PROGRAM LINKAGES
User Manual

By Robert L. Norton P.E.

INTRODUCTION

A Student Edition of Program Linkages is provided with the text Design of Machinery, 5ed. by Robert L. Norton. A student edition may only be used for educational purposes. For commercial applications, a professional version with extended capabilities is available at **http://www.designofmachinery.com/**. Program Linkages is based on the mathematics derived in Chapters 4 to 7 and 10 to 14 of the text and uses the equations presented therein to solve for position, velocity, and acceleration in linkages of several types. The program is 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 the noted 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 *Brute Force* and *Ignorance!* **Engineer** your solutions and understand the theory behind them.

A.1   GENERAL INFORMATION

Hardware/System Requirements

These programs require Windows 2000/NT/XP/Vista/Win 7, either 32 or 64 bit operating systms. A DVD drive is needed, as is a hard disk drive. Any processor with sufficient power and memory to run Windows in any of the versions listed will run this program.

Installing the Software

The DVD contains the executable program files plus all ancillary files needed to run the programs. Run the INSTALL 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. After installation you will be prompted to check for an update. Do so, as this will give you the latest version.

License

Purchase of the Design of Machinery text book provides a 2-year limited license to use the program for educational purposes only. Please backup these license file as insructed and store in a safe place.

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.

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.

GENERAL PROGRAM OPERATION

At start-up, a splash screen appears that 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 also defines the registered owner.

The next screen, the *Title* screen, allows the input of any user name 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 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 most programs (See Figure 1). These will be described below.

General User Actions Possible Within the Program

The program is 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 the *Tab* key will move you from box to box. 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; others require you to select one from the list. 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

The *Help* menus on some screens provide online access to this manual as well as specific instructions for various functions within the program. Some instructional videos may also be 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

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

The *Examples* pull-down menu on the *Home* screen 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*, *Recalc*, *Run*, or *Step* on the presented screen to see the results.

Creating New, Saving, and Opening Files (*File*)

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 the *Home* screen (Figure 1). Selecting *New* from this menu will zero any data you may have already created within the program, but before doing so will give a warning and prompt you to save the currrent 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 (.bar). 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, (.bar) 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 this program.   Linkages will open files saved from the earlier versions of this program (which used to be five separate programs), Fourbar (.4br), Fivebar (.5br), Sixbar (.6br), Slider (.sld), and Engine (.eng).
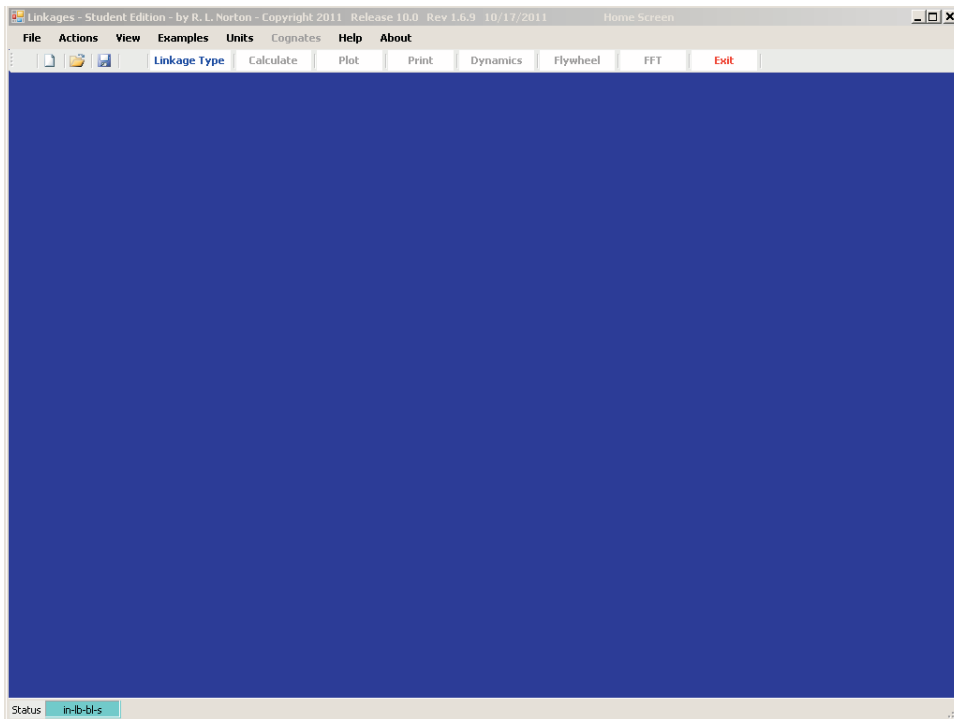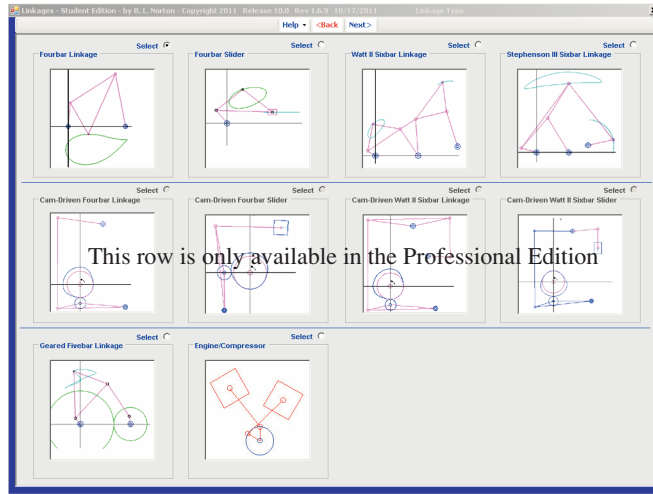

FIGURE 1

The Home Screen

FIGURE 2

The Linkagetype Screen

LinkageType Screen

The only choice (other than Exit) that is available when the program starts is the Linkagetype Screen as shown in Figure 2. This is where you choose the type of linkage that you want to create. The choices are: Fourbar, Four-link Slider, Watt's II Sixbar, Stevenson's III Sixbar, Geared Fivebar, and Engine. The middle row of Cam-Driven Linkages is only available in the Professional Edition of Linkages. You may either click on the Select Button above the desired linkage type and then click Next, or double-click on the desired linkage graphic icon and either will take you to the Input screen with an example linkage's data preloaded in the boxes.

Input screen

Once a linkage type has been chosen, the *Calculate* button becomes available on the *Home Screen* and you will be taken directly to it from the *LinkageType* screen. Figure 3 shows the *Input scr*een for a Fourbar linkage selection. The first thing needed is to select a calculation type from the dropdown menu as shown in Figure 4. The choices are: *One Position, Constant Velocity, Constant Acceleration*, or *Synthesize a Fourbar Linkage*. This defaults to *Constant Velocity* when the program first runs.

      The upper set of yellow boxes in Figure 6 allow the link dimensions to be input as defined in Figures 5 and 6. The lower set of yellow boxes in Figure 6 allow the initial conditions to be input. Note that these vary with the choice of calculation type. The *Recalc* button will calculate after any changes are made. If you check the *Autocalc* button at upper left, then any change of dimensions or conditions will cause an automatic recalculation. Other buttons in the gray bar below the menu items will switch the calculation from the open to the crossed circuit of the linkage (Loop 1 Mode). The buttons labeled *Ground*
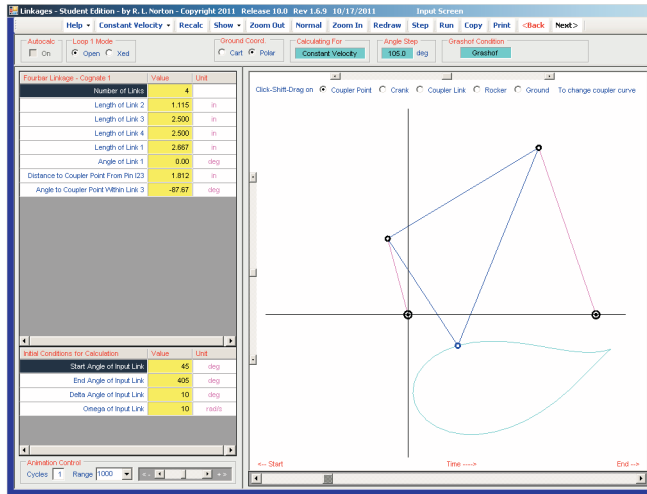
FIGURE 3

