SOLUTIONS MANUAL

KINEMATICS AND DYNAMICS OF MACHINERY

THIRD EDITION

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A Guide for Instructors

In solving the problems, Dr. Sadler and I used various analytical and graphical methods, aided by various types of software. It is expected that professors assigning problems from the text will select solution methods and software in accordance with goals they have set for their students. Although we have used reasonable care in solving the problems, errors always creep in. We will be grateful for any corrections or comments related to the text or this guide.

If you recently taught kinematics and dynamics of machinery, you have probably already decided on the course content based on the needs and abilities of your students. And, you may have a wealth of material to supplement the course based on your teaching experience, industrial experience, research, or consulting. The comments that follow are for professors who have not taught the course recently, or wish to revise the content.

Goals for Your Students; Encouraging Students to Think

Thomas Edison said that "All progress, all success, springs from thinking." But in his laboratory, Edison posted a quote from Sir Joshua Reynolds: "There is no expedient to which a man will not resort to avoid the real labor of thinking." We often face a similar problem. Some of our students calculate the solution to an academic exercise without understanding why the problem was assigned, and with little understanding to the meaning and significance of their answer. It may be impossible to teach our students how to think. But we can assign tasks that encourage them to think as engineers must think. We can ask students to

- identify a need
- propose a linkage or some other system to meet that need
- perform some of the tasks required to design that component or system
- analyze a tentative design: determine motion, velocity, acceleration and forces including inertial effects
- interpret the results of their analysis
- propose changes to improve that design
- communicate their results through written and oral reports, graphs, and motion simulations and field questions related to the significance of their analysis

Each chapter has a few homework problems designed to encourage in-depth analysis and thinking. Motion simulation software and mathematics software relieve the user of repetitive calculations, and allow a more thorough presentation of results. Students can examine linkages through a full cycle of motion, or evaluate the effect of an array of possible design changes. For example, we can ask students to design a crank-rocker linkage to produce a given range of output motion, while optimizing transmission angle. We can ask students to look into a series of reverted gear trains for producing a range of speed reductions, while using minimum tooth numbers consistent with avoiding interference. Or they can plot and examine a large number of coupler curves in an attempt to design a linkage with specified motion requirements.

Developing a Syllabus for a Course in Kinematics and Dynamics of Machinery

Every topic in the text was added or retained on the recommendation of one or more reviewers. Nevertheless, a typical course in kinematics and dynamics of machinery does not allow enough time to cover all of the topics in the text. Obviously, the desired outcomes of your course will govern your selection of topics to emphasize, topics to cover quickly, and topics to delete. I can only offer a few suggestions based on my own goals for a course of kinematics and dynamics of machinery and my interpretation of the criteria of the Accrediting Board for Engineering Technology (ABET).

A Few Comments on Selection of Topics

Chapter 1

You may find the following topics important as a basis for further study: computer use; terminology and definitions; degrees of freedom; Grashof criterion; transmission angle. If motion simulation software is available, students can simulate the motion of various classes of four-bar linkages, verifying the Grashof criterion. You may want to assign one of the homework problems that requires a contour plot showing an envelope of acceptable linkage proportions based on range of motion and transmission angle. If time is short, you may want to delete topics like limiting position of offset slider crank linkages, and put the section on mechanisms for specific applications in a "read only" category. Numerical procedures are now incorporated in various software packages; there is no need for students to write numerical method programs unless programming is a specific goal of the course.

Chapter 2

Important items include unit vectors, dot and cross product, and vector differentiation. Vectors are useful for solving planar linkages, and the only practical way to solve spatial linkages. For students already proficient in simple vector operations a quick review is all that is needed. If graphical methods are emphasized, position analysis of planar linkages is a trivial exercise. If you intend to rely on motion simulation software for planar linkage analysis, then position calculations are not absolutely necessary. But, I prefer to have the students spot-check results obtained with motion simulation software. Although it seems complicated, I prefer the cross-product method for position analysis of planar four-bar linkages. If the cross-product method is selected, it is not necessary to teach the dot product method. Complex number methods offer no advantages over other methods of position analysis. But complex number methods can be introduced at this point if you intend to use them for velocity and acceleration analysis.

