ratio (λ) and the phase angle (ϕ). The phase angle is defined as the angle of link 5 when link 2 is at 0° as shown in Figure A-11. Note that the gear ratio as shown in the figure is a *negative ratio* because the external gears turn in opposite directions. The addition of an idler gear will create a positive gear ratio. It is also worth noting that the gear ratios defined in the *ZNH Atlas of Geared Fivebar Linkages*[*] are the reciprocal of the gear ratio in program FIVEBAR. So, when transferring data from this atlas to the program, the gear ratio must be reciprocated in order to get the same linkage as shown in the atlas. Otherwise the coupler curve will be a mirror image of the one in the atlas.

The coupler point *P* is defined in the same way as in the fourbar linkage. A coupler point can only be placed on link 3 in this program. If you want a coupler point on link 4, mirror your linkage and renumber the links to put the coupler point on link 3.

Basic data for the fivebar linkage is defined on the *Input* screen which is similar to that for FOURBAR shown in Figure A-6 (p. 781). The *Input* screen is activated by selecting the *Input* button on the *Home* screen. When you open this screen for the first time, it will have default data for all link parameters. You may change any of these by typing over the data in the yellow text boxes.

Select the type of calculation desired in the upper right corner of the screen, one of *Angle Steps, Time Steps*, or *One Position*. The *Calculate* button will compute all data for your linkage and show it in an arbitrary position on the screen. If the white linkage display window is blank, the *Calculate* button will bring back the image. See the discussion of calculations for the FOURBAR program in Section A.3 (p. 778). They are similar in FIVEBAR.

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[*] The ZNH Atlas is on the DVD.

After you have calculated the linkage, the *Animate* and *Next* buttons on the *Input* screen will become available. *Animate* takes you to the *Animation screen* where you can run the linkage through any range of motion to observe its behavior. You can also change any of the linkage parameters on the *Animatio*n screen and then recalculate the results with the *Recalc* button. The *Next* button on either the *Input* or *Animatio*n screen returns you to the *Home* screen. The *Plot* and *Print* buttons will now be available as well as the *Animate* button which returns you to the *Animatio*n screen.

Animation (FIVEBAR)

In program FIVEBAR, the *Animation* screen and its features are essentially similar to those of program FOURBAR. The only exception is the lack of a centrode selection in FIVEBAR. See the *Animation* discussion for FOURBAR in Section A-3 (p. 778) for more information.

Dynamics (FIVEBAR *Dynamics* Screen)

Input data for dynamics calculation in FIVEBAR are similar to that for program FOURBAR with the addition of one more link. However, linkage balancing is not available in FIVEBAR. See the discussion of dynamics calculations for program FOURBAR in Section A-3 (p. 778) for more information.

Other

See Section A.2, General Program Operation (p. 771) for information on *New*, *Open, Save, Save As, Plot, Print, Units,* and *Quit* functions.

A.5 PROGRAM SIXBAR

SIXBAR is a linkage design and analysis program intended for use by students, engineers, and other professionals who are knowledgeable in or are learning the art and science of linkage design. It is assumed that the user knows how to determine whether a linkage design is good or bad and whether it is suitable for the application for which it is intended. The program will calculate the kinematic and dynamic data associated with any linkage design but cannot substitute for the engineering judgment of the user. The linkage theory and mathematics on which this program is based are documented in Chapters 4 to 10, and 11 of this textbook. Please consult them for explanations of the theory and mathematics involved.

The SIXBAR program is generally similar to the FOURBAR program. It will analyze the **Watt's II** and the **Stephenson's III** linkage isomers as defined in Figure 2-14 (p. 48). These are two of the five distinct sixbar isomers. The **Watt's II** mechanism is shown in Figure A-12 with the program's input parameters defined. The **Stephenson's III** mechanism is shown in Figure A-13 (p. 780) with its input parameters defined. Note that the program divides the sixbar into two stages of fourbar linkages. Stage 1 is the left half of the mechanism as shown in Figures A-12 and A-13. Stage 2 is the right half. The X axis of the global coordinate system is defined by instant centers $I_{1,2}$ and $I_{1,4}$ with its origin at $I_{1,2}$. The third fixed pivot $I_{1,6}$ can be anywhere in the plane. Its coordinates must be supplied as input.

The Sixbar *Home* Screen

Initially, only the *Input* and *Quit* buttons are active on the *Home* screen. Typically, you will start a linkage design with the *Input* button, but for a quick look at a linkage as drawn by the program, one of the examples under the *Example* pull-down menu can be selected and it will draw a linkage. If you activate one of these examples, when you return from the *Animati*on screen you will find all the other buttons on the *Home* screen to be active. We will address each of these buttons in due course below.

The *Home* screen's *Examples* pull-down menu includes both Watt's and Roberts' straight-line fourbar linkage stages driven by dyads (making them sixbars), a single-dwell sixbar linkage similar to that of Example 3-13 (p. 137) and Figure 3-31 (p. 138), and a double-dwell sixbar linkage that uses an alternate approach to that of Example 3-14 (p. 139) and Figure 3-32 (p. 140).

Input Data (Sixbar *Input* Screen)

Much of the basic data for the linkage design is defined on the *Input* screen which is activated by selecting the *Input* button on the *Home* screen. When you open this screen for the first time, it will have default data for all link parameters. You may change any of these by typing over the data in the yellow text boxes. A choice of Watt's or Stephenson's linkage must be made on the *Input* screen. The link information differs for the Watt's and Stephenson's linkages.

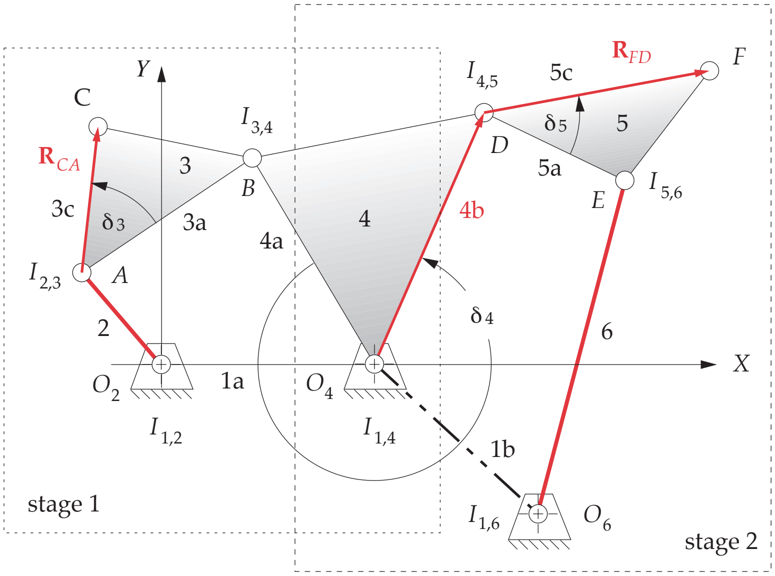


FIGURE A-12

Input data for program Sixbar—a Watt's II linkage

WATT'S II LINKAGE For the Watt's linkage (Figure A-12) the stage 1 data is: crank, first coupler, first rocker, and ground link segment from instant centers $I_{1,2}$ to $I_{1,4}$. These correspond to links 2, 3a, 4a, and 1a, respectively, as labeled in the Figure A-12. The stage 2 data are: second crank, second coupler, second rocker, corresponding respectively to links 4b, 5a, and 6 in Figure A-12. The angle δ_4 that the second crank (4b) makes with the first rocker (4a) is also requested. Note that this angle obeys the right-hand rule as do all angles in these programs.

Two coupler points are allowed to be defined in this linkage, one on link 3 and one on link 5. The method of location is by polar coordinates of a position vector embedded in the link as was done for the fourbar and fivebar linkages. The first coupler point C is on link 3 and is defined in the same way as in FOURBAR. Program SIXBAR requires the length (3c) of its position vector $\mathbf{R}_{ca}$ and the angle δ_3 which that vector makes with line 3a in Figure A-12. The second coupler point F is on link 5 and is defined with a position vector $\mathbf{R}_{fD}$ rooted at instant center $I_{4,5}$. The program requires the length (5c) of this position vector $\mathbf{R}_{fD}$ and the angle δ_5 which that vector makes with line 5a. The X and Y components of the location of the third fixed pivot $I_{1,6}$ are also needed. These are with respect to the global X,Y axis system whose origin is at $I_{1,2}$.

STEPHENSON'S III LINKAGE The stage 1 data for the Stephenson's linkage is similar to that of the Watt's linkage. The first stage's crank, first coupler, first rocker, and ground link segment from instant centers $I_{1,2}$ to $I_{1,4}$ correspond to links 2, 3a, 4, and 1a, respectively, in Figure A-13. The link lengths in stage 2 of the linkage are: second coupler and second rocker corresponding, respectively, to links 5a and 6 in Figure A-13.

Note that, unlike the Watt's linkage, there is no "second crank" in the Stephenson's linkage because the second stage is driven by the coupler (link 3) of the first stage. In this program link 5 is constrained to be connected to link 3 at link 3's defined coupler point C which then becomes instant center $I_{3,5}$. The data for this are requested in similar format to the Watt's linkage, namely, the length of the position vector $\mathbf{R}_{ca}$ (line 3c) and its angle δ_3. The second coupler point location on link 5 is defined, as before, by position vector $\mathbf{R}_{fc}$ with length 5c and angle δ_5.

The X and Y components of the location of the third fixed pivot $I_{1,6}$ are required. These are with respect to the global X,Y axis system.

Select the type of calculation desired in the upper right corner of the screen, one of *Angle Steps, Time Steps*, or *One Position*. The *Calculate* button will compute all data for your linkage and show it in an arbitrary position on the screen. If at any time the linkage display window is blank, the *Calculate* button will bring back the image. See the description of calculations for program FOURBAR in Section A.3 (p. 779). They are similar in SIXBAR.

After you have calculated the linkage, the *Animate* and *Next* buttons on the *Input* screen will become available. *Animate* takes you to the *Animation* screen where you can run the linkage through any range of motion to observe its behavior. You can also change any of the linkage parameters on the *Animation* screen and then recalculate the results with the *Recalc* button. The *Next* button on either the *Input* or *Animation* screen returns you to the *Home* screen. The *Plot* and *Print* buttons will now be available as well as the *Animate* button which returns you to the *Animation* screen.