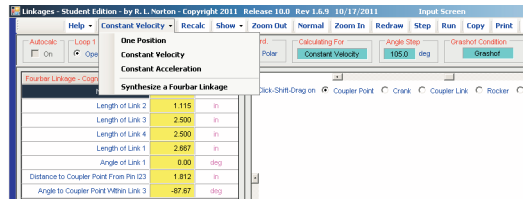The Input Screen

Select a calculation type
from the dropdown menu

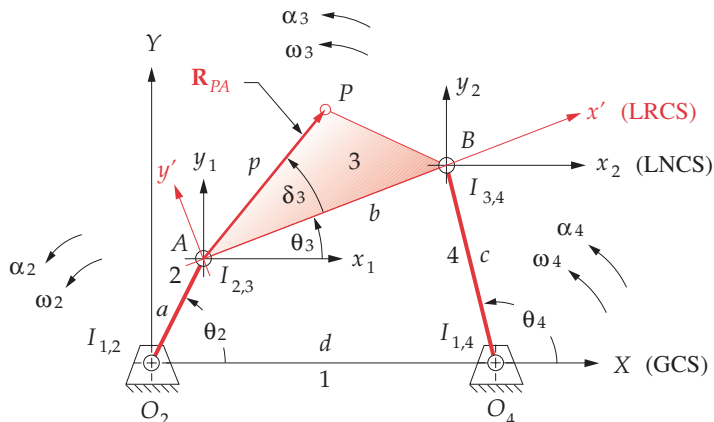**FIGURE 4**

Selecting the Calculation Type

FIGURE 5
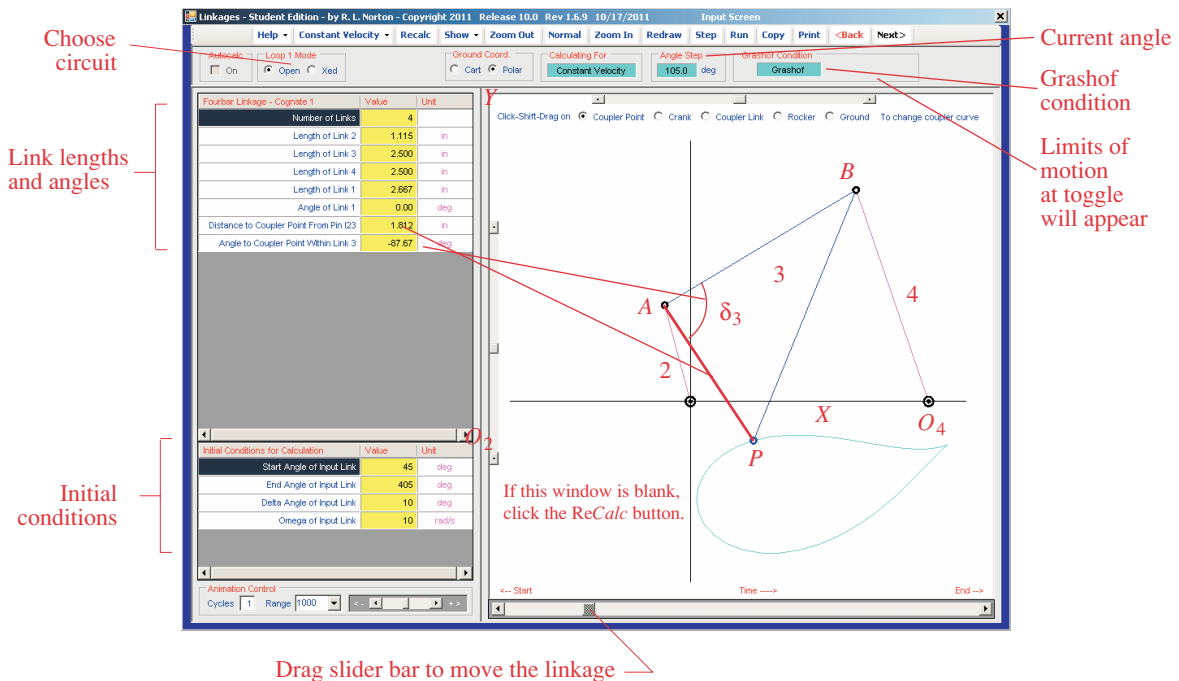
Linkage data for Fourbar inkage type

FIGURE 6

Input screen for Fourbar linkage type

Coord allow you to enter the ground link (link 1) dimensions in either cartesian or polar coordinates as you prefer. The cyan boxes feed back info on current conditions such as the calculation type currently selected, the curent crank angle, and the Grashof condition.

Calculation

Basic data for a linkage design is defined on the *Input scre*en shown in Figure 6, which is activated by selecting the *Calculate* 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 6. Select the type of calculation desired, one of *Constant Velocity, Constant Acceleration*, or *One Position* (Figure 4). 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.

CONSTANT VELOCITY   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.

CONSTANT ACCELERATION   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 **Constant Acceleration**, **Constant Velocity,** and **Constant Acceleration** analyses can be used to simulate the start-up, steady-state, and deceleration phases, respectively, of a system for a complete analysis.

RECALC   The *Recalc* button will compute all data for your linkage and show it in an arbitrary position in the linkage window on the *Input scre*en. If at any time the white linkage window is blank, the *Recalc* or *Redraw* 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. The *Run* button animates the linkage.

CALCULATION ERRORS   If a position is encountered that cannot be reached by the links (in either the constant velocity or constant acceleration 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 scr*een. **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 or the *Slider Bar*.

GRASHOF CONDITION   Once the calculation is done, the linkage's Grashof condition is displayed in a panel at the upper 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 upper 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   The *Run* button activates the linkage and runs it through the range of motion defined in its most recent calculation. 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.

CENTRODES   Only FOURBAR 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. (See Show Menu below.)

ZOOM OUT - NORMAL - ZOOM IN   The linkage animation plot is normally auto-scaled to fit the screen based on the size of the linkage and its coupler curves (but not of the centrodes as they can go to infinity). These menu controls along with the sliders at left and top allow the resizing and repositioning of the image in the window.

SHOW MENU   Allows you to show or suppress various aspects of the linkage during amimation. The links can be shown or suppressed as can the coupler curve. Show Coupler lines will put short lines at each coupler point to show the angle of the coupler at each position. Centrodes can be turned on or off. 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 from the list across the top of the graphic window. Then *Shift-Click-Drag* the coupler point or end of link with the mouse to change its dimension and watch the coupler curve and linkage parameters update dynamically.

LEAVING THE SCREEN   The *Next* button returns you to the *Home Screen* as will the *Back* button. The difference is that if you *Back* out of a screen, the program assumes you do NOT want to retain the most recent changes, but the *Next* button retains all changes made on that screen. When you return to the *Home Scree*n, the *Plot, Print*, and *Dynamics* buttons will be active.

Copying Screens to Clipboard or Printer (*Copy*)

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*. The graphic can then be printed from the program into which it was pasted.

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

Selecting the *Print* button from the *Home* screen will open the *Print* screen containing lists of variables that may be printed (see Figure 7). A dropdown menu in the upper left-corner will select *Screen* or *Disk* and explain how to get a printout 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 *Scree*n will result in a scrollable screen window full of the requested data as shown in Figure 8. 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 *Disk* as the output device from the menu in upper left corner 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* screen has two modes for data selection, *Preset Formats* and *Mix and Match*. The former provides preselected sets of four variables for printing. You may override these selections with the four dropdown menus across the top. These allow indicidual selection of any set of the available variables for printing. You may choose to print one, two, or four variables at a time in either mode by checking the appropriate button labeled *Functions*. You may select the number of decimal places and the frequency of data to be printed from dropdowns at upper left. The minimum, maximum, and peak-to-peak values are shown in the right sidebar. The left sidebar reports problem setup data.

Plotting Data (*Plot* Button)

The *Plot* button on the *Home* screen brings up the *Plot* screen (Figure 9). The dropdown menus to select *Preset Collections* of functions or to *Mix and Match* any set of choice are the same as on the *Print* screen (Figure 7). The former provides preselected collections of functions, and the latter allows you to select up to four functions from those available
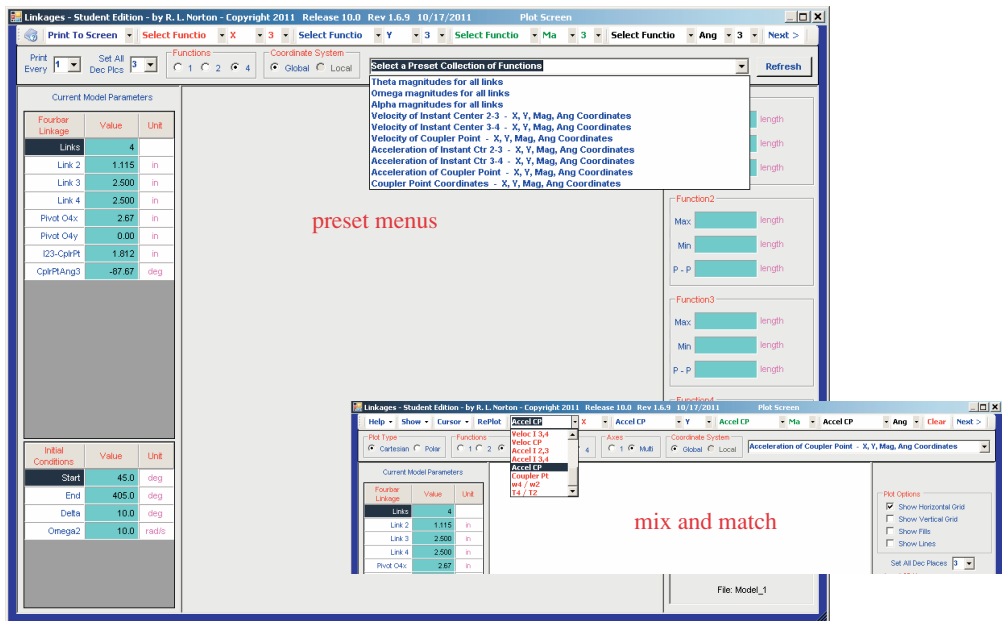

FIGURE 7

Print screen with dropdown menu of preset collections and a mix and match menu shown

Linkages - Student Edition - by R. L. Norton - Copyright 2011 Release 10.0 Rev I.6.9 10/17/2011   Plot Screen

Print To Screen ▾ Veloc CP ▾ X ▾ 3 ▾ Veloc CP ▾ Y ▾ 3 ▾ Veloc CP ▾ Ma ▾ 3 ▾ Veloc CP ▾ Ang ▾ 3 ▾ Next >

Print Every 1 ▾ Set All Dec Plcs 3 ▾   Functions: ○ 1 ○ 2 ◉ 4   Coordinate System: ◉ Global ○ Local   Velocity of Coupler Point - X, Y, Mag, Ang Coordinates ▾   Refresh

Current Model Parameters

Fourbar Linkage	Value	Unit
Links	4	
Link 2	1.115	in
Link 3	2.500	in
Link 4	2.500	in
Pivot O4x	2.67	in
Pivot O4y	0.00	in
I23-CplrPt	1.812	in
CplrPtAng3	-87.67	deg

Initial Conditions	Value	Unit
Start	45.0	deg
End	405.0	deg
Delta	10.0	deg
Omega2	100.0	rad/s