A graphical method can be used to check analytical position analysis of a spatial linkage for one instant in time. But it is not an easy task. I prefer to skip graphical analysis of spatial linkages entirely, relying on verification tests that can be built into a computer solution.

Chapter 3

Important topics include the vector cross product equations for velocity, particularly for spatial linkages. Matrix methods for solving a set of linear differential equations are important too, but this will be a quick review for some.

I think that analytical velocity analysis should be included, even though it is not absolutely necessary if you intend to rely on motion simulation software for planar linkage analysis. My personal preference is the complex number method, but there is strong support for vector methods as well. If your students use mathematics software that solves matrices directly, they will not need determinant methods, except possibly for use on tests where computers are unavailable.

A velocity polygon can be used to spot-check analytical results and motion simulation plots at one instant in time. Unless you want to concentrate on graphical methods, you will probably cover velocity polygons briefly, and eliminate centro methods entirely. Kinematics analysis using spreadsheets will probably be eliminated unless you want to introduce spreadsheets for use in other courses.

Chapter 4

I think that analytical acceleration analysis should be included, even though it is not absolutely necessary if you intend to rely on motion simulation software for planar linkage analysis. Again, I prefer the complex number method, but if you specified vector methods for velocity analysis, you will want to specify vectors for acceleration as well. Unless you want to concentrate on graphical methods, you may want to skip acceleration polygons. Results obtained from analytical acceleration calculations and motion simulation software can be checked by numerical differentiation of the results of analytical velocity analysis. Acceleration analysis using spreadsheets will probably be eliminated unless you plan to use spreadsheets for other courses as well.

Chapter 5

Important points include the boundary conditions required to generate "good" cams. You will probably want to emphasize cycloidal motion and 5^{th} order and 8^{th} order polynomial motion. You may want to skip graphical construction of cam profiles, since it is not a step in the generation of actual cams. You will probably allot a few minutes to harmonic, parabolic, and constant acceleration follower motion, showing why these motion forms are inferior. The theory of envelopes is an advanced topic—its inclusion depends on how much time you have to cover cams.

Chapter 6

Gear nomenclature, tooth proportions, and standard pressure angles are essential topics. Interference and contact ratio are also important, as are free-body diagrams of individual gears showing forces and torques. Ask your students to evaluate their results and make design changes where indicated. For example, if a tentative design results in interference, have them suggest changes to correct this problem. Gear topics should be coordinated with machine design courses to ensure adequate coverage without excessive repetition.

Chapter 7

Helical gears on parallel shafts and worm drives deserve the most emphasis. Thrust forces on helical gears, and balancing of thrust forces in helical gear countershafts are important topics. If time is limited, other types of gears may be placed in the "read only" category. Again, topics should be coordinated with machine design courses to ensure adequate coverage without excessive repetition.

Chapter 8

Speed ratios in planetary and non-planetary gear trains are important. The superposition method for analyzing planetary trains is nice because its tabular form allows for adding gear dimensions, forces, torques, and power. But the formula method for analyzing planetary trains is best for analyzing differentials. If you do not have the luxury of teaching both methods, the formula method is probably the best choice. Important also are free body diagrams of individual gears, and a torque balance of planetary train. You will probably want to assign a study showing the speed ratio of a series of proposed planetary train designs, and the number of planets that will produce a balanced train in each case. If time is short, you may have to skip chain drives, friction drives, and gear train diagnostics based on noise and vibration frequencies.

Chapter 9

Important topics include analytical static-force analysis and computer-aided simulations. Unless you intend to emphasize graphical methods throughout, graphical examples can be treated as demonstrations and as a means to develop analytical models.