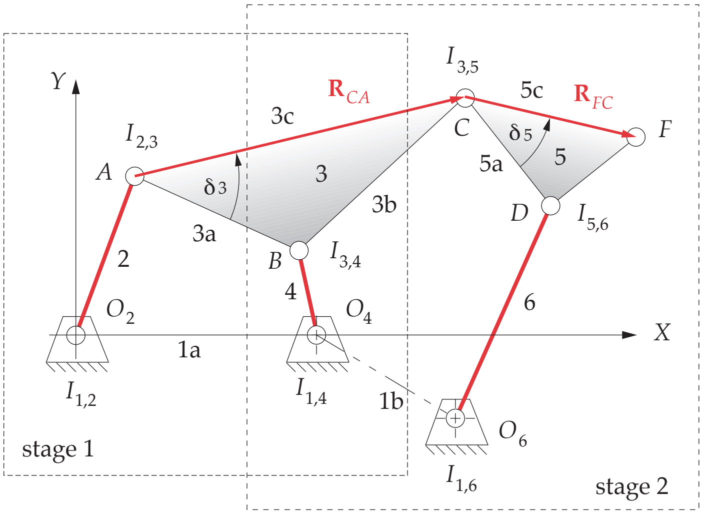


FIGURE A-13

Input data for program SIXBAR—a Stephenson's III linkage

Animation (SIXBAR)

The *Animation* screen and its features in SIXBAR are essentially similar to those of program FOURBAR. The only exception is the lack of a *Centrode* selection in SIXBAR. See the Animation discussion for FOURBAR in Section A.3 (p. 782) for more information.

Dynamics (SIXBAR *Dynamics* Screen)

Input data for dynamics calculation in SIXBAR are similar to that for program FOURBAR with the addition of two links. See the discussion of dynamics calculations for program FOURBAR in Section A.3 (p. 783) for more information.

Other

See Section A.2, General Program Operation (p. 771) for information on *New, Open, Save, Save As, Plot, Print, Units*, and *Quit* functions.

A.6 PROGRAM SLIDER

SLIDER is a linkage design and analysis program intended for use by students, engineers, and other professionals who are knowledgeable in or are learning the art and science of linkage design. It is assumed that the user knows how to determine whether a linkage design is good or bad and whether it is suitable for the application for which it is intended. The program will calculate the kinematic and dynamic data associated with any linkage design, but cannot substitute for the engineering judgment of the user. The linkage theory and mathematics on which this program is based are documented in Chapters 4 to 10, and 11 of this textbook. Please consult them for explanations of the theory and mathematics involved.

The SLIDER *Home* Screen

Initially, only the *Input* and *Quit* buttons are active on the *Home* screen. Typically, you will start a linkage design with the *Input* button, but for a quick look at a linkage as drawn by the program, one of the examples under the *Example* pull-down menu can be selected and it will draw a linkage. If you activate one of these examples, when you return from the *Animati*on screen you will find all the other buttons on the *Home* screen to be active. We will address each of these buttons below.

Input Data (SLIDER *Input* Screen)

Basic data for the sixbar linkage is defined on the *Input* screen, which is activated by selecting the *Input* button on the *Home* screen. When you open this screen for the first time, it will have default data for all link parameters. You may change any of these by typing over the data in the yellow text boxes.

Figure A-14 defines the input parameters for the fourbar slider-crank linkage. The link lengths needed are input link 2 and coupler link 3, defined by their pin-to-pin distances and labeled *a* and *b* in the figure. The *X* axis lies along the line *d*, through instant center $I_{1,2}$ (point O_2) and parallel to the direction of motion of slider 4. Instant center $I_{1,2}$, the driver crank pivot, is the origin of the global coordinate system. The slider offset *c* is the perpendicular distance from the *X* axis to the sliding axis. Slider position *d* will be calculated for all positions of the linkage.

In addition to the link lengths, you must supply the location of one coupler point on link 3 to find that point's coupler curve positions, velocities, and accelerations. This point is located by a position vector rooted at $I_{2,3}$ (point *A*) and directed to the coupler point *P* of interest which can be anywhere on link 3. The program requires that you input the polar coordinates of this vector which are labeled *p* and δ_3 in Figure A-14. The program needs the distance from $I_{2,3}$ to the coupler point *p* and the angle δ_3 that the coupler point makes with link 3. Note that angle δ_3 is not referenced to either the global coordinate system *X,Y* or to the local nonrotating coordinate system *x,y* at point *A*. Rather, it is referenced to the line *AB* which is the pin-to-pin edge of link 3. Angle δ_3 is a property of link 3 and is embedded in it. The angle which locates vector $\mathbf{R}_{CA}$ in the *x,y* coordinate system is the sum of angle δ_3 and angle θ_3. This addition is done in the program, after θ_3 is calculated for each position of the input crank.

The definition of θ_3 is different in program SLIDER than in Figure 4-9 and the derivations in Section 4.6 (p. 178). This was done to maintain consistency of input data among all the linkage programs in this package. Actually, within program SLIDER, the angle shown in Figure A-14 (p. 793) that you input as θ_3 is converted using the law of cosines to the one shown in Figure 4-9 (p. 178) before the calculations are done with the equations from Section 4.6 (p. 178).

Calculation (SLIDER *Input* Screen)

See the description of calculations for program FOURBAR in Section A.3 (p. 779) for more information. They are similar in SLIDER. Select the type of calculation desired in the upper right corner of the screen, one of *Angle Steps, Time Steps*, or *One Position*. The *Calculate* button will compute all data for your linkage and show it in an arbitrary posi-

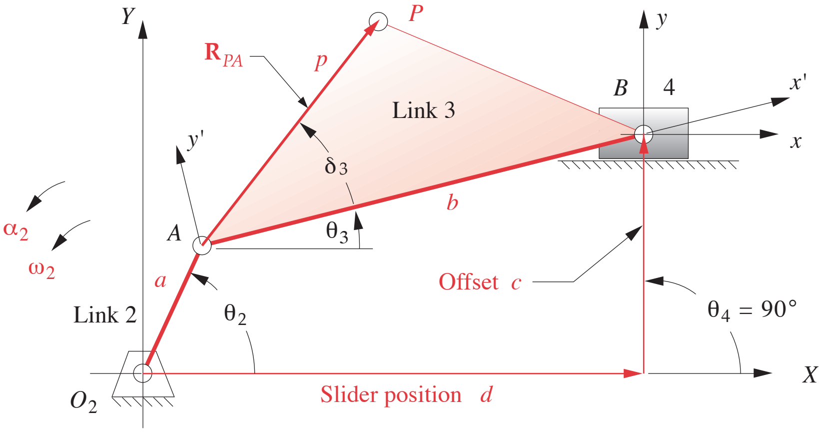


FIGURE A-14

Input data for Program SLIDER

tion on the screen. If at any time the white linkage window is blank, the *Calculate* button will bring back the image.

After you have calculated the linkage, the *Animate* and *Next* buttons on the *Input* screen will become available. *Animate* takes you to the *Animation* screen where you can run the linkage through any range of motion to observe its behavior. You can also change any of the linkage parameters on the *Animation* screen and then recalculate the results with the *Recalc* button. The *Next* button on either the *Input* or *Animation* screen returns you to the *Home* screen. The *Plot* and *Print* buttons will now be available as well as the *Animate* button which returns you to the *Animation* screen.

Animation (SLIDER *Animation* Screen)

The *Animation* screen and its features in SLIDER are essentially similar to those of program FOURBAR. An exception is the lack of a *Centrode* selection in SLIDER. See the discussion of the *Animation* screen for FOURBAR in Section A.3 (p. 782) for more information.

Dynamics (SLIDER *Dynamics* Screen)

Input data for dynamics calculation in SLIDER are similar to that for program FOURBAR. See the discussion of dynamics calculations for Program FOURBAR in Section A.3 (p. 783) for more information.

Other

See Section A.2, General Program Operation (p. 771) for information on *New, Open, Save, Save As, Plot, Print, Units*, and *Quit* functions.

A.7 PROGRAM DYNACAM

DYNACAM is a cam design and analysis program intended for use by students, engineers, and other professionals who are knowledgeable in the art and science of cam design. It is assumed that the user knows how to determine whether a cam design is good or bad and whether it is suitable for the application for which it is intended. The program will calculate the kinematic and dynamic data associated with any cam design but cannot substitute for the engineering judgment of the user. The cam theory and mathematics on which this program is based are shown in Chapter 8 and 15 of this text. Please consult them for complete explanations of the theory and mathematics involved.

The DYNACAM *Home* Screen

Initially, only the *SVAJ* and *Quit* buttons are active on the *Home* screen. Typically, you will start a cam design with the *SVAJ* button, but for a quick look at a cam as drawn by the program, one of the examples under the *Example* pull-down menu can be selected and it will draw a cam profile. If you activate one of these examples, when you return from the *Cam Profile* screen you will find all the other buttons on the *Home* screen to be active. We will address each of these buttons in due course below.