Input Angle (deg)	Veloc CP X (in/sec)	Veloc CP Y (in/sec)	Veloc CP Mag (in/sec)	Veloc CP Ang (deg)
45	-133.833	22.850	-133.833	170.311
55	-137.101	23.218	-137.101	170.388
65	-137.401	17.994	-137.401	172.539
75	-135.165	8.544	-135.165	176.383
85	-130.375	-3.748	-130.375	181.647
95	-122.863	-17.629	-122.863	188.165
105	-112.475	-31.997	-112.475	195.880
115	-99.154	-45.878	-99.154	204.830
125	-82.973	-58.404	-82.973	215.142
135	-64.158	-68.812	-64.158	227.005
145	-43.096	-76.440	-43.096	240.586
155	-20.343	-80.751	-20.343	255.860
165	3.388	-81.360	3.388	-87.615
175	27.255	-78.063	27.255	-70.754
185	50.340	-70.866	50.340	-54.612
195	71.725	-59.995	71.725	-39.911
205	90.576	-45.890	90.576	-26.869
215	106.215	-29.177	106.215	-15.360
225	118.166	-10.617	118.166	-5.134
235	126.174	8.928	126.174	4.047
245	130.207	28.535	130.207	12.361
255	130.440	47.248	130.440	19.912
265	127.231	64.082	127.231	26.733
275	121.094	78.020	121.094	32.793
285	112.652	87.989	112.652	37.992
295	102.544	92.838	102.544	42.156
305	91.252	91.332	91.252	45.025
315	78.779	82.278	78.779	46.244

Veloc CP X — Max 130.440 in/sec — Min -137.401 in/sec — P - P 267.841 in/sec

Veloc CP Y — Max 92.838 in/sec — Min -81.360 in/sec — P - P 174.198 in/sec

Veloc CP Mag — Max 130.440 in/sec — Min -137.401 in/sec — P - P 267.841 in/sec

Veloc CP Ang — Max 255.860 deg — Min -87.615 deg — P - P 343.476 deg

Robert L. Norton
Design No. 1
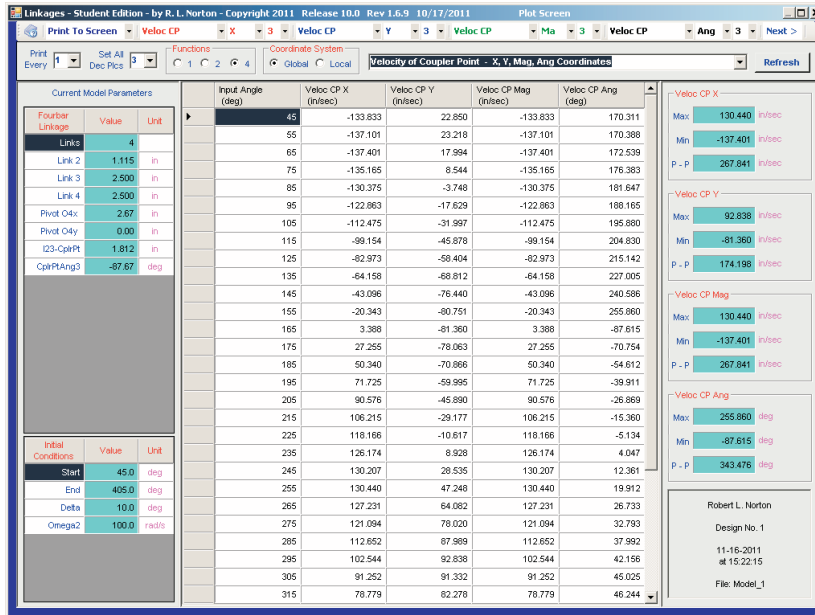11-16-2011 at 15:22:15
File: Model_1

FIGURE 8

Print screen with dropdown menu of preset collections

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*. Either cartesian or polar plots can be made by selecting the appropriate button at upper left.

CARTESIAN PLOTS depict a dependent variable versus an independent variable on cartesian (*x, y*) axes. The independent variable shown on the *x* axis may be either time or angle, depending on the calculation choice made. The variables for the *y* axes are selected from the dropdown menus. 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. Other vectors such as linear accelerations are shown as cartesian pairs (x, y coordinates) or as polar coordinates (magnitude and angle).

Several modes of display are selectable from the buttons labeled *Functions, Windows*, and *Axes*. Figure 9 shows four functions on four separate axes and Figure 10 shows some of the alternate plotting arrangements available for cartesian plots. Experiment to find the one that best suits your particular situation to most effectively display the data.

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) is
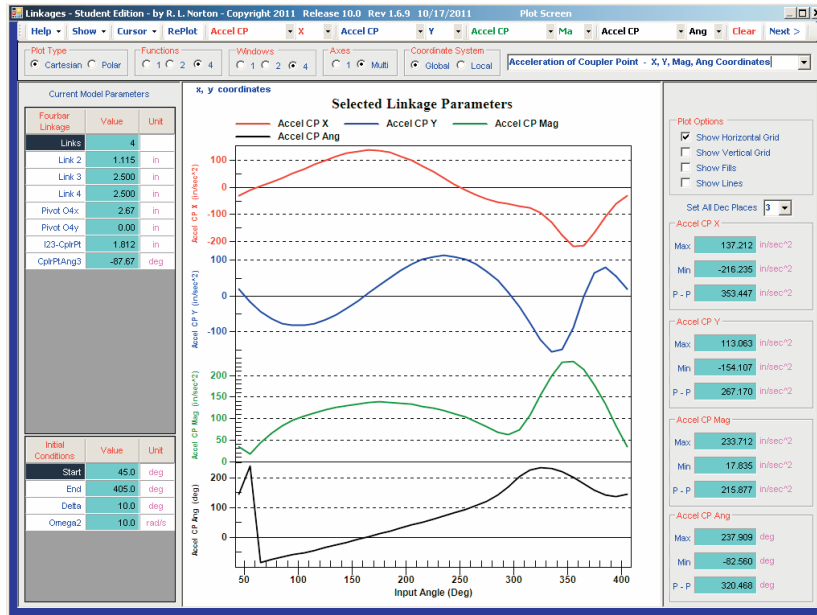
FIGURE 9

Plot screen with four functions shown on four plots

to make a polar plot with respect to a local, nonrotating 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. Figure 11 shows a polar plot.

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**.

COORDINATE SYSTEMS For particular variables, a choice of coordinate system is provided for display of vector information in plots. The *Coordinate System* panel 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 5. For polar plots the vectors shown with the *Global* choice actually are drawn in a local, nonrotating coordinate system (LNCS) 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 5. The
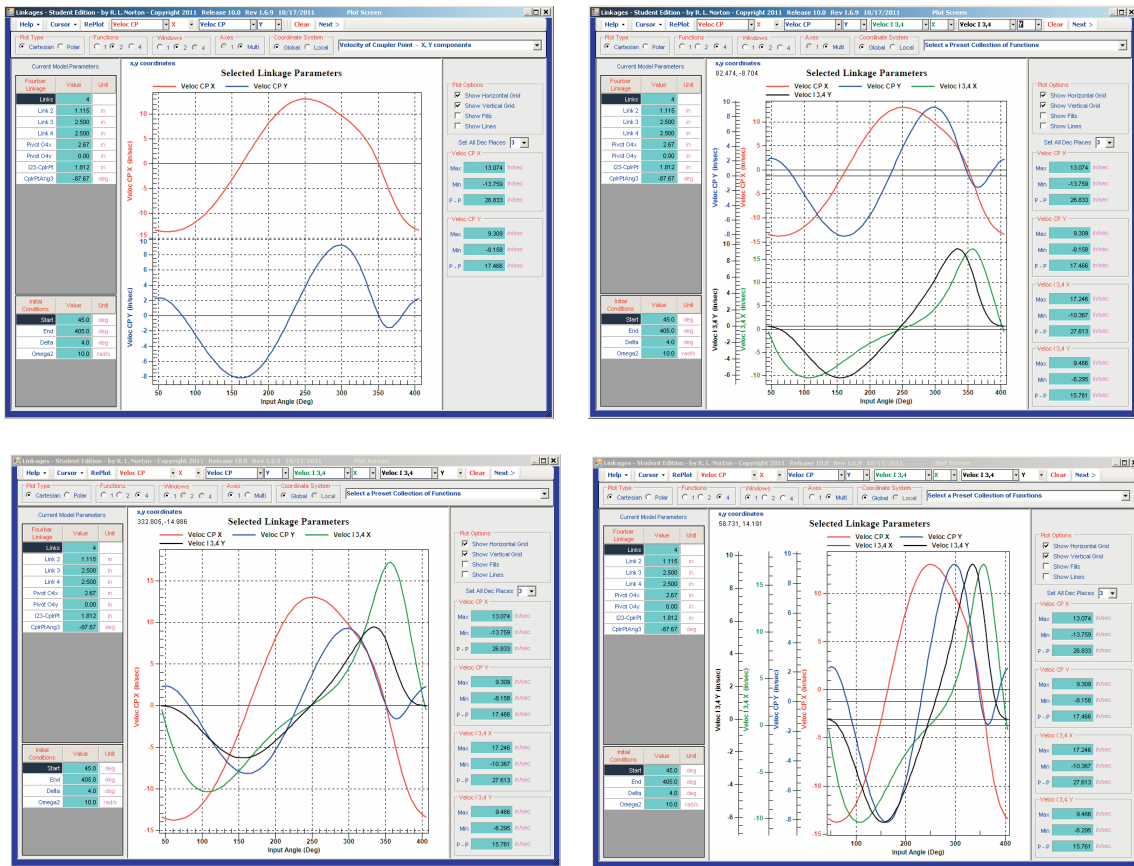
FIGURE 10

Plot screen with alternate arrangements of cartesian plots shown. Many others are possible.

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 5. 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 in the link.