Chapter 10

Important topics include analytical dynamic-force analysis and computer-aided simulations. D'Alembert's principle is the key because it transforms a dynamics problem into a statics-type problem. Unless you intend to emphasize graphical methods throughout, graphical examples can again be treated as demonstrations and as a means to develop analytical models. Motion simulation software will be particularly helpful in determining dynamic motion analysis for an assumed input torque. You may choose to skip balancing, particularly if this topic is covered in another course.

Chapter 11

Important topics include two- and three-position synthesis, design of a function generator, and coupler curves. The results of three-position synthesis can be checked with motion simulation software. If you have used complex numbers for velocity and acceleration analysis, your students will probably prefer the complex matrix method for design of a function generator. Design of a function generator may involve many attempts and a long time in front of a computer if the end-result is to have continuous motion and acceptable transmission angles. If motion simulation software is available, students can generate a large number of coupler curves before selecting the best one for a specified application. You may want to skip velocity and acceleration synthesis by the complex number method. It is an interesting exercise, but has little practical value.

Chapter 12

Important topics include degrees of freedom and transformation matrices. Motion simulation software may be used to analyze simple manipulators with planar motion. If a separate course in robot design is offered, you will probably assign only a small part of this chapter, if any.

Projects

Projects can be rewarding if time allows. They can approximate real-world engineering design practice, and allow for more imagination and creativity than standard homework problems. A few project suggestions follow the problem sections in some chapters. Additional projects can be developed from your research or consulting. Or, you can base projects on articles in engineering periodicals. If you use group projects, oral reports and questions to individual members of the group will help you evaluate each student's degree of participation level of understanding.

General Comments

Working smart

Encourage your students to work smart by becoming familiar with mathematics software as early as possible. Tell them to include titles and descriptive comments in their work so that they can refer to it later. Do not let them lose sight of the underlying engineering principles and mathematical concepts, and the implications of their results. If our students do not understand what they are doing and why they are doing it, they are wasting their time and our time as well.

Work smart yourself by including self-verifying steps in problems. For example, consider analysis of a planar or spatial linkage. Require the students to check for closure of the vector loop at some instant in time. Can they check their acceleration analysis by numerical differentiation?

Problems, answers, and examinations

In most cases, a given concept is evaluated by two or three problems so that you do not have to assign the same homework problem term after term. Partial answers are given for most of the odd-numbered problems. If you give open-book examinations that include text problems, you might select even-numbered problems for the examinations, and odd-numbered problems for homework. In each chapter, those problems near the end of the problem set are likely to involve detailed analysis and plotting and include self-verification of some results.

I hope that your course in kinematics and dynamics of machinery is challenging and rewarding to your students. And, may you find satisfaction in sharing your knowledge with them.

CHARLES E. WILSON
New Jersey Institute of Technology

Chapter 1
Mechanisms and Machines: Basic Concepts

1.1 a. The ball-joint (spherical pair) has three degrees-of-freedom, the prismatic pair one, and the cylindrical pair two. The number of degrees-of-freedom of the spatial linkage is given by

$$DF_{(spatial)} = 6(n_L - n_J - 1) + \Sigma f_i$$

$$= 6(4 - 3 - 1) + 3 + 1 + 2$$

$$= 6 \text{ degrees-of-freedom}$$

(We do not need the inequality sign for this open-loop chain).

b. Treating the construction equipment schmatic as a spatial linkage:

$$DF_{(spatial)} \geq 6(n_L - n_J - 1) + \Sigma f_i$$

$$\geq 6(9 - 11 - 1) + 9 + 2 \times 2$$

$$DF_{(spatial)} \geq -5$$

c. Treating the construction equipment schematic as a planar linkage, where a sliding pair has only one degree-of-freedom in plane motion:

$$DF_{(planar)} = 3(n_L - n_J - 1) + \Sigma f_i$$

$$DF_{(planar)} = 3(9 - 11 - 1) + 9 + 2$$

$$DF_{(planar)} = 2$$

d. The planar motion assumption applies if motion occurs in a plane or in a set of parallel planes. The planes of motion of the links must all be parallel. The revolute joint axes must be perpendicular to those planes. These conditions do apply to the construction machinery. The operator controls the linkage via the two hydraulic cylinders.