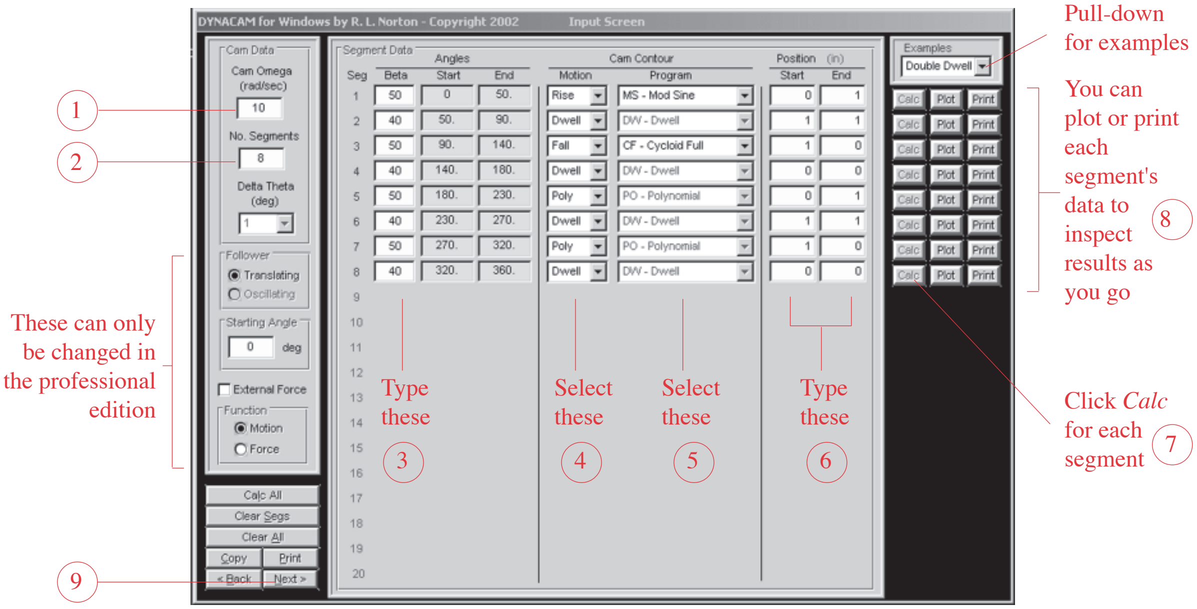
Input Data (DYNACAM *Input* Screen)

Much of the basic data for the cam design is defined on the *Input* screen shown in Figure A-15 (p. 796), which is activated by selecting the *SVAJ* button on the *Home* screen. When you open this screen for the first time, it will be nearly blank, with only one segment's row visible. (Note that the built-in examples can also be accessed from this form at its upper right corner.) If you selected an example cam from the pull-down menu on the *Home* screen, making the *Input* screen nonblank, please now select the *Clear All* button on the *Input* screen to zero all the data and blank the screen, in order to better follow the presentation below. We will proceed with the explanation as if you were typing your data into an initially blank *Input* screen.

If you use the *Tab* button, it will lead you through the steps needed to input all data. On a blank *Input* screen, *Tab* first to the *Cam Omega* box in the upper left corner and type in the speed of the camshaft. *Tab* again (or mouse click if you prefer) to the *Number of Segments* box and type in any number desired between 1 and 24. That number of rows will immediately become visible on the *Input* screen. Note that some of this screen's choices such as *Osclt* (oscillating arm follower) and *Delta Theta* are disabled in the student edition of the program.

Another *Tab* should put your cursor in the box for the *Beta* (segment duration angle) of segment 1. Type any desired angle (in degrees). Successive *Tabs* will take you to each *Beta* box to type in the desired angles. All *Betas* must, of course, sum to 360 degrees. If they do not, a warning will appear.

As you continue to *Tab* (or click your mouse in the appropriate box, if you prefer), you will arrive at the boxes for *Motion* selection. These boxes offer a pull-down selection of *Rise, Fall, Poly*, and *Dwell*. You may select from the pull-down menus with the mouse, or you can type the first letter of each word to select them. Rise, fall, and dwell have obvious meanings. The Poly choice indicates that you wish to create a customized



Cam Omega (rad/sec): 10

No. Segments: 8

Delta Theta (deg): 1

Follower: ● Translating ○ Oscillating

Starting Angle: 0 deg

☐ External Force

Function: ● Motion ○ Force

Examples: Double Dwell

Seg	Angles Beta	Angles Start	Angles End	Cam Contour Motion	Cam Contour Program	Position (in) Start	Position (in) End
1	50	0	50.	Rise	MS - Mod Sine	0	1
2	40	50.	90.	Dwell	DW - Dwell	1	1
3	50	90.	140.	Fall	CF - Cycloid Full	1	0
4	40	140.	180.	Dwell	DW - Dwell	0	0
5	50	180.	230.	Poly	PO - Polynomial	0	1
6	40	230.	270.	Dwell	DW - Dwell	1	1
7	50	270.	320.	Poly	PO - Polynomial	1	0
8	40	320.	360.	Dwell	DW - Dwell	0	0
9							
10							
11							
12							
13							
14							
15							
16							
17							
18							
19							
20							

Pull-down for examples

You can plot or print each segment's data to inspect results as you go

Click *Calc* for each segment

These can only be changed in the professional edition

Type these

Select these

Select these

Type these

FIGURE A-15

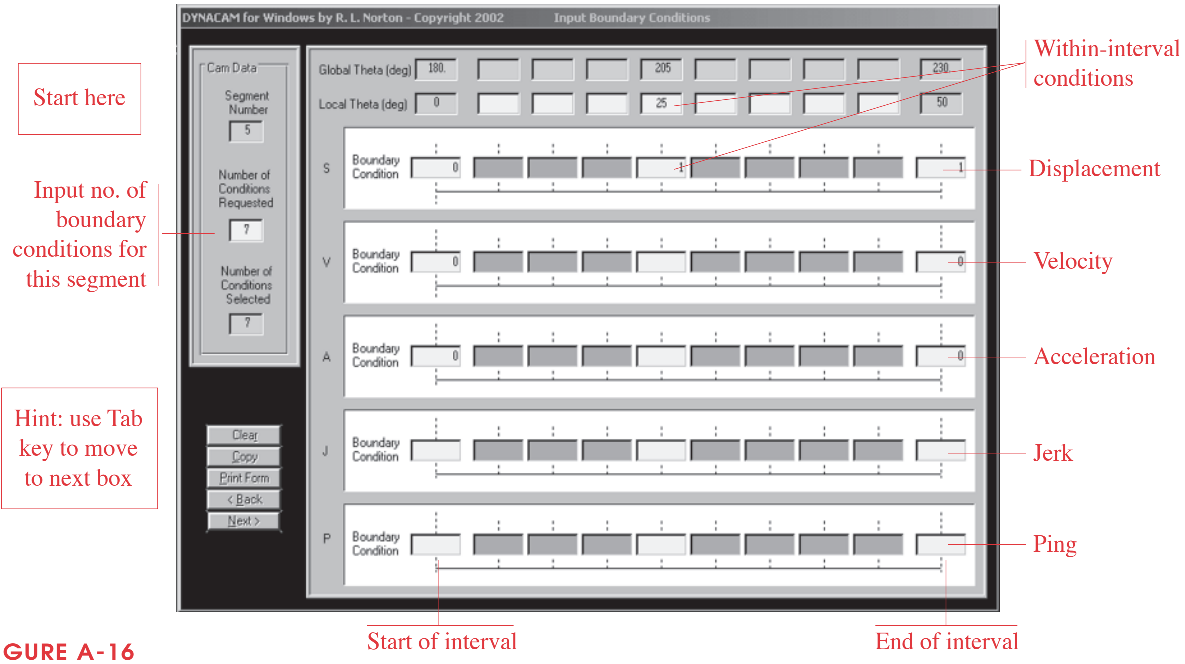
S V A J Input screen for program DYNACAM

polynomial function for that segment, and this will later cause a new screen to appear on which you will define the boundary conditions of your desired polynomial function.

The next set of choices that you will *Tab* or mouse click to are the *Program* pull-downs. These provide a menu of standard cam functions such as *Modified Trapezoid, Modified Sine,* and *Cycloid*. Also included are portions of functions such as the first and second halves of cycloids and simple harmonics that can be used to assemble piecewise continuous functions for special situations.

After you have selected the desired *Program* functions for each segment, you will *Tab* or *Click* to the *Position Start* and *End* boxes. *Start* in this context refers to the beginning displacement position for the follower in the particular segment, and *End* for its final position. You may begin at the "top" or "bottom" of the displacement "hill" as you wish, but be aware that the range of position values of the follower must be from a zero value to some positive value over the whole cam. In other words, **you cannot include any anticipated base or prime circle radius in these position data**. These position numbers represent the excursion of the so-called *S* diagram (displacement) of the cam and cannot include any prime circle information (which will be input later).

As each row's (segment's) input data are completed, the *Calc* button for that row will become enabled. Clicking on this button will cause that segment's *S, V, A,* and *J* data to be calculated and stored. After the *Calc* button has been clicked for any row, the *Plot* and *Print* buttons for that segment will become available. Clicking on these buttons will bring up a plot or a printed table of data for *S, V, A, J* data for that segment only. More detailed plots and printouts can be obtained later from the *Home* screen.



DYNACAM for Windows by R. L. Norton - Copyright 2002 Input Boundary Conditions

Cam Data

Segment Number: 5

Number of Conditions Requested: 7

Number of Conditions Selected: 7

Global Theta (deg): 180. 205 230.

Local Theta (deg): 0 25 50

S Boundary Condition: 0 1 1

V Boundary Condition: 0 0

A Boundary Condition: 0 0

J Boundary Condition:

P Boundary Condition:

FIGURE A-16

Boundary Condition Input screen for polynomial functions in program DYNACAM—3-4-5-6 single-dwell function shown

Polynomial Functions

If any of your segments specified a *Poly* motion, clicking the *Calc* button will bring up the *Boundary Condition* screen shown in Figure A-16. The cursor will be in the box for *Number of Conditions Requested*. Type the number of boundary conditions (BCs) desired, which must be between 2 and 20 inclusive. When you hit *Enter* or *Tab* or mouse click away from this box, the rest of the screen will activate, allowing you to type in the desired values of BCs. Note that the start and end values of position that you typed on the *Input* screen are already entered in their respective *S* boundary condition boxes at the beginning and end of the segment. Type your additional end of interval conditions on *V*, *A,* and *J* as desired. If you also need some BCs within the interval, click or tab to one of the boxes in the row labeled *Local Theta* at the top of the screen and type in the value of the angle at which you wish to provide a BC. That column will activate and you may type whatever additional BCs you need.

The box labeled *Number of Conditions Selected* monitors the BC count, and when it matches the *Number of Conditions Requested,* the *Next* button becomes available. Note that what you type in any (yellow) text box is not accepted until you hit *Enter* or move off that box with the *Tab* key or the mouse, allowing you to retype or erase with no effect until you leave the text box. (This is generally true throughout the program.)