SAVING PLOTS   From the *Plot* screen you may copy to the clipboard for pasting into another application such as Word. The *Back* and *Next* buttons return you to the *Home Screen*.
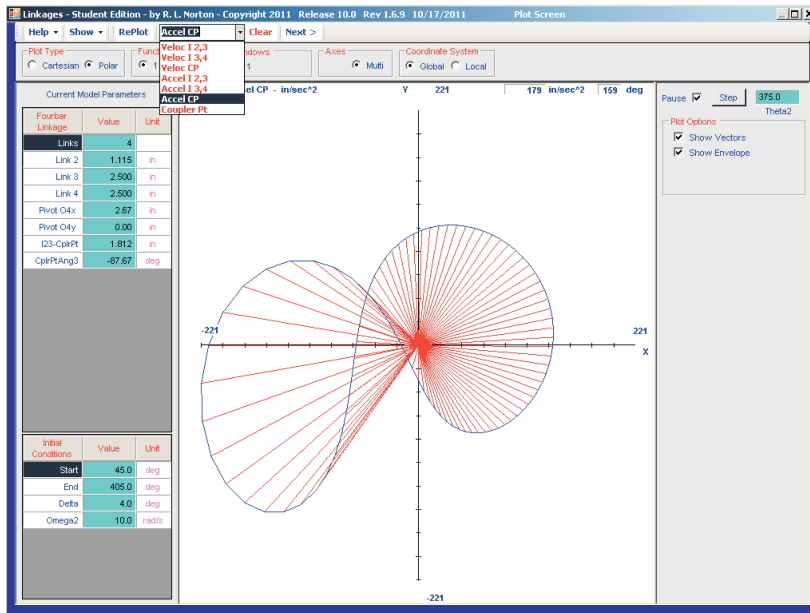
FIGURE 11

Polar plot screen.

The *About* Menu

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 the Program

Choosing either the *Exit* button or *Exit* on the *File* pull-down menu on the *Home Screen* or clicking on the X in upper right corner of te window 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.

WARNING: It is critical that you always close the program this way! Do not shut down the computer or terminate a Remote Desktop Session with this program running:, That WILL lock up the license and cause the program to cease functioning.

DETAILED PROGRAM OPERATION

The preceding section gives an overview of program operation from starting it up, selecting a linkage type from the LinkageType Screen, calculating data (for a Fourbar linkage as an example), printing and plotting those data, saving the file and closing the program. All of those functions are common to all types of linkages handled by the program. The remainder of this manual will address each type of linkage covered by the program in more detail.

FOURBAR LINKAGE

Figure 5 defines the input parameters, link numbering, and the axis systems used for a FOURBAR linkage The link lengths needed are the 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. 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. However, 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 in the program.

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 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 5 are consistent with those that are used in the derivation of the equations for the fourbar linkage in the text Design of Machinery.

Dynamics (FOURBAR, FIVEBAR, SIXBAR, and SLIDER)

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 12 labeled 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 Figure 12, link 2's *CG* vector is

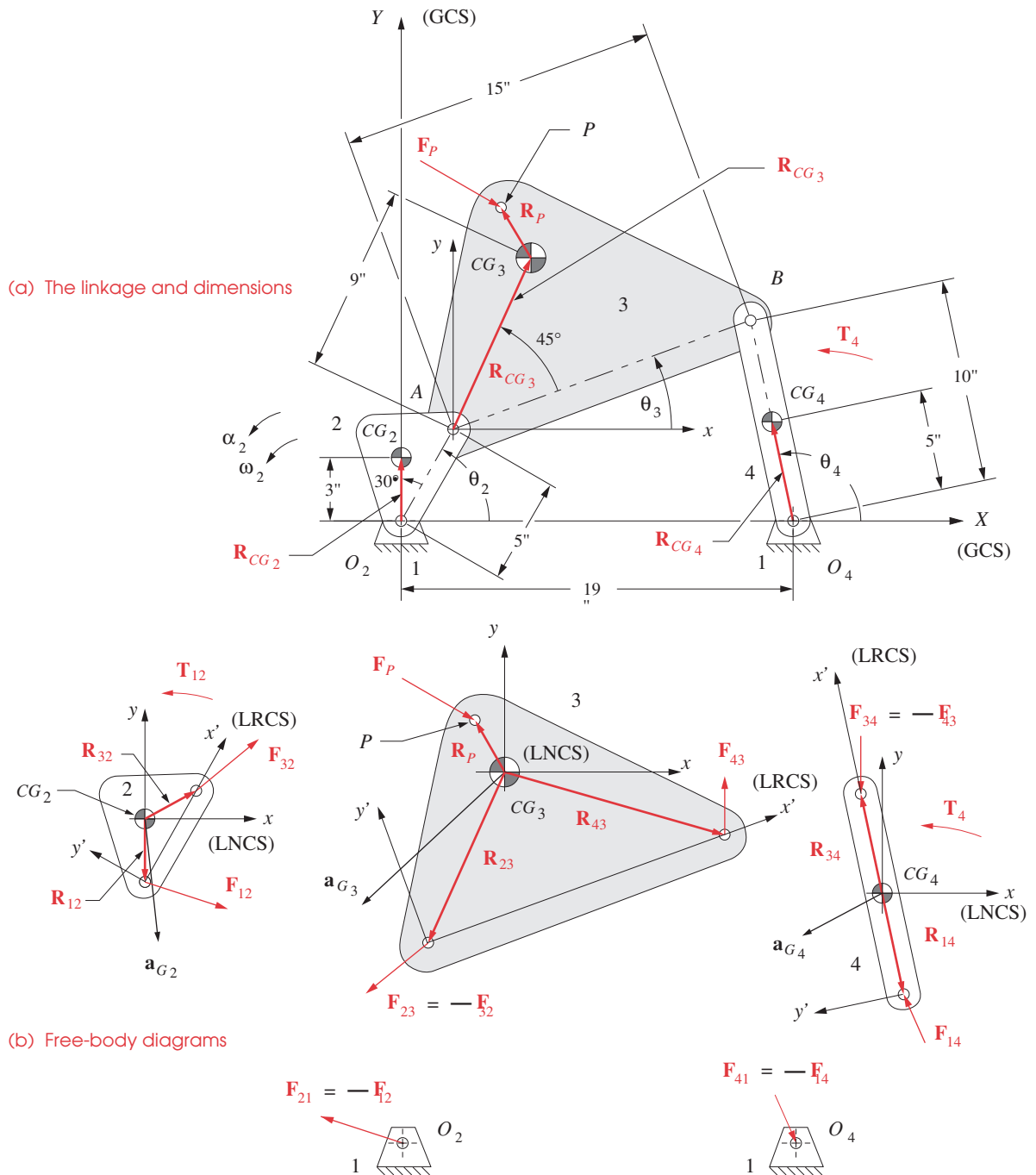**(a) The linkage and dimensions**

(b) Free-body diagrams

FIGURE 12

Definition of data needed for dynamics calculations ifor a FOURBAR

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 R_{12}, R_{32}, R_{23}, R_{43}, R_{34}, and R_{14} needed for the dynamic force equations as shown in the free-body diagrams in Figure 12b. 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 that are applied to links 3 or 4 are typed in the appropriate boxes on the *Dynamics* screen as shown in Figure 13a. 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

(a)

(b)
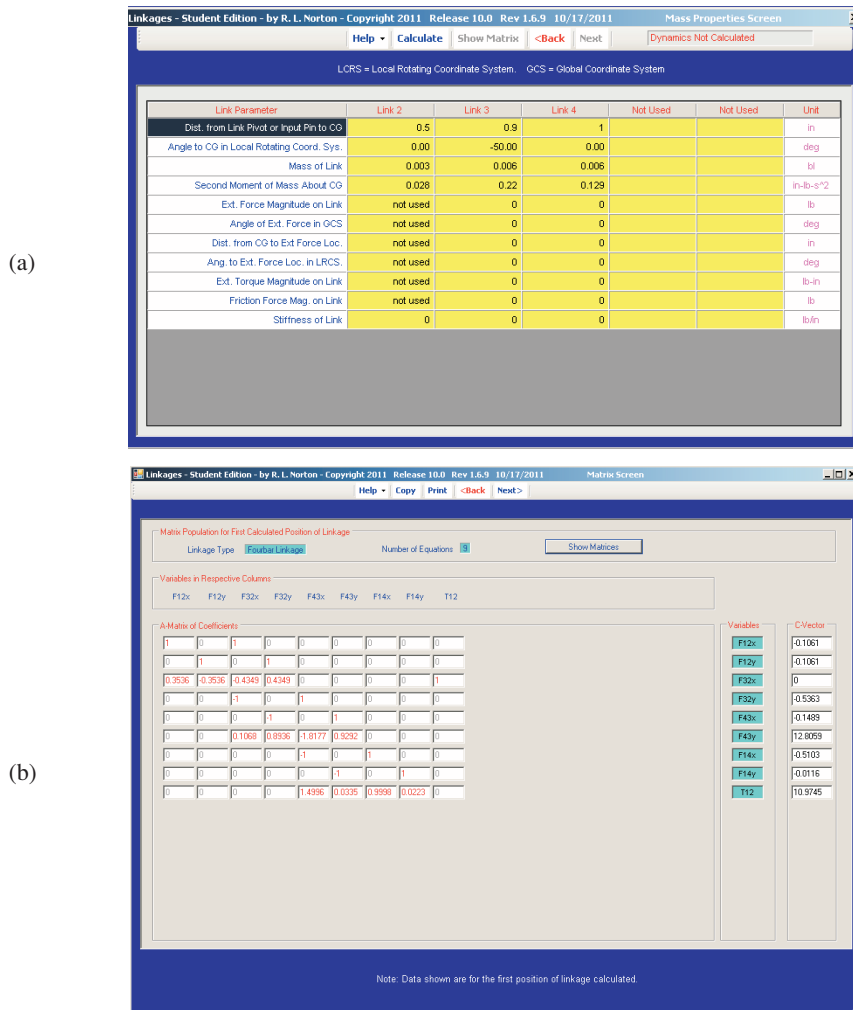
FIGURE 13

Fourbar Dynamics screen and Matrix screen.