1.2(a) For the linkage as sketched originally,

$DF = 3(n_L-1) - 2n_{J'} = 3(9-1) - 2x12 = 0$

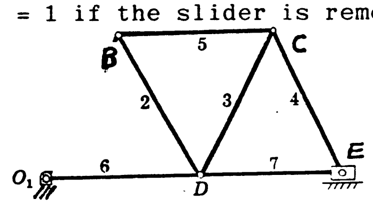
a) Removing any single link (one through seven) reduces n_L by one and $n_{J'}$ by two from which

$DF = 3(8-1) - 2x10 = 1.$

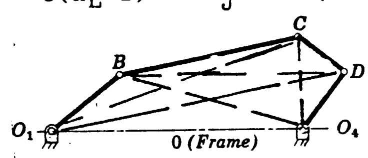
b) Also, we obtain DF = 1 by removing links 1, 2 and 5; or 3, 4 and 5; or 1, 2, 3, 4, and 5.

c) DF = 1 if all links are removed except link 1, or 6 or the slider.

d) DF = 1 if the slider is removed, but the joint at E retained.



1.2(b) Add one link extending from O_1 to C, or B to D, or C to O_4, or B to O_4, or O_1 to D. Then, $DF = 3(n_L-1) - 2n_J' = 3(6-1) - 2x7 = 1.$



1.3 Stroke length S = 2R.

$v_{(avg)} = 2Sn = 2(4\text{ in})(3000\text{ rev/min}) = 24{,}000\text{ in/min or }400\text{ in/sec}).$

1.4 R = 2, L = 4, E = 1 in. $\omega = \frac{2\pi}{60}(3000) = 314$ rad/sec

Referring to fig. 1.16

$\phi_1 = \arcsin E/(L-R) = 30^o.$

$\phi_2 = \arcsin E/(L+R) = 9.6^o.$

$\alpha = 180^o + \phi_1 - \phi_2 = 200.4^o$ or 3.50 rad.

$\beta = 180^o - \phi_1 + \phi_2 = 159.6^o$ or 2.79 rad.

Stroke $S = [(L+R)^2 - E^2]^{1/2} - [(L-R)^2 - E^2]^{1/2} = 4.184$ in.

"Forward" stroke time $t_1 = \alpha/\omega = 0.01114$ sec. $v_{1(avg)} = S/t_1 = 375.5$ in/sec.

"Return" stroke time $t_2 = \beta/\omega = 0.00889$ sec. $v_{2(avg)} = S/t_2 = 470.6$ in/sec.

1.5 (see 1.4) $\phi_1 = 48.5^o$, $\phi_2 = 14.5^o$, $\alpha = 3.73$ rad, $\beta = 2.55$ rad.

$S = 4.49$ in, $t_1 = 0.01187$ sec, $v_{1(avg)} = 378$ in/sec.

$t_2 = 0.00812$ sec, $v_{2(avg)} = 553$ in/sec.

1.6 $\omega = 3000\ \pi/30 = 314.16$ rad/s

$$\phi_1 = \arcsin\ (E/(L-R))$$
$$= \arcsin\ (50/(200-100)) = .5236 \text{ rad}$$
$$\phi_2 = \arcsin\ (E/(L+R))$$
$$= \arcsin\ (50/(200+100)) = .1674 \text{ rad}$$

$\alpha = \pi + \phi_1 - \phi_2 = 3.4977$ rad $\quad \beta = \pi - \phi_1 + \phi_2 = 2.7854$ rad

Forward stroke time $t_1 = \alpha/\omega = .01113$ s.

Return stroke time $t_2 = \beta/\omega = .008866$ s.