Selecting the *Next* button from the BC screen calculates the coefficients of the polynomial by a Gauss-Jordan reduction method with partial pivoting. All computations are done in double precision for accuracy. If an inconsistent set of conditions is sent to the solver, an error message will appear. If the solution succeeds, it calculates *s v a j* for the segment. When finished, it brings up a summary screen that shows the BCs you selected and also the coefficients of the polynomial equation that resulted. You may at this point want to print this screen to the printer or copy and paste it into another document for your records. You will only be able to reconstruct it later by again defining the BCs and recalculating the polynomial.

Back to the *Input* Screen

Completing a polynomial function returns you to the *Input* screen. When all segments are calculated, select the *Next* button on the *Input* screen (perhaps after copying it to the clipboard or printing it to the printer with the appropriate buttons). This will bring up the *Continuity Check* screen.

Continuity Check Screen

This screen provides a visual check on the continuity of the cam design at the segment interfaces. The values of each function at the beginning and end of each segment are grouped together for easy viewing. The fundamental law of cam design requires that the *S, V,* and *A* functions be continuous (see Chapter 8). This will be true if the boundary values for those functions shown grouped as pairs are equal. If this is not true, then a warning dialog box will appear when the *Next* button is clicked. It is possible that the mismatch is due to numerical roundoff error and is irrelevant. The error is shown as a true percent of the maximum value of the function to allow you to decide whether it is significant or not. You will have the choice to proceed to the *Home* screen or return to the *Input Data* screen to correct the problem.

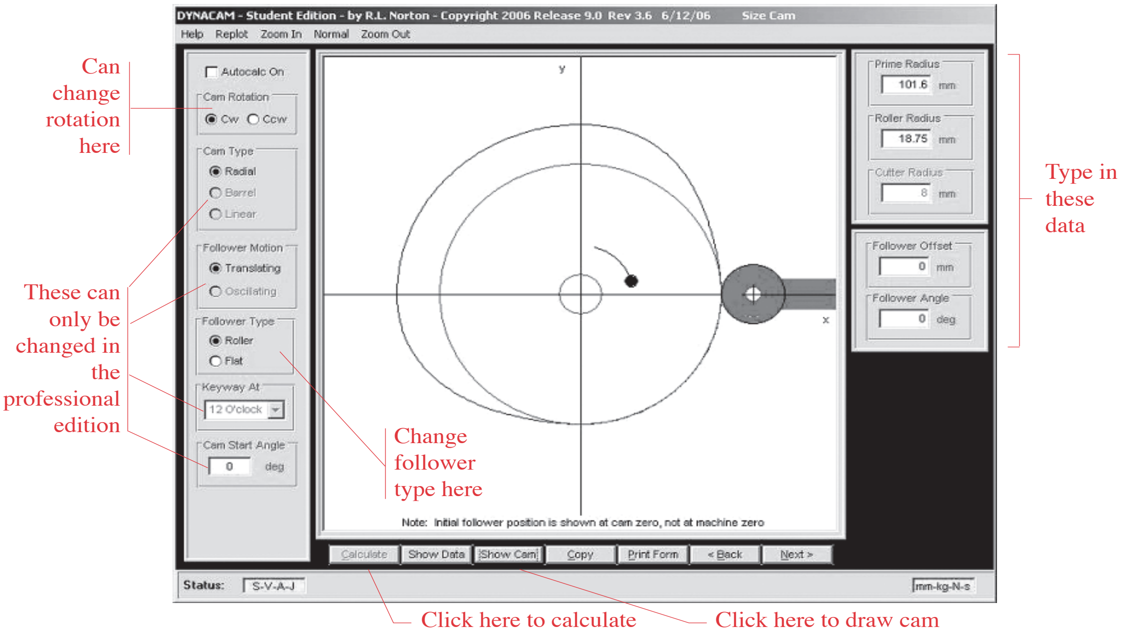
Sizing the Cam

Once the *S V A J* functions have been defined to your satisfaction, it remains to size the cam and determine its pressure angles and radii of curvature. This is done from the *Size Cam* screen shown in Figure A-17, which is accessible from the button of that name on the *Home* screen. The *Size Cam* screen allows the cam rotation direction and follower type (flat or roller) to be set. The cam type (radial or barrel) and follower motion (translating or oscillating) are only available in the professional version. The prime circle radius and follower offset for a translating follower can be typed into their boxes. When a change is made to any of these parameters, the schematic image of cam and follower is updated.

Select the *Calc* button to compute the cam size parameters. The max and min pressure angles will appear in the boxes at the top of the screen. For more information, select the *Show Summary* button at the upper right. This will change the schematic image to a summary of pressure angle and radius of curvature information. When you hit the *Next* button, the cam profile will be drawn.

Drawing the Cam

The cam profile shown when leaving the *Size Cam* screen can be independently accessed at any time from the *Home* screen with the *Draw Cam* button. The *Draw Cam* screen shown in Figure A-18 (p. 800), allows the cam rotation direction, prime circle radius, roller radius, and offset (if available) to be changed. The cam size data will be recalculated and the new profile displayed.


DYNACAM - Student Edition - by R.L. Norton - Copyright 2006 Release 9.0 Rev 3.6 6/12/06 Size Cam

☐ Autocalc On

Cam Rotation: ● Cw ○ Ccw

Cam Type: ● Radial ○ Barrel ○ Linear

Follower Motion: ● Translating ○ Oscillating

Follower Type: ● Roller ○ Flat

Keyway At: 12 O'clock

Cam Start Angle: 0 deg

Prime Radius: 101.6 mm

Roller Radius: 18.75 mm

Cutter Radius: 8 mm

Follower Offset: 0 mm

Follower Angle: 0 deg

Note: Initial follower position is shown at cam zero, not at machine zero

Status: S-V-A-J

mm-kg-N-s

Can change rotation here

These can only be changed in the professional edition

Change follower type here

Type in these data

Click here to calculate

Click here to draw cam

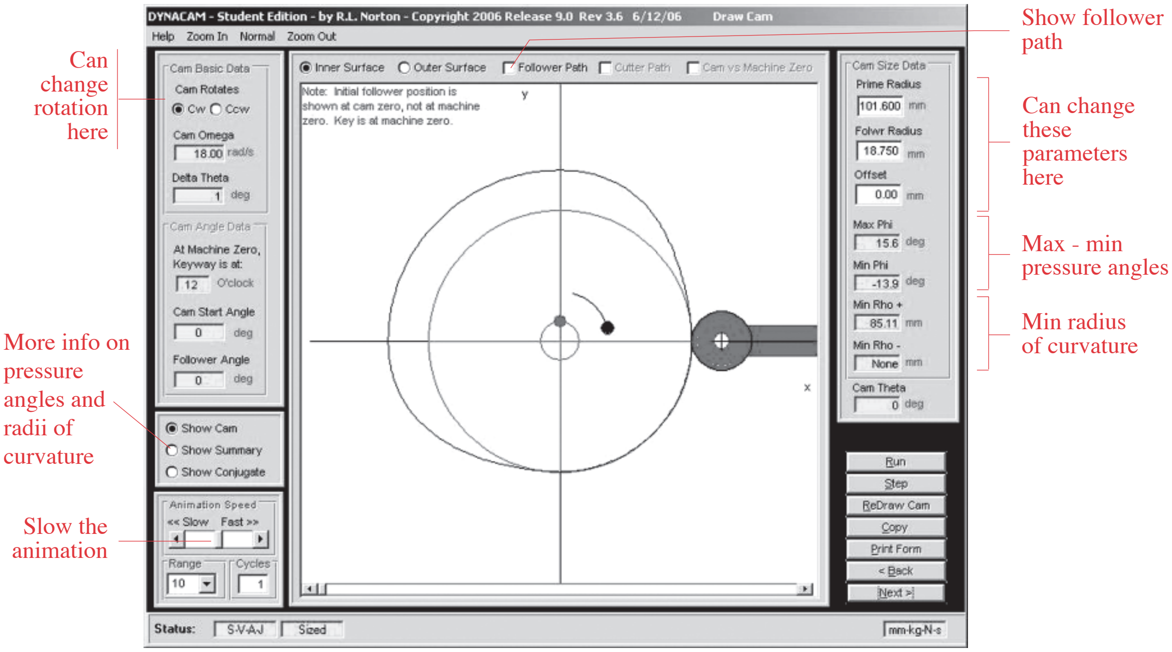
FIGURE A-17

Size Cam screen from DYNACAM

In the cam profile drawing, a curved arrow indicates the direction of cam rotation. The initial position of a roller follower at cam angle θ = 0 is shown as a filled circle with rectangular stem, and of a flat-faced follower as a filled rectangle. Any eccentricity shows as a shift up or down of the filled follower with respect to the *X* axis through the cam center. The smallest filled circle on the cam centerline represents the camshaft. The smallest unfilled circle is the base circle. The prime circle may be somewhat obscured by the repeated drawings of the follower diameter, which sweep out the cam surface. The pitch curve is drawn along the locus of the roller follower centers. The radial lines that form pieces of pie within the base circle represent the segments of the cam. If the cam turns counterclockwise, the radial lines are numbered clockwise around the circumference and vice versa.

Follower Dynamics (DYNACAM Only)

When the cam has been sized, the *Dynamics* button on the *Home* screen will become available. This button brings up the *Dynamics* screen shown in Figure A-19 (p. 801). Text boxes are provided for typing in values of the effective mass of the follower system, the effective spring constant, the spring preload, and a damping factor. By effective mass is meant the mass of the entire follower system as reflected back to the cam-follower roller centerline or cam contact point. Any link ratios between the cam-follower and any physical masses must be accounted for in calculating the effective mass. Likewise the effective spring in the system must be reflected back to the follower. The damping is defined by the damping ratio zeta, as defined for second-order vibrating systems. See Chapter 10 for further information.



DYNACAM - Student Edition - by R.L. Norton - Copyright 2006 Release 9.0 Rev 3.6 6/12/06 Draw Cam

Note: Initial follower position is shown at cam zero, not at machine zero. Key is at machine zero.