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.

After solving (by clicking the *Calculate* button), clicking the *Show Matrix* button will display the dynamics matrix for the linkage as shown in Figure 12b. 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 and Engine Only)[*]

When a fourbar linkage is selected, the *Balance* button on the *Home* screen brings up the *Balance* screen shown in Figure 14, 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 by typing the appropriate values in the yellow boes in left sidebar, the shaking force will

[*] ENGINE's *Balance Screen* is completely different than FOURBAR's and so will be discussed separately in the section on the ENGINE program.
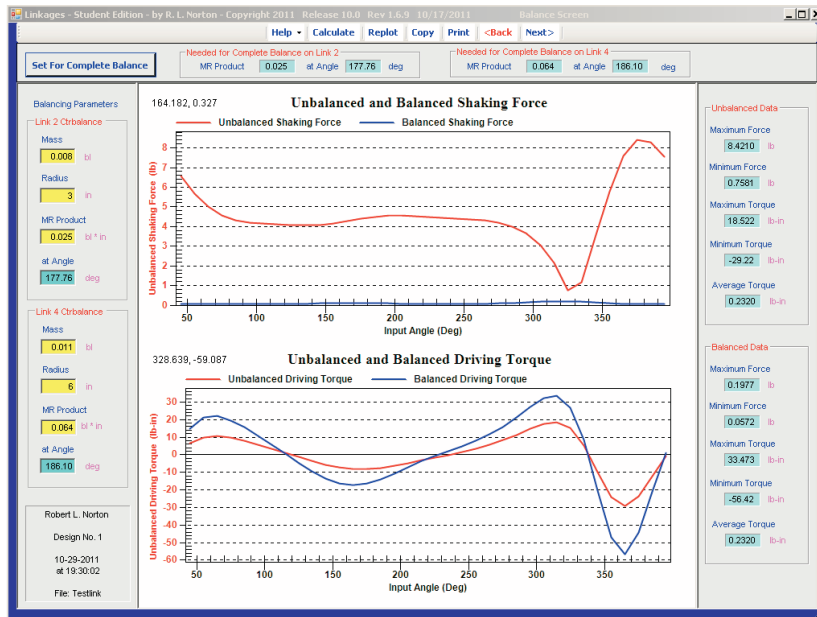

FIGURE 14

Fourbar linkage balance screen

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 right sidebar shows the maximum, minimum and average values of the force and torque functions..

Flywheel

The effect of a flywheel on dynamic torque can be calculated for any selected coefficient of fluctuation desired and the results seen on the Flywheel Screen (Figure 15) that is selected with the Flywheel button on the Home Screen (Figure 1). Two plots are shown, the linkage driving torque both before and after the addition of a flywheel superposed on the same axes.

The data in the right sidebar show the values of the integrals of the torque curve for each pulse of torque either above or below the average line. These values represent the energy in each pulse of the torque-time curve and can be used to size the flywheel.   See Section 11.11 of *Design of Machinery* 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 upper left.

Cognates (FOURBAR Only)

The *Cognates* pull-down menu on the Home Screen allows switching among the three cognates that create the same coupler curve. Switching among them requires recalcula-
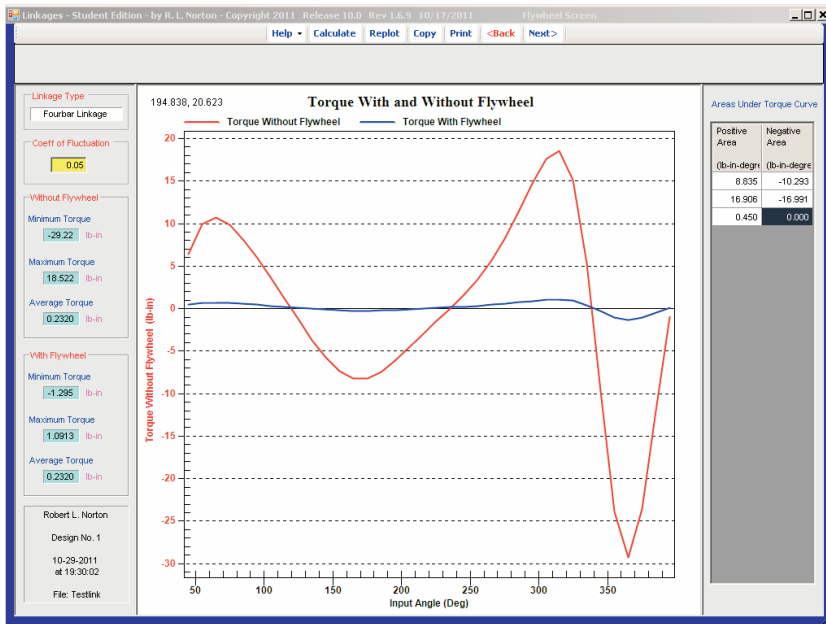
FIGURE 15

Flywheel screen
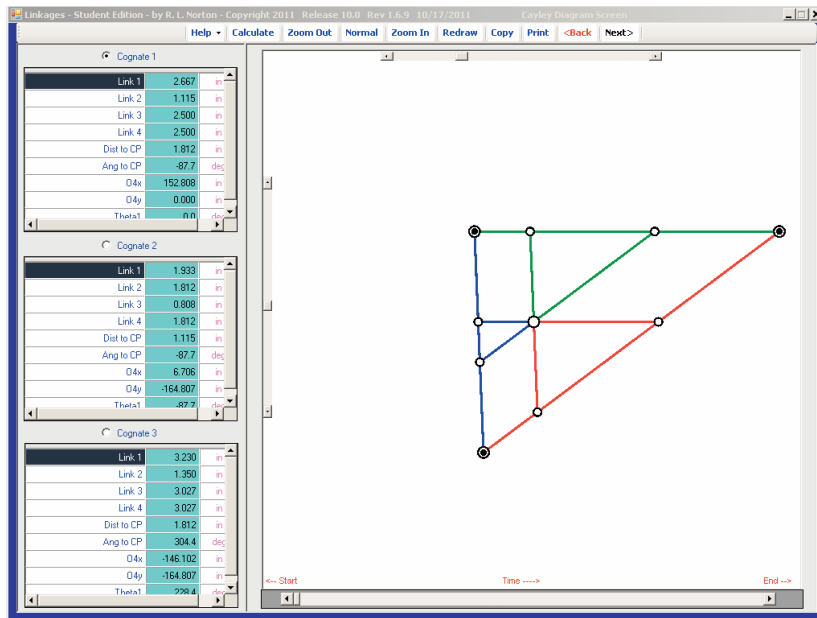
FIGURE 16

Fourbar linkage Cayley diagram screen

tion 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 and their dimensions. See Figure 16. 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)

The program will synthesize a fourbar linkage for two- or three-positions of the coupler, each with a choice of two methods. See Chapter 5 in Design of Machinery for a discussion of these methods and derivations of the equations used. Figure 17 shows he Synthesize Screen, which is accessed from the Calculation Type dropdown menu on the Input screen. See Figure 4. (Note that this menu may be labeled Constant Velocity, Constant Acceleration, or One Position depending on your most recent choice of calculation type.) Figure 16 shows the Synthesize screen set up for a three position sythesis problem. The synthesis parameters are input at upper left and the resulting linkage geometry is reported at upper right with the necessary initial conditions defined below. All the animation features of the Input screen are provided on this screen as well.
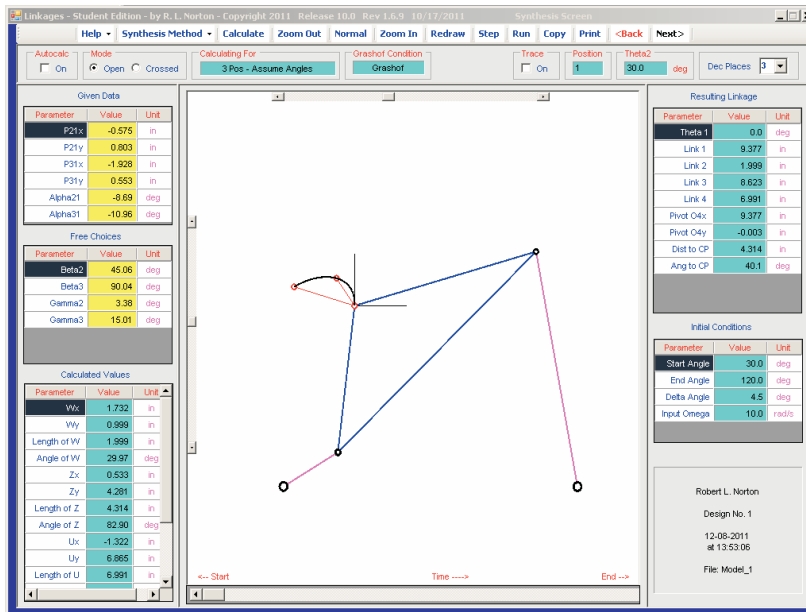
FIGURE 17

Fourbar linkage Synthesis screen

GEARED FIVEBAR LINKAGE

Linkage Geometry and Parameters

The geared fivebar mechanism (GFBM) requires more input data than for the fourbar mechanism. Five link lengths must be supplied as shown in Figure 18: driver crank (link 2), first coupler (link 3), second coupler (link 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 18. 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 scre*en as shown in Figure 19. This screen is activated by selecting the *LinkageType* button on the *Home* screen and then selecting the fivebar linkage. When you open this screen for the first time, it will

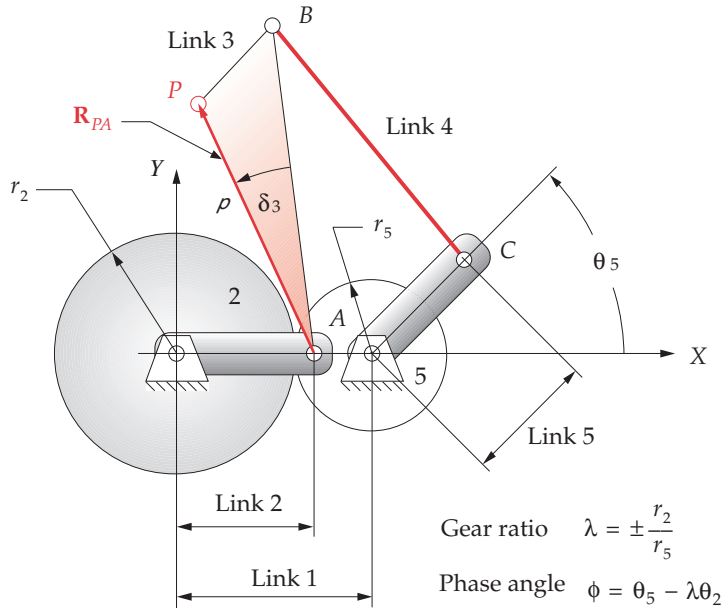_____

* The ZNH Atlas is on the DVD.