Stroke $S = \sqrt{(L+R)^2 - E^2} - \sqrt{(L-R)^2 - E^2} = 209.20$ mm

Avg. vel. forward $v_{1(avg)} = S/t_1 = 18790$ mm/s

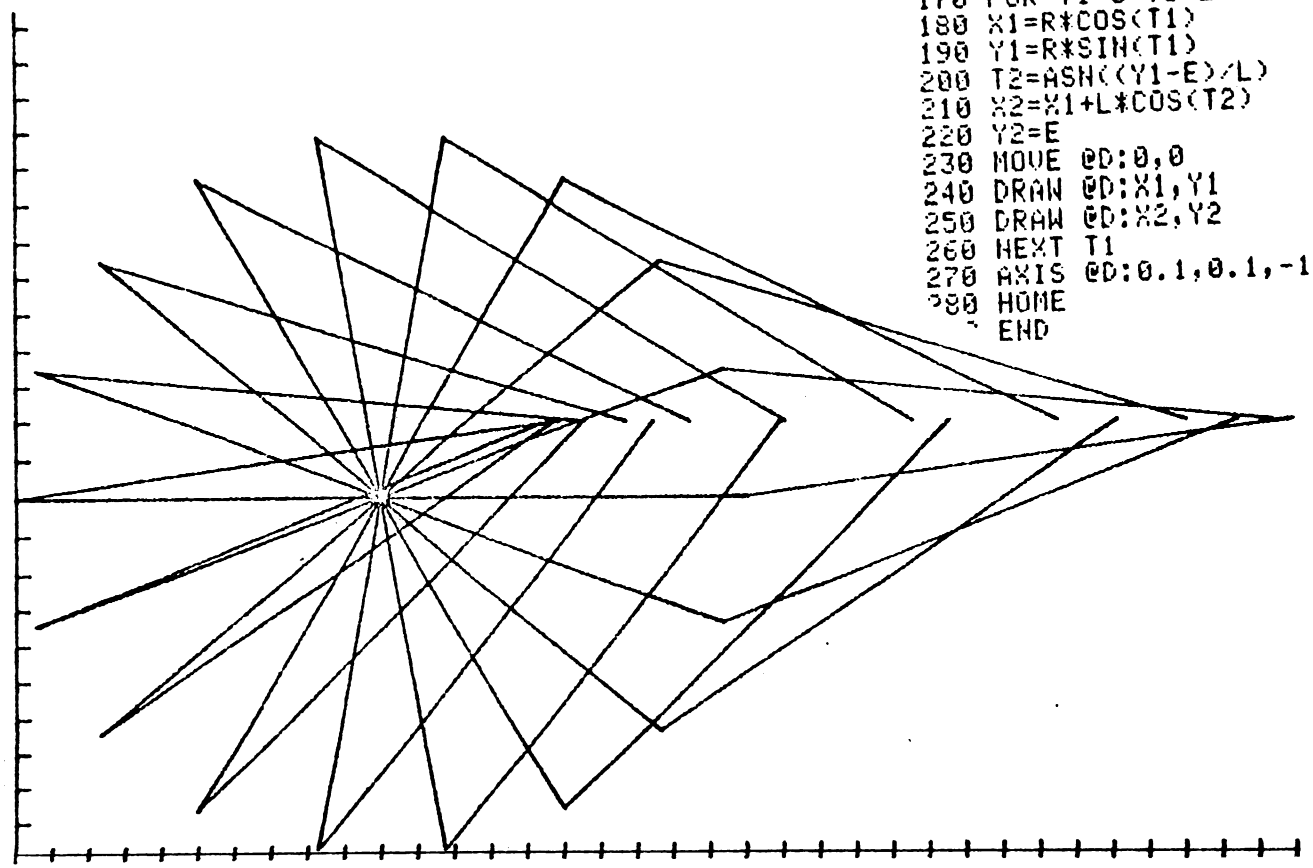
Avg. vel. return $v_{2(avg)} = S/t_2 = 23595$ mm/s

1.7 The crank and connecting rod positions are determined as in the flow chart. The linkage skeleton diagram is shown on the sketch for L/R=1.5, E/R=0.2 where crank angle T_1 varies from 0^o to 340^o in 20^o steps.