Cam Basic Data
Cam Rotates: ● Cw ○ Ccw
Cam Omega: 18.00 rad/s
Delta Theta: 1 deg

Cam Angle Data
At Machine Zero, Keyway is at: 12 O'clock
Cam Start Angle: 0 deg
Follower Angle: 0 deg

● Show Cam
○ Show Summary
○ Show Conjugate

● Inner Surface ○ Outer Surface ☐ Follower Path ☐ Cutter Path ☐ Cam vs Machine Zero

Cam Size Data
Prime Radius: 101.600 mm
Folwr Radius: 18.750 mm
Offset: 0.00 mm
Max Phi: 15.6 deg
Min Phi: -13.9 deg
Min Rho +: 85.11 mm
Min Rho -: None mm
Cam Theta: 0 deg

Range: 10
Cycles: 1

Status: S-V-A-J Sized mm-kg-N-s

Can change rotation here

More info on pressure angles and radii of curvature

Slow the animation

Show follower path

Can change these parameters here

Max - min pressure angles

Min radius of curvature

FIGURE A-18

Cam Profile screen in program DYNACAM

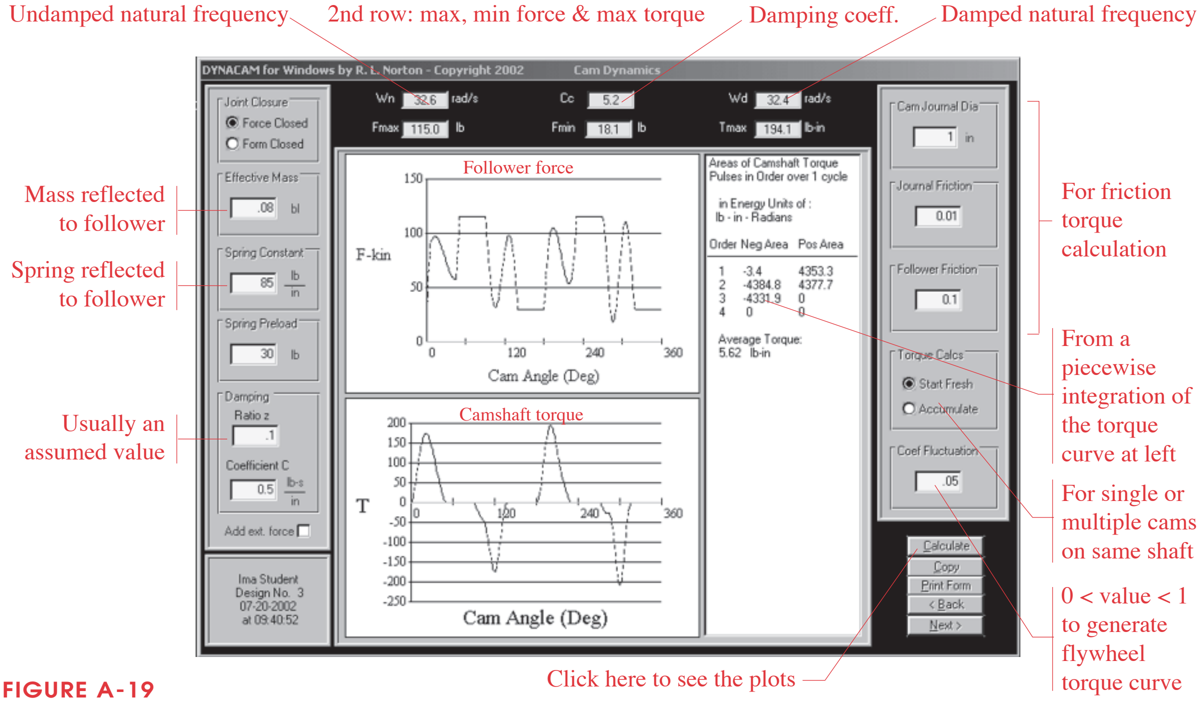
The journal diameter and the coefficients of friction are used for calculating the friction torque on the shaft. The *Start New* or *Accumulate* switch allows you to either make a fresh torque calculation or accumulate the torques for several cams running on a common shaft. The energy information in the window can be used to calculate a flywheel needed for any coefficient of fluctuation chosen as described in Section 11.11 (p. 586). The program calculates a smoothed torque function by multiplying the raw camshaft torque by the coefficient of fluctuation specified in the box at lower right of the screen.

Other

See Section A.2, General Program Operation (p. 771) for information on *New, Open, Save, Save As, Plot, Print, Units*, and *Quit* functions.

A.8 PROGRAM ENGINE

ENGINE is an internal combustion (IC) engine design and analysis program intended for use by students, engineers, and other professionals who are knowledgeable in the art and science of engineering design. It is assumed that the user knows how to determine whether a design is good or bad and whether it is suitable for the application for which it is intended. The program will calculate the kinematic and dynamic data associated with any engine design, but cannot substitute for the engineering judgment of the user. The theory and mathematics on which this program is based are shown in Chapters 13 and



Undamped natural frequency

2nd row: max, min force & max torque

Damping coeff.

Damped natural frequency

Mass reflected to follower

Spring reflected to follower

Usually an assumed value

For friction torque calculation

From a piecewise integration of the torque curve at left

For single or multiple cams on same shaft

0 < value < 1 to generate flywheel torque curve

Click here to see the plots

DYNACAM for Windows by R. L. Norton - Copyright 2002 Cam Dynamics

Wn 32.6 rad/s
Cc 5.2
Wd 32.4 rad/s
Fmax 115.0 lb
Fmin 18.1 lb
Tmax 194.1 lb-in

Joint Closure
● Force Closed
○ Form Closed

Effective Mass .08 bl

Spring Constant 85 lb/in

Spring Preload 30 lb

Damping
Ratio z .1
Coefficient C 0.5 lb-s/in

Add ext. force ☐

Ima Student
Design No. 3
07-20-2002
at 09:40:52

Areas of Camshaft Torque Pulses in Order over 1 cycle

in Energy Units of :
lb - in - Radians

Order	Neg Area	Pos Area
1	-3.4	4353.3
2	-4384.8	4377.7
3	-4331.9	0
4	0	0

Average Torque:
5.62 lb-in

Cam Journal Dia 1 in

Journal Friction 0.01

Follower Friction 0.1

Torque Calcs
● Start Fresh
○ Accumulate

Coef Fluctuation .05

FIGURE A-19

Cam Dynamics screen in DYNACAM

14 of this textbook. Please consult them for an explanation of the theory and mathematics involved.

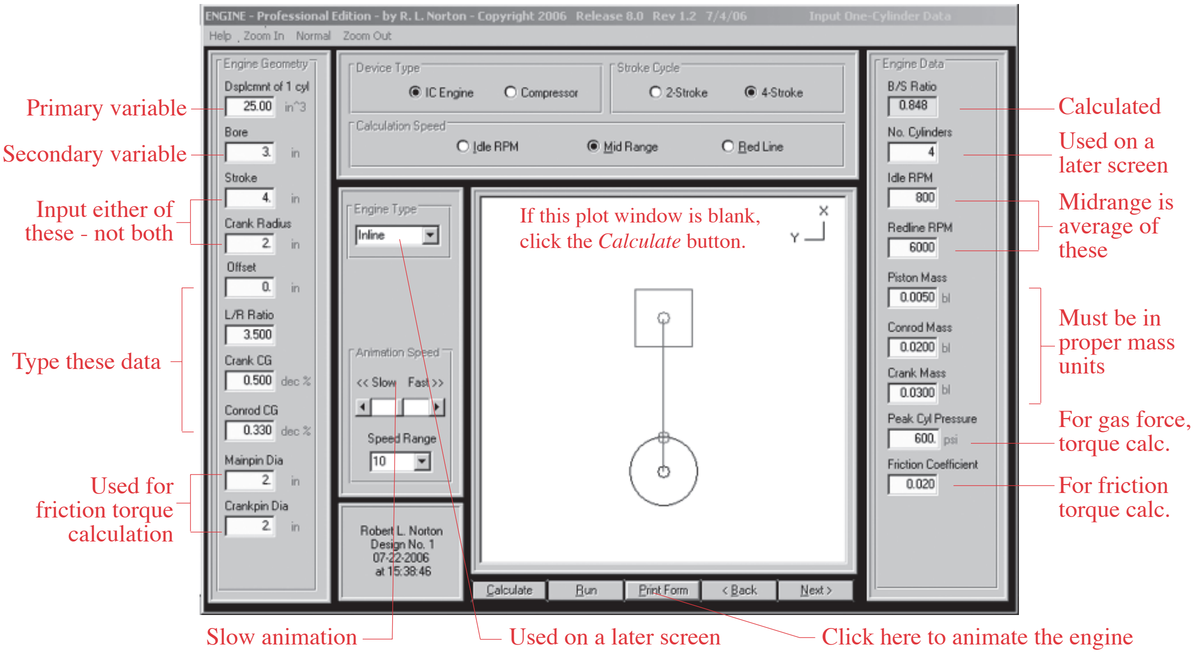
The ENGINE *Home* Screen

Initially, only the *Input* and *Quit* buttons are active on the *Home* screen. Typically, you will start a design with the *Input* button, but before doing so, one of the examples under the *Example* pull-down menu can be selected. If you activate one of these examples, it will calculate the result and take you to the *Engine Data* screen (see Figure A-22, p. 805). Click on the *Run* button to see the engine in operation. When you return to the *Home* screen you will find all the other buttons to be active. We will address each of these buttons below.

Single-Cylinder Engine (*Input One-Cylinder Data* Screen)

This program can be thought of as being used in two stages, each of which roughly corresponds to the topics in Chapters 13 and 14, respectively. That is, the *Input* and *Balance* buttons on the *Home* screen deal with single-cylinder engines (Chapter 13), and the *Assemble* button with multicylinder engines (Chapter 14). The *Flywheel* button can be used with either a single- or multicylinder design.