FIGURE 18

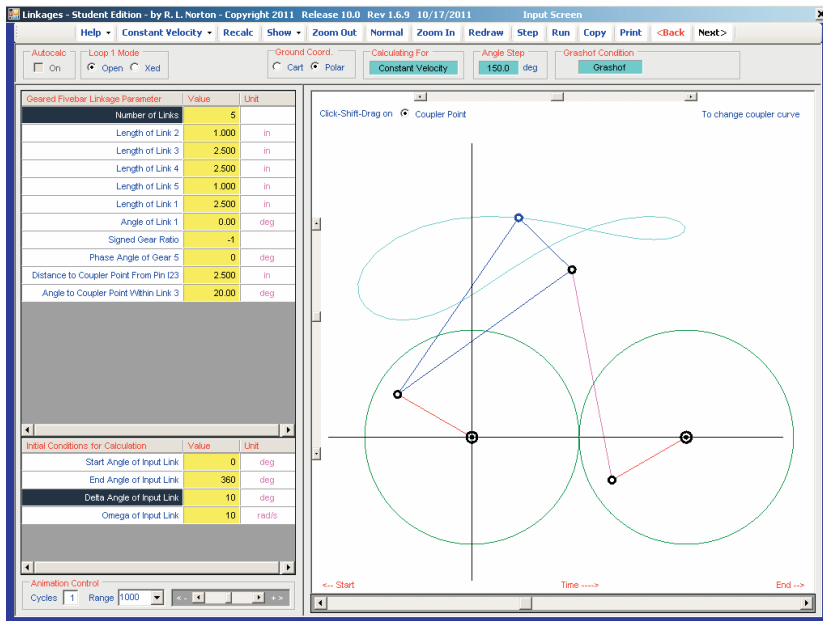Geometry data for a geared fivebar linkage.

FIGURE 19

Fiverbar linkage Calculate screen

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 left corner of the screen, one of *Constant Velocity, Constant Acceleration*, or *One Position* as shown in Figure 6. The *Recalc* 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 *Redraw* button will bring back the image.

After you have calculated the linkage. you can run the linkage through any range of motion to observe its behavior using the *Step* and *Run* buttons or the *Slider Control* at the bottom. You can change any of the linkage parameters and then recalculate with the *Recalc* button. The *Next* button returns you to the *Home* screen. The *Plot* and *Print* buttons will now be available and work as described previously.

Dynamics

Input data for dynamics calculation in a FIVEBAR are similar to that for a FOURBAR with the addition of one more link. See Figures 12 and 13 and their discussion for more information.

Flywheel

The Flywheel Screen is the same for all linkages, See Figure 15 and its discussion.

WATT II SIXBAR LINKAGE

Linkage Geometry and Parameters

The **Watt's II** mechanism is shown in Figure 20 with the program's 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 Figure 20. 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 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 Figure 20. The stage 2 data are: second crank, second coupler, second rocker, corresponding respectively to links 4b, 5a, and 6 in Figure 20. The angle δ_4 that the second crank (4b) makes with the first rocker (4a) is also required. Note that this angle obeys the right-hand rule as do all angles in the program. Two coupler points may 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 the FOURBAR. A 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 20. The second coupler point F is on link 5 and is
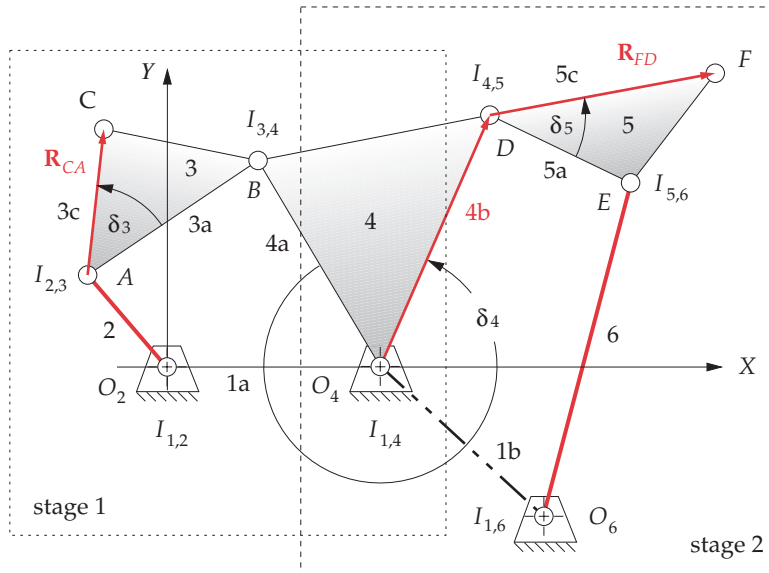
FIGURE 20

Input data for the Watt's II sixbar linkage

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 $I_{1,2}$.

Basic data for the Watt II Sixbar linkage is defined on the *Input scre*en as shown in Figure 21. This screen is activated by selecting the *LinkageType* button on the *Home* screen and then selecting the Watt II Sixbar Linkage. 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 left corner of the screen, one of *Constant Velocity, Constant Acceleration*, or *One Position* as shown in Figure 6. The *Recalc* 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 *Redraw* button will bring back the image.

After you have calculated the linkage. you can run the linkage through any range of motion to observe its behavior using the *Step* and *Run* buttons or the slider control at the bottom. You can change any of the linkage parameters and then recalculate with the *Recalc* button. The *Next* button returns you to the *Home* screen. The *Plot* and *Print* buttons will now be available and work as described previously.
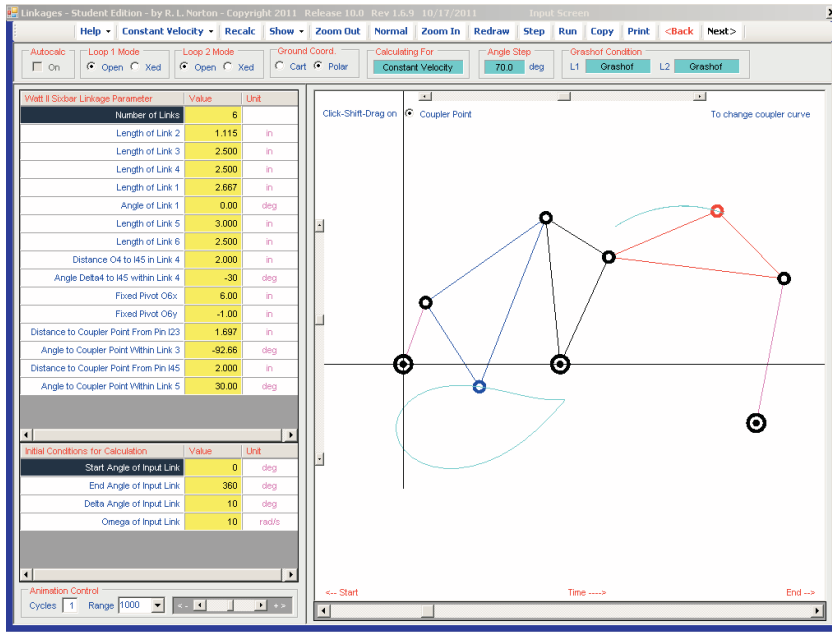
FIGURE 21

Watt II sixbar linkage Calculate screen

STEPHENSON'S III LINKAGE

Linkage Geometry and Parameters

The **Stephenson's III** mechanism is shown in Figure 22 with its input parameters defined. The stage 1 data for the Stephenson's linkage is similar to that of the Watt 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 22. The link lengths in stage 2 of the linkage are: second coupler and second rocker corresponding, respectively, to links 5a and 6 in Figure 22.

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 also required. These are with respect to the global *X,Y* axis system.