THE *INPUT* BUTTON on the *Home* screen brings up the *Input One-Cylinder Data* screen shown in Figure A-20 (p. 802). Default data are present in all entry boxes. De-



ENGINE - Professional Edition - by R. L. Norton - Copyright 2006 Release 8.0 Rev 1.2 7/4/06 Input One-Cylinder Data

Engine Geometry
Dsplcmnt of 1 cyl: 25.00 in^3
Bore: 3. in
Stroke: 4. in
Crank Radius: 2 in
Offset: 0. in
L/R Ratio: 3.500
Crank CG: 0.500 dec %
Conrod CG: 0.330 dec %
Mainpin Dia: 2 in
Crankpin Dia: 2 in

Device Type: ● IC Engine ○ Compressor
Stroke Cycle: ○ 2-Stroke ● 4-Stroke
Calculation Speed: ○ Idle RPM ● Mid Range ○ Red Line

Engine Type: Inline

Animation Speed: << Slow Fast >>
Speed Range: 10

Robert L. Norton
Design No. 1
07-22-2006
at 15:38:46

If this plot window is blank, click the *Calculate* button.

Engine Data
B/S Ratio: 0.848
No. Cylinders: 4
Idle RPM: 800
Redline RPM: 6000
Piston Mass: 0.0050 bl
Conrod Mass: 0.0200 bl
Crank Mass: 0.0300 bl
Peak Cyl Pressure: 600. psi
Friction Coefficient: 0.020

Primary variable

Secondary variable

Input either of these - not both

Type these data

Used for friction torque calculation

Calculated

Used on a later screen

Midrange is average of these

Must be in proper mass units

For gas force, torque calc.

For friction torque calc.

Slow animation

Used on a later screen

Click here to animate the engine

FIGURE A-20

Program ENGINE *Input* screen for one-cylinder engine data

vice type can be set to either an IC engine or compressor. The only difference between these two choices is the magnitude of the cylinder pressure used in the calculations. The default pressure for either device can also be changed in the box at lower right. The stroke cycle can be specified as 2 or 4 stroke. Two operating speeds must be specified, idle and redline. The midrange speed is the average of the two speeds supplied. One of three calculation speeds must be selected from the *Idle*, *Midrange,* and *Redline* options. The number of cylinders can be specified in the *No. Cylinders* box, and *Engine Type* can be selected from its pull-down menu. At this screen, only one cylinder of the engine is being calculated, so the choices of number of cylinders and engine type are not used until later when the engine is assembled. Choices made on this screen will be carried forward to the *Assemble* screen and also can be changed there if desired. The *CG* locations of crank and conrod, expressed as a percent of length are typed in boxes on the left. The masses of crank, conrod, and piston, must be supplied (in proper units) in the boxes at the right.

Text boxes in the *Engine Geometry Panel* on the left allow typing of the cylinder displacement, bore, stroke or crank radius, and *L/R* ratio. Cylinder displacement is the primary variable in this program. Any displacement volume can be achieved with an infinity of combinations of bore and stroke. To resolve this indeterminacy, bore is arbitrarily given precedence over stroke when the displacement is changed. That is, a change of displacement will force a change in stroke, leaving the bore unchanged. Changing the bore will force a change in stroke, keeping the specified displacement. Either the stroke or the crank radius may be changed, but either will force the other to change accordingly since stroke is always twice the crank radius, so only one need be input. The bore/stroke ratio is calculated and displayed at upper right.

The diameters of main pins and crankpins are used only to calculate an estimated friction torque in combination with an estimate of friction coefficient in the engine. The friction torque is calculated by multiplying the user-specified coefficient of friction by the forces calculated at the piston-cylinder interface and at the main pin and crankpin journals. These last two friction forces are multiplied by the journal radii supplied by the user to obtain friction torque. The piston friction creates friction torque through the geometry described in the gas torque equation 13.8 (p. 653). The other torque values (gas torque, inertia torque, and total torque) are **not** reduced in the program by the amount of the calculated friction torque, which is at best a crude estimate.

CALCULATION When all data are supplied, a click of the *Calculate* button will cause the piston position, velocity, and acceleration; the inertia forces and torques; and pin forces plus gas force and gas torque to be calculated for two revolutions of the crankshaft. At this screen, these data are computed only for one cylinder of the engine, regardless of how many cylinders were specified. The gas force and gas torque calculation is based on a built-in gas pressure curve similar to the one shown in Figure 13-4e (p. 642). This gas pressure function in the program is kept the same at all engine speeds as discussed in Section 13.1 (p. 640). Though this is not accurate in a thermodynamic sense, it is both necessary and appropriate for the purpose of comparing designs based solely on their kinematic and dynamic factors.

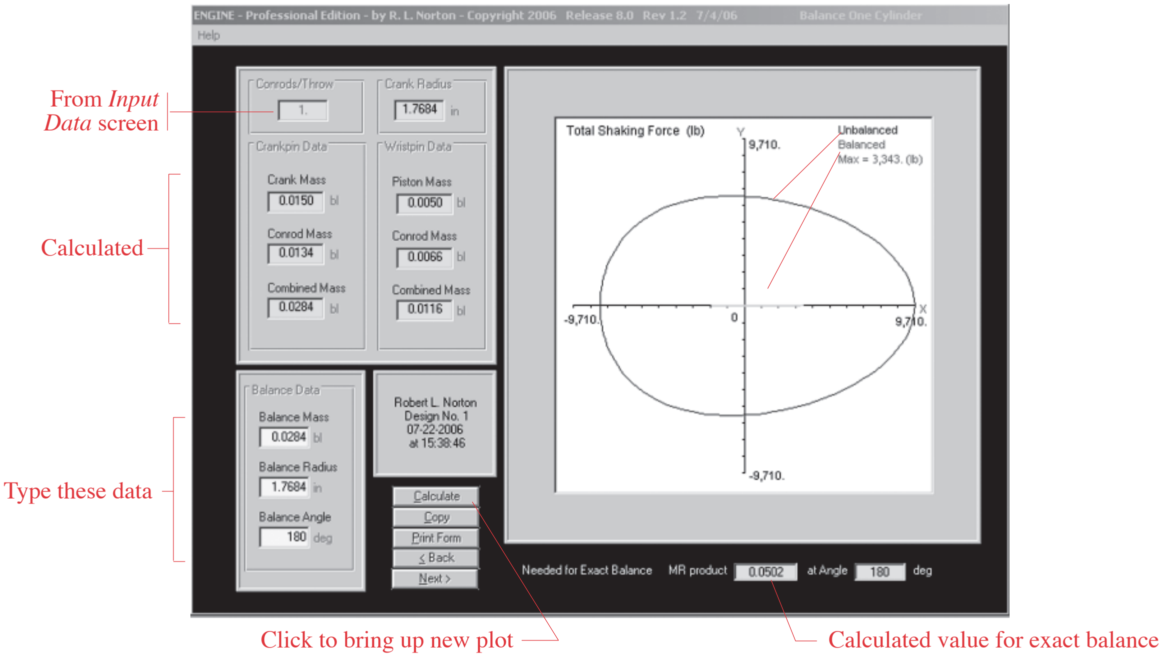
Calculations are done for all parameters at 3° increments over two crankshaft revolutions, giving 241 data points per variable. When calculations are complete, the plot window will show a schematic of the single-cylinder engine that can be animated with the *Run* button. The bore, stroke, and conrod dimensions are to scale in the animation. The *Time Delay* value can be increased to slow the animation.

The *Next* button returns you to the *Home* screen where you can use the *Plot* and *Print* buttons to display the results of the single-cylinder calculations. See Section A.2 (p. 771) for information on the *Print* and *Plot* screens.

Balancing the Crank (ENGINE *Balance* Screen)

The *Balance* button on the *Home* screen brings up the *Balance* screen shown in Figure A-21 (p. 804). The bottom of this screen displays the mass-radius product needed on the crank to cancel the primary component of unbalance due to the mass at the crankpin. The unbalanced shaking force is displayed as a hodograph in a plot window. Information on the amounts of mass estimated to be located at the crankpin and wrist pin is displayed in the sidebar. These data provide enough information to determine the counterweight parameters needed to either exactly balance or optimally overbalance the single-cylinder engine. Three text boxes at the bottom left of the screen allow input of the desired mass, radius, and angle of the counterweight proposed to be placed on the crankshaft.

Clicking the *Calculate* button recomputes the shaking force and torque with the added counterweight and superposes a hodograph of the new, balanced shaking force on the plot of the unbalanced force at the same scale so the improvement can be seen. See Chapter 13 for a discussion of the meaning and use of these data. Note that if the engine design has enough cylinders to allow a crankshaft arrangement that will cancel the iner-



ENGINE - Professional Edition - by R. L. Norton - Copyright 2006 Release 8.0 Rev 1.2 7/4/06 Balance One Cylinder

Conrods/Throw: 1.

Crank Radius: 1.7684 in

Crankpin Data
Crank Mass: 0.0150 bl
Conrod Mass: 0.0134 bl
Combined Mass: 0.0284 bl

Wristpin Data
Piston Mass: 0.0050 bl
Conrod Mass: 0.0066 bl
Combined Mass: 0.0116 bl

Balance Data
Balance Mass: 0.0284 bl
Balance Radius: 1.7684 in
Balance Angle: 180 deg

Robert L. Norton
Design No. 1
07-22-2006
at 15:38:46

Needed for Exact Balance MR product 0.0502 at Angle 180 deg

From *Input Data* screen

Calculated

Type these data

Click to bring up new plot

Calculated value for exact balance

FIGURE A-21

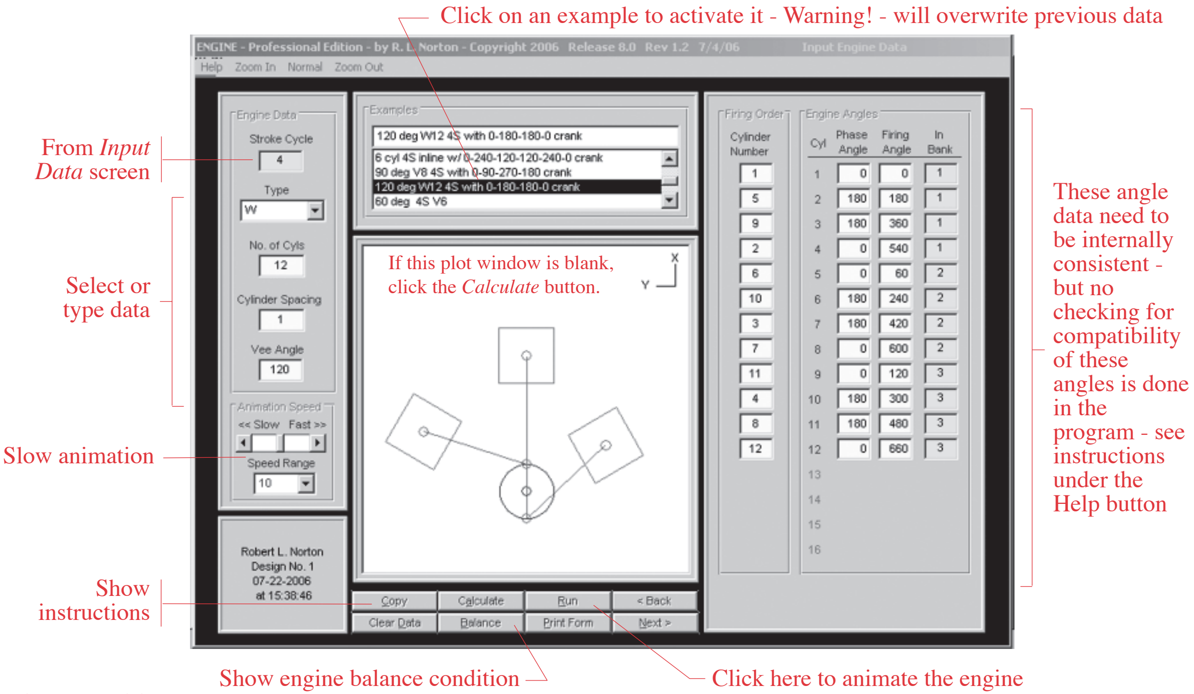
Single-cylinder *Balance* screen from program ENGINE

tial forces, then there may be no advantage to overbalancing the crank. But, for a single-cylinder engine and some two-cylinder engines (twins), overbalancing the crank can significantly reduce the shaking force. Partial overbalancing is sometimes done in multicylinder engines to reduce the mainpin forces as discussed in Chapter 13.

Assembling a Multicylinder Engine (*Engine Data* Screen)

Once the single-cylinder configuration is satisfactorily designed and balanced, the engine can be assembled. Figure A-22 shows the *Engine Data* screen used for assembly of a multicylinder engine. Its *Help* button brings up the information shown in Figure A-23, which points out that the crank phase diagram (called a **Power Chart** in program ENGINE) as defined in Section 14.2 (p. 688) and shown in Figures 14-9, 14-12, 14-14, 14-16, 14-18, and 14-24 (pp. 691-715) should be defined and drawn manually before proceeding with the assembly of the engine. The assumptions and conventions used in the program to number the cylinders and banks are also stated on the screen shown in Figure A-23. These are the same conventions as were defined in Section 14.2 (p. 688). The upper limit stated in item 7 of Figure A-23 for the acceptable range of power stroke angles will be either 360° for a two-stroke engine or 720° (as shown) for a four-stroke engine.

The firing order, the crankshaft phase angles, and the angles at which the cylinders fire (firing angles)—all angles in cylinder order—are typed in the boxes on the right of the *Engine Data* screen based on an arrangement according to the rules in Figure A-23. Note that **the program does not do any internal check on the compatibility of these**



ENGINE - Professional Edition - by R. L. Norton - Copyright 2006 Release 8.0 Rev 1.2 7/4/06 Input Engine Data

Engine Data

Stroke Cycle: 4

Type: W

No. of Cyls: 12

Cylinder Spacing: 1

Vee Angle: 120

Animation Speed

Speed Range: 10

Examples

120 deg W12 4S with 0-180-180-0 crank

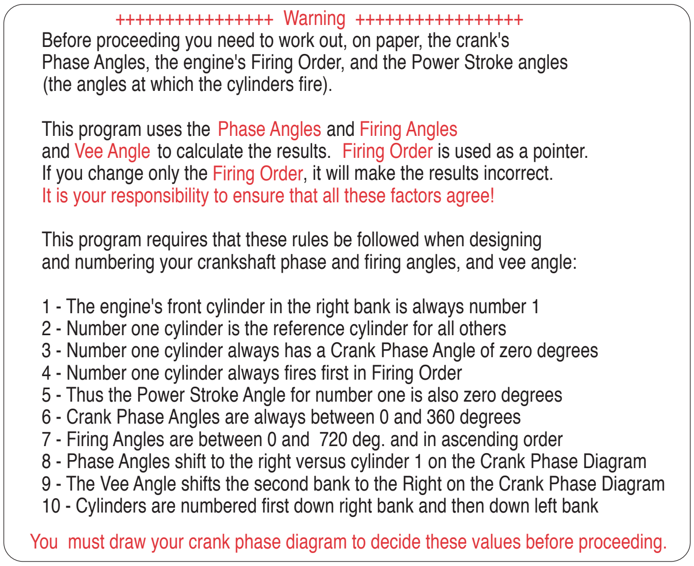
6 cyl 4S inline w/ 0-240-120-120-240-0 crank
90 deg V8 4S with 0-90-270-180 crank
120 deg W12 4S with 0-180-180-0 crank
60 deg 4S V6

Robert L. Norton
Design No. 1
07-22-2006
at 15:38:46

Firing Order Cylinder Number	Cyl	Phase Angle	Firing Angle	In Bank
1	1	0	0	1
5	2	180	180	1
9	3	180	360	1
2	4	0	540	1
6	5	0	60	2
10	6	180	240	2
3	7	180	420	2
7	8	0	600	2
11	9	0	120	3
4	10	180	300	3
8	11	180	480	3
12	12	0	660	3
	13			
	14			
	15			
	16			

FIGURE A-22

The *Input Engine Data* screen in program ENGINE is used to assemble multicylinder engines



++++++++++++++++ Warning +++++++++++++++++

Before proceeding you need to work out, on paper, the crank's
Phase Angles, the engine's Firing Order, and the Power Stroke angles
(the angles at which the cylinders fire).

This program uses the Phase Angles and Firing Angles
and Vee Angle to calculate the results. Firing Order is used as a pointer.
If you change only the Firing Order, it will make the results incorrect.
It is your responsibility to ensure that all these factors agree!

This program requires that these rules be followed when designing
and numbering your crankshaft phase and firing angles, and vee angle:

1 - The engine's front cylinder in the right bank is always number 1
2 - Number one cylinder is the reference cylinder for all others
3 - Number one cylinder always has a Crank Phase Angle of zero degrees
4 - Number one cylinder always fires first in Firing Order
5 - Thus the Power Stroke Angle for number one is also zero degrees
6 - Crank Phase Angles are always between 0 and 360 degrees
7 - Firing Angles are between 0 and 720 deg. and in ascending order
8 - Phase Angles shift to the right versus cylinder 1 on the Crank Phase Diagram
9 - The Vee Angle shifts the second bank to the Right on the Crank Phase Diagram
10 - Cylinders are numbered first down right bank and then down left bank

You must draw your crank phase diagram to decide these values before proceeding.

FIGURE A-23

Rules for assembling a multicylinder engine in program ENGINE

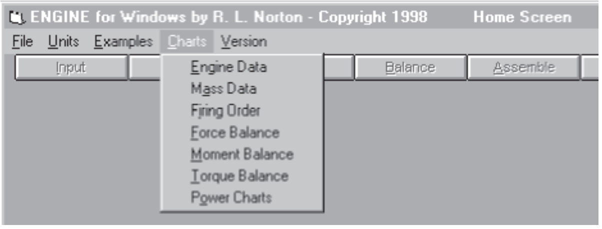


FIGURE A-24

Charts available from pull-down menu in program ENGINE

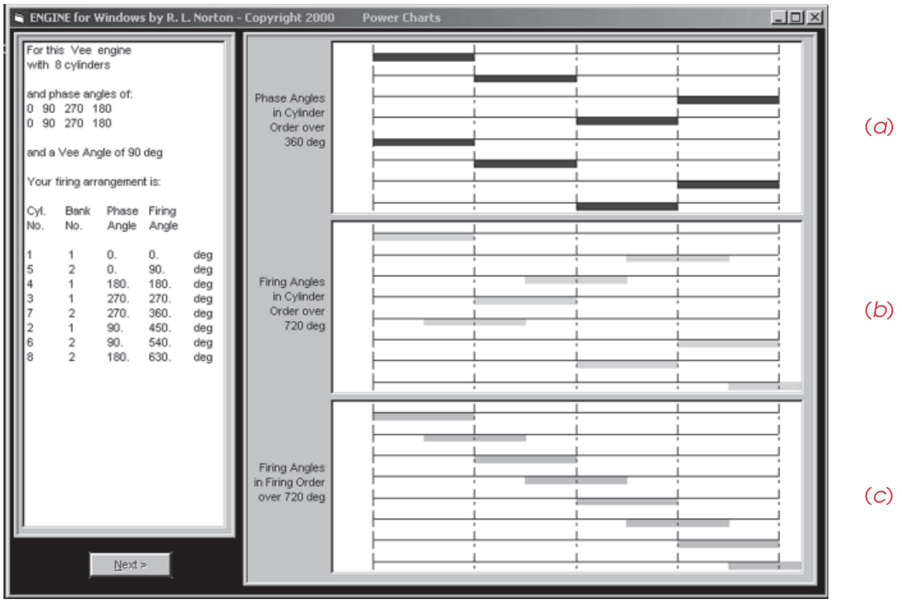
data. It will accept any combination of phase angles, firing orders, and power stroke angles you provide. It is up to you to ensure that these data are compatible and realistic.

The program also needs the distance between cylinders which is defaulted to one. This information is used to define the z_i in equations 14.11 (pp. 710-711). If you want to compute the correct magnitude of the shaking moment, the actual cylinder spacing of your design needs to be supplied in the box at the lower left of the screen in Figure A-22 (p. 805). If you only want to compare two or more engine designs on the basis of relative shaking moment, then the default value of one will suffice. The computation sums moments about the first cylinder, so its moment arm is always zero. The small offset between a vee engine's banks, due to having two conrods per crank throw, is ignored in the moment calculation.