Basic data for the Stevenson III Sixbar linkage is defined on the *Input scre*en as shown in Figure 23. This screen is activated by selecting the *LinkageType* button on the
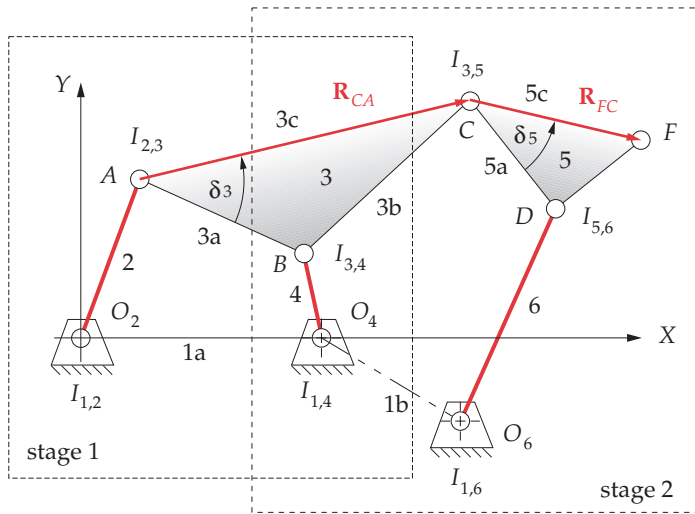
FIGURE 22

Input data for Stephenson's III linkage

Home screen and then selecting the Stevenson III Sixbar Linkage. 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.
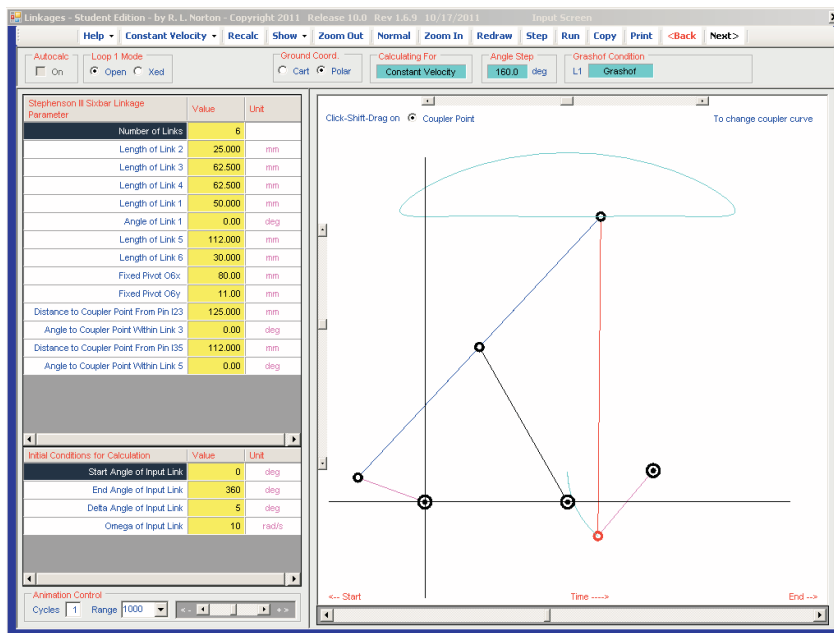

FIGURE 23

Stevenson III sixbar linkage Calculate screen

Select the type of calculation desired in the upper left corner of the screen, one of *Constant Velocity, Constant Acceleration*, or *One Position* as shown in Figure 6. The *Recalc* 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 *Redraw* button will bring back the image.

After you have calculated the linkage. you can run the linkage through any range of motion to observe its behavior using the *Step* and *Run* buttons or the slider control at the bottom. You can change any of the linkage parameters and then recalculate with the *Recalc* button. The *Next* button returns you to the *Home* screen. The *Plot* and *Print* buttons will now be available and work as described previously.

Dynamics

Input data for dynamics calculation in SIXBAR are similar to that for program FOURBAR with the addition of two links. See Figures 12 and 13 and their discussion for more information.

Flywheel

The Flywheel Screen is the same for all linkages, See Figure 15 and its discussion.

FOURBAR SLIDER

Linkage Geometry and Parameters

The Fourbar Slider geometry and parameters are defined in Figure 24. 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 $I_{1,2}$
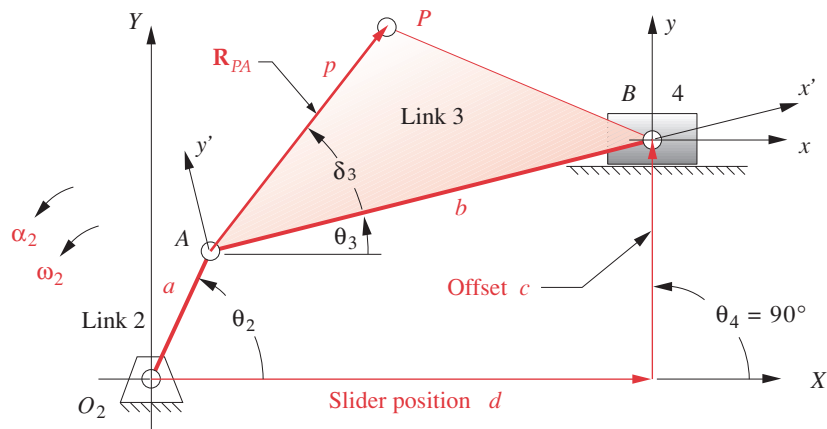

FIGURE 24

Input data for Program SLIDER

(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 24. 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.

Data for the slider linkage are defined on the *Input scre*en, (Figure 25) which is activated by selecting the *LinkageType* button on the *Home* screen and then selecting the Fourbar Slider Linkage. 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.
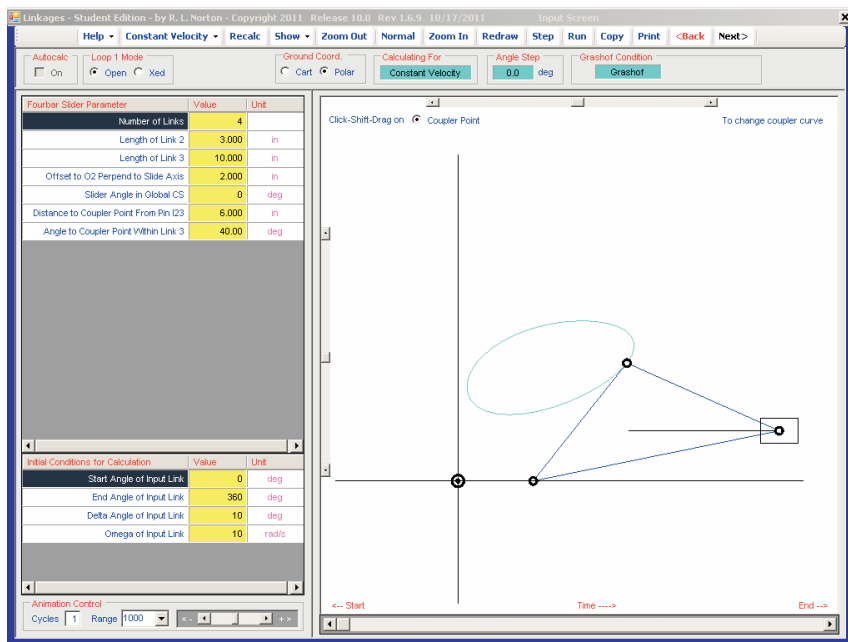

FIGURE 25

Fourbar Slider linkage Calculate screen

Calculation

See the description of calculations for the FOURBAR for more information. They are similar in SLIDER. Select the type of calculation desired in the upper left corner of the screen, one of *Constant Velocity, Constant Acceleration*, or *One Position* as shown in Figure 6. The *Recalc* 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 *Redraw* button will bring back the image. After you have calculated the linkage. you can run the linkage through any range of motion to observe its behavior using the *Step* and *Run* buttons or the slider control at the bottom. You can change any of the linkage parameters and then recalculate with the *Recalc* button. The *Next* button returns you to the *Home* screen. The *Plot* and *Print* buttons will now be available and work as described previously.

Dynamics

Input data for dynamics calculation in SLIDER are similar to that for program FOUR-BAR. See Figures 12 and 13 and their discussion for more information.

Flywheel

The Flywheel Screen is the same for all linkages, See Figure 15 and its discussion.

ENGINE/COMPRESSOR

ENGINE is an internal combustion (IC) engine and air compressor 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. It 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 14 of Design of Machinery. Please consult them for an explanation of the theory and mathematics involved.

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 *Calculate* 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.

   Data for the Engine mechanism are defined on the *Engine Input* screen, (Figure 26) which is initially activated by selecting the *LinkageType* button on the *Home* screen and then selecting *Engine/Compresssor*. 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.

THE *CALCULATE* BUTTON   on the *Home* screen brings up the *Engine Input* screen shown in Figure 26 provided that *Engine/Compressor* was selected on the *LinkageType* screen. Default data are present in all entry boxes.   Device type can be set to either an IC engine or compressor. The principal difference between these two choices is the magnitude of the cylinder pressure used in the calculations, which can be changed at lower left. 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 bottom of the left panel.

Text boxes in the *Engine Geometry Panel* on the upper left allow typing of the cylinder displacement, bore, stroke, and conrod/crank (*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. Changing the strokewill force a change in bore, keeping the specified displacement. The bore/stroke ratio is calculated and displayed at upper right.
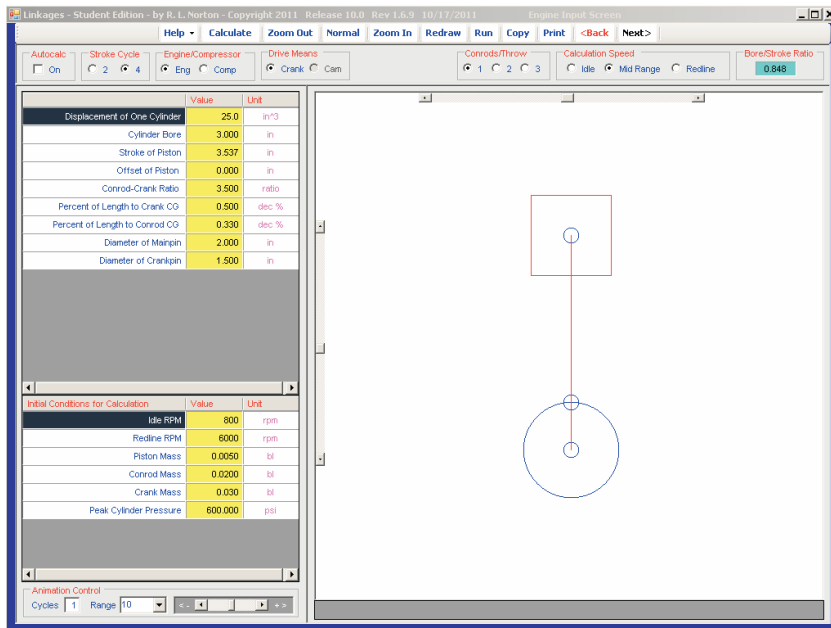

FIGURE 26

Engine Input screen

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. 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. This gas pressure function in the program is kept the same at all engine speeds as discussed in Section 13.1. 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 on the Engine Input screen 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.