Charts (Pull-Down Menu)

Figure A-24 shows the *Charts* pull-down menu on the *Home* screen. Several summaries of engine information are available there. The *Force Balance*, *Moment Balance*, and *Torque Balance* menu selections display the results of engine balance condition calculations, i.e., equations 14.3a and 14.3b (p. 692) for force balance; 14.7a and 14.7b (p. 695) for moment balance; and 14.5a, 14.5b, and 14.5c (p. 694) for torque balance. (These charts are also accessible from the *Engine Data* screen via its *Balance* button.)

The **Power Chart** selection presents the three plots shown in Figure A-25. Figure A-25a is a plot of the crankshaft phase angles over 360° for the 90° vee-eight engine designed in Section 14.7 (p. 705). Figure A-25b shows the power stroke angles in cylinder order over 720° for this vee eight. This is the same as the crank phase diagram shown in Figure 14-24 (p. 715) and indicates when the power pulses will occur in each cylinder during the cycle. Figure A-25c shows the power stroke angles in firing order over 720°. This third plot rearranges the order of the cylinders on the power chart to match that of the selected firing order. If these three factors, *crankshaft phase angles, firing order,* and *firing angles* have all been correctly chosen for compatibility, this third power chart plot will appear *as a staircase*. The power pulses should occur in equispaced steps across the cycle if even firing has been achieved. Thus these power chart plots can serve as a check on the correct choices of these factors. Note that the program only draws the boxes on the crank phase diagrams and power charts which represent the power strokes of each cylinder. The other piston strokes shown in Figures 14-9, 14-12, 14-14, 14-16, 14-18, and 14-24 (pp. 691-715) are not drawn.

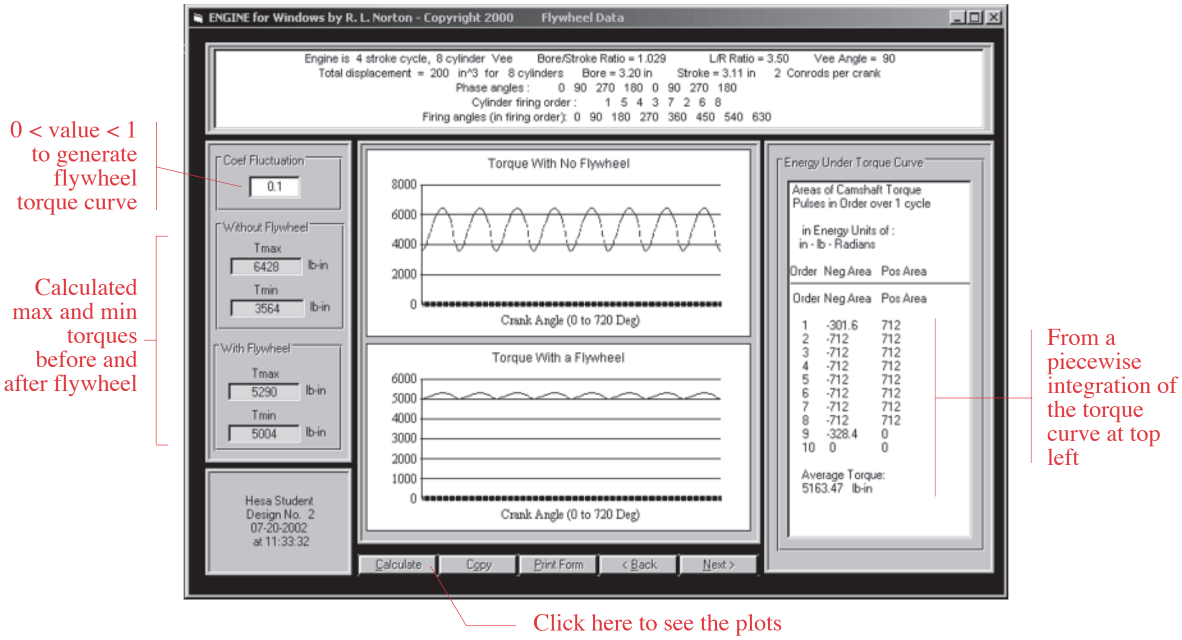


ENGINE for Windows by R. L. Norton - Copyright 2000 Power Charts

```
For this  Vee  engine
with  8 cylinders

and phase angles of:
0   90   270   180
0   90   270   180

and a Vee Angle of 90 deg

Your firing arrangement is:

Cyl.     Bank     Phase   Firing
No.      No.      Angle   Angle

1         1       0.      0.        deg
5         2       0.      90.       deg
4         1       180.    180.      deg
3         1       270.    270.      deg
7         2       270.    360.      deg
2         1       90.     450.      deg
6         2       90.     540.      deg
8         2       180.    630.      deg
```

FIGURE A-25

Phase angle and power charts for a vee-eight engine from program ENGINE. Compare to Figure 14-24 in text.



ENGINE for Windows by R. L. Norton - Copyright 2000 Flywheel Data

```
Engine is  4 stroke cycle,  8 cylinder  Vee      Bore/Stroke Ratio = 1.029        L/R Ratio = 3.50      Vee Angle =  90
   Total displacement  =  200   in^3  for   8 cylinders     Bore = 3.20 in      Stroke = 3.11 in     2  Conrods per crank
                        Phase angles :      0   90   270   180   0   90   270   180
                           Cylinder firing order :       1   5   4   3   7   2   6   8
                   Firing angles (in firing order):  0   90   180   270   360   450   540   630
```

Coef Fluctuation: 0.1

Without Flywheel
Tmax: 6428 lb-in
Tmin: 3564 lb-in

With Flywheel
Tmax: 5290 lb-in
Tmin: 5004 lb-in

Hesa Student
Design No. 2
07-20-2002
at 11:33:32

Energy Under Torque Curve

```
Areas of Camshaft Torque
Pulses in Order over 1 cycle

  in Energy Units of :
 in - lb - Radians

Order  Neg Area   Pos Area
-------------------------
Order Neg Area   Pos Area

  1     -301.6     712
  2     -712       712
  3     -712       712
  4     -712       712
  5     -712       712
  6     -712       712
  7     -712       712
  8     -712       712
  9     -328.4     0
  10     0         0

  Average Torque:
  5163.47   lb-in
```

0 < value < 1 to generate flywheel torque curve

Calculated max and min torques before and after flywheel

From a piecewise integration of the torque curve at top left

Click here to see the plots

FIGURE A-26

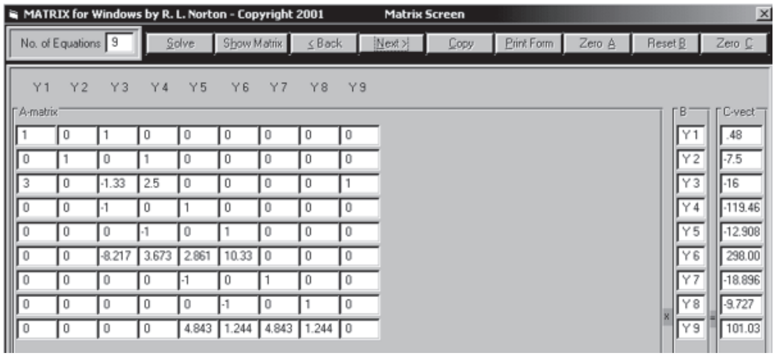
Flywheel Data screen from program ENGINE for a vee-eight engine

Flywheel Calculations

Figure A-26 shows the *Flywheel Data* screen from program ENGINE. The only input to this screen is the flywheel coefficient of fluctuation which must be between 0 and 1. When the *Calc* button is clicked, it does the same pulse-by-pulse integration of the total torque curve as is done in program FOURBAR. See Section 11.11 (p. 586) and Figure 11-11 (p. 589). The areas under the pulses of the total torque curve are a measure of energy variation in the cycle. The flywheel size is based on these energy variations as defined in Section 11.11. The total torque curve for this example vee-eight engine is shown in the upper plot of Figure A-26 (p. 807). The areas under its pulses are shown in the table at the right of the screen. Note that for a properly designed, even firing, multicylinder engine, the absolute values of all pulse areas will be the same. In that case the energy value needed for the flywheel calculation is just the area under any one pulse. These data can be used in equation 11.22 (p. 591) to compute the required flywheel moment of inertia based on a chosen coefficient of fluctuation k. Program ENGINE then calculates a smoothed total torque function by multiplying the raw torque by the specified coefficient of fluctuation. The lower plot in Figure A-26 shows the flywheel smoothed torque for the example vee-eight engine with $k = 0.1$. The torque function with the flywheel added is nearly a constant value, which is desirable. The pulses due to the individual cylinder's explosions have been effectively masked by the flywheel. The maximum and minimum values of torque with and without the flywheel are shown in boxes at the left of the screen. Data for the engine design are displayed in the panel at the top of the screen.

A.9 PROGRAM MATRIX

Program MATRIX solves a matrix equation of the form **A** X **B** = **C**. **A** must be square and can have up to 16 rows and 16 columns. **C** must be a vector with as many elements as **A** has rows. When the data have all been typed in and checked as shown in Figure A-27, click the *Solve* button and it will compute the terms of vector **B**. The results can be printed to screen, printer, or a disk file in the same manner as described in Section A.2 (p. 771). If the matrix is singular or the solution fails for other reasons, an error message will be returned. No plotting or animation is provided in this program.



No. of Equations 9

Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	B	C-vect
1	0	1	0	0	0	0	0	0	Y1	.48
0	1	0	1	0	0	0	0	0	Y2	-7.5
3	0	-1.33	2.5	0	0	0	0	1	Y3	-16
0	0	-1	0	1	0	0	0	0	Y4	-119.46
0	0	0	-1	0	1	0	0	0	Y5	-12.908
0	0	-8.217	3.673	2.861	10.33	0	0	0	Y6	298.00
0	0	0	0	-1	0	1	0	0	Y7	-18.896
0	0	0	0	0	-1	0	1	0	Y8	-9.727
0	0	0	0	4.843	1.244	4.843	1.244	0	Y9	101.03

FIGURE A-27

Program Matrix input and calculation screen