Balancing the Crank (*Engine Balance* Screen)

The *Balance* button on the *Home Screen* brings up the *Engine Balance* screen shown in Figure 27. The left panel 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. After calculating 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 left sidebar. These data provide enough information to determine the counterweight parameters needed to either exactly balance or optimally overbalance the single-cylinder engine. Three yellow text boxes at the lower 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 inertial 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.
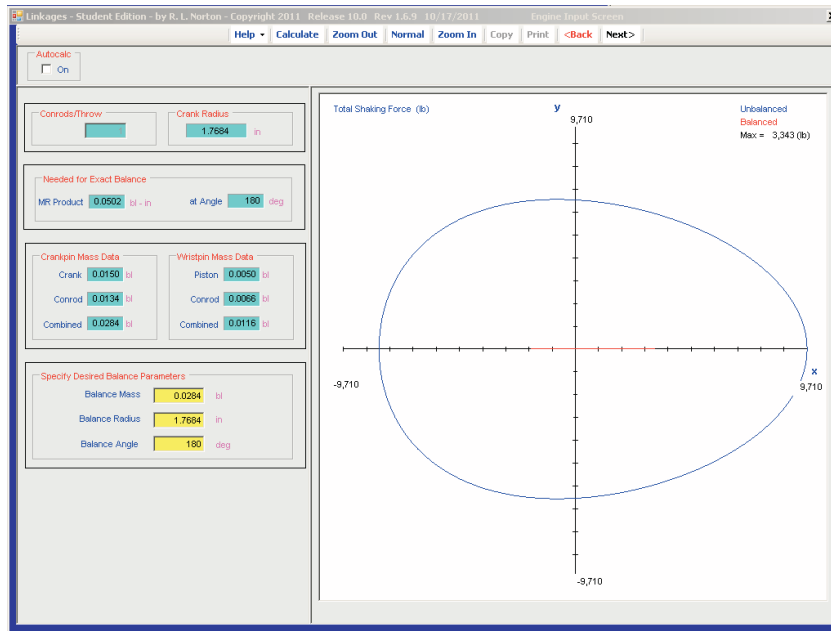
FIGURE 27

Engine Balance screen

Assembling a Multicylinder Engine (*Engine Assemble* Screen)

Once the single-cylinder configuration is satisfactorily designed and balanced, the engine can be assembled. Figure 28 shows the *Engine Assemble* screen used for assembly of a multicylinder engine. Its *Help* button brings up information on how to use this screen, pointing out that the crank phase diagram (called a **Power Chart**) as defined in Section 14.2 and shown in Figures 14-9, 14-12, 14-14, 14-16, 14-18, and 14-24 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 stated on the *Help/Guidelines* screen. These are the same conventions as were defined in Section 14.2 of the text. The upper limit stated in item 7 of the *Guidelines* 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 left of the *Engine Assemble* screen based on an arrangement according to the rules in the *Guidelines*. Note that **the program does not do any internal check on the compatibility of these 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. If you want to compute the correct magnitude of the shaking moment, the actual cylinder spacing of your design
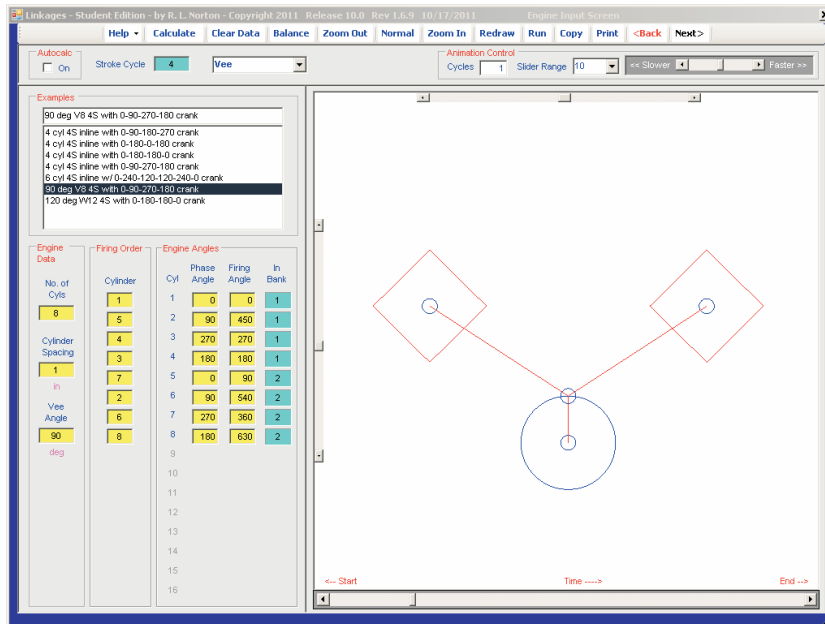
FIGURE 28

Engine Assemble screen

needs to be supplied in the box at the left of the screen in Figure 28. 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 on Home Screen)

The *Charts* pull-down menu on the *Home Screen* shows several summaries of engine information. 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 for force balance; 14.7a and 14.7b for moment balance; and 14.5a, 14.5b, and 14.5c 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 29. The top plot shows the crankshaft phase angles over 360° for the 90° vee-eight engine designed in Section 14.7. The middle plot 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 and indicates when the power pulses will occur in each cylinder during the cycle. The bottom plot shows the power stroke angles in firing order over 720°. This 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*.
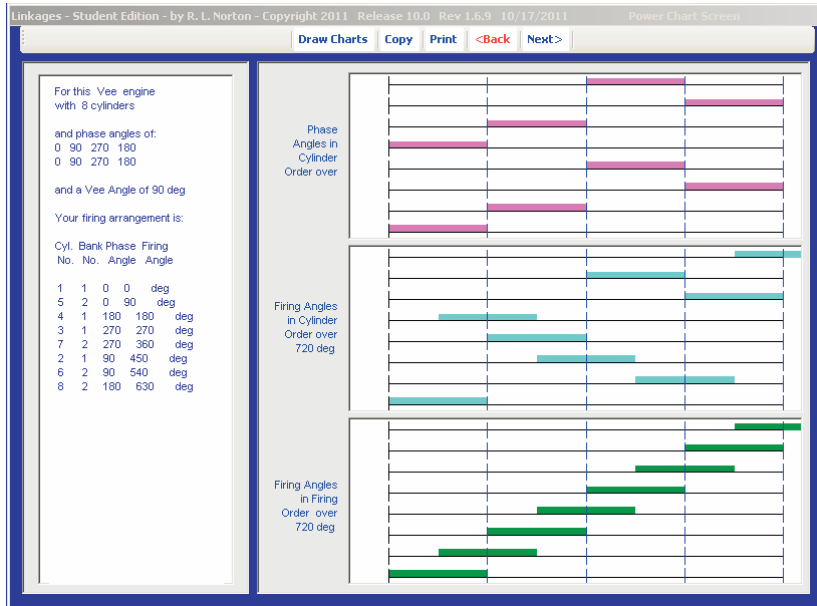
FIGURE 29

Engine Power Charts

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 are not drawn.

Flywheel Calculations (Flywheel Button)

Figure 30 shows the *Flywheel Data* screen for an engine. The only input to this screen is the flywheel coefficient of fluctuation which must be between 0 and 1. When the *Calculate* button is clicked, it does the same pulse-by-pulse integration of the total torque curve as is done for all the linkages. See Section 11.11 and Figure 11-11. The flywheel size is based on these integral values as defined in Section 11.11.

The total torque curve for an example vee-eight engine is shown in the plot of Figure 30. The areas under its pulses are shown in the table at the right of the screen and are a measure of energy variation in the cycle. 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 to compute the required flywheel moment of inertia based on a chosen coefficient of fluctuation k.

The program calculates a smoothed total torque function by multiplying the raw torque by the specified coefficient of fluctuation. The second plot in Figure 30 shows
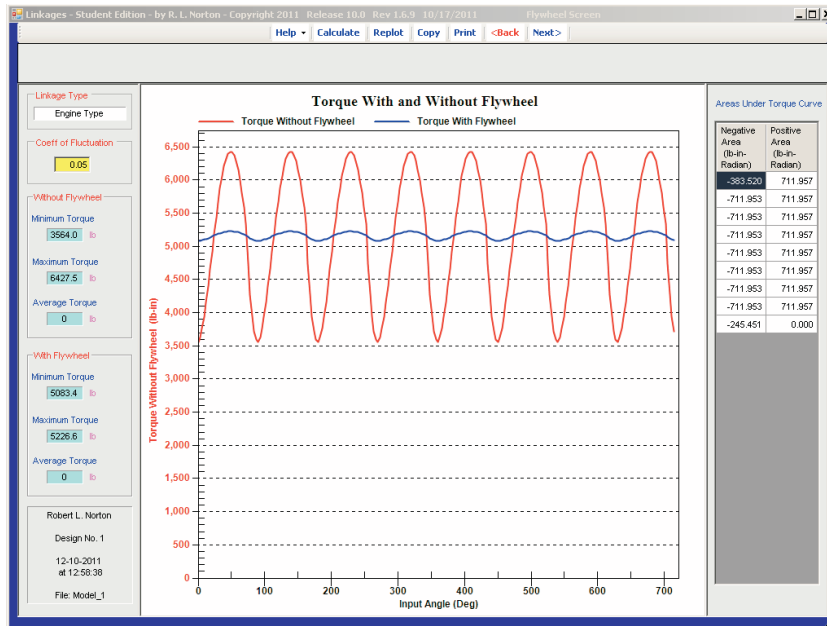
FIGURE 30

Engine flywheel screen

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.