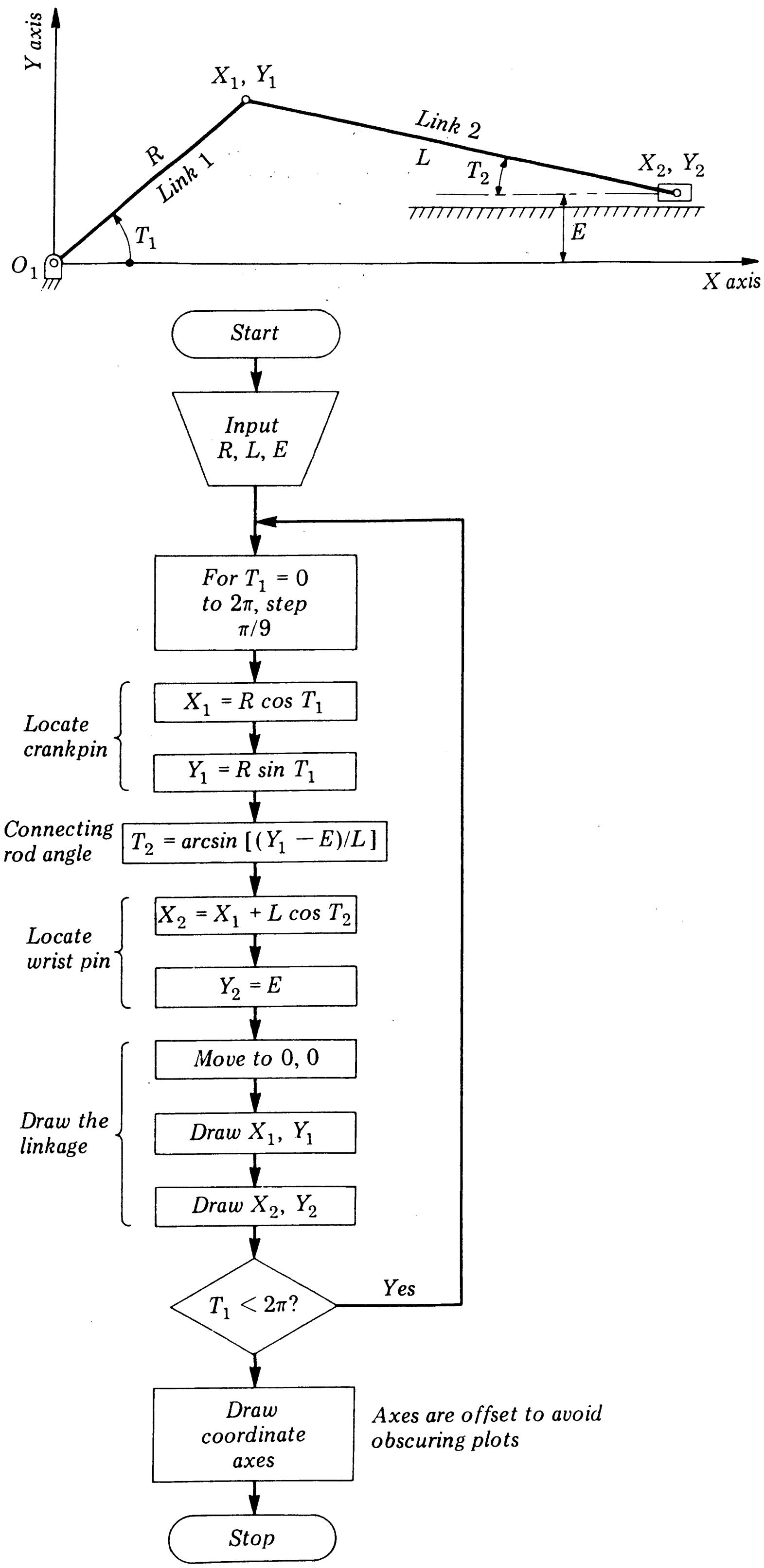
Angles T_1 and T_2 and slider location X_2 are tabulated below for R=1:

T1	T2	X2
0	-7.66225566077	2.48660687473
20	5.43290764513	2.43295424518
40	17.1690352815	2.19920149408
60	26.3604597467	1.84402758957
80	31.5474944957	1.45195830359
100	31.5474944957	1.12466195325
120	26.3604597467	0.844227589566
140	17.1690352815	0.667112607638
160	5.43290764513	0.553569803609
180	-7.66225566076	0.4866026874732
200	-21.1829283574	0.438954641475
220	-34.1844166885	0.474805686816
240	-45.2985623587	0.555267662011
260	-52.1735359216	0.746259740205
280	-52.1735359216	1.09355610154
300	-45.2985623587	1.55526766291
320	-34.1844166865	2.80689457325
340	-21.1829283574	2.38833968325
360	-7.66225566877	2.48668687473

```
120 R=1
130 L=1.5
140 E=0.2
150 WINDOW -1,2.5,-1.346,1.346
160 VIEWPORT 0,130,0,100
170 FOR T1=0 TO 2*PI STEP PI/9
180 X1=R*COS(T1)
190 Y1=R*SIN(T1)
200 T2=ASN((Y1-E)/L)
210 X2=X1+L*COS(T2)
220 Y2=E
230 MOVE @D:0,0
240 DRAW @D:X1,Y1
250 DRAW @D:X2,Y2
260 NEXT T1
270 AXIS @D:0.1,0.1,-1,-1
280 HOME
  END
```



1.7



1.7 Flow chart.

1.8 5000 rev/min x1min/60s x 360°/rev x 0.002s = 60°

From the tabulated data or the figure, the piston moves from

x_2 = 2.4866R to 1.8440R = -0.6426R

= 64.26 mm to the left as the crank rotates from T_1=0 to 60°.

Average velocity during the interval is

64.26 mm/0.002s =32,600 mm/s

= 32.6 m/s (ans)

to the left.

1.9 Angles T_1 and T_2 (degrees) and slider location X_2 are tabulated below for R=1:

T1	T2	X2
0	-12.8395884069	2.75499287748
20	-1.84587544996	2.73875858295
40	7.75179688929	2.54959544598
60	15.2249801317	2.2386259871
80	18.9591044355	1.87599946124
100	18.9591044355	1.52872310571
120	15.0049801317	1.2386259871
140	7.75179688929	1.01750655824
160	-1.84587544996	0.859373341279
180	-12.8395884069	0.754992877478
200	-24.3452117363	0.722248264398
220	-35.4031826419	0.701127687127
240	-44.6961999153	0.779523222322
260	-50.294446759	0.976263119063
280	-50.294446759	1.3235644734
300	-44.6961999153	1.77952322252
320	-35.4031826419	2.23321655337
340	-24.3452117363	2.57963352597
360	-12.8395884069	2.75499287748

1.10 a) The time interval is $\Delta t = (40^\circ \times \frac{\pi \text{ rad}}{180^\circ})/\omega$ rad/s

The displacement, from the solution to the above problem, is $\Delta x = (2.5496 - 2.7550)R$

$$v_{avg} = \Delta x/\Delta t = \frac{(2.5496 - 2.7550)50}{(40\pi/180)/500}$$

v_{avg} = -7355 mm/s (7355 mm/s to the left). (ans)

1.10 b) $v_{avg} = \Delta x/\Delta t = \dfrac{(.7545 - 2.7545)R}{\pi/\omega}$

$= -2\ R\omega/\pi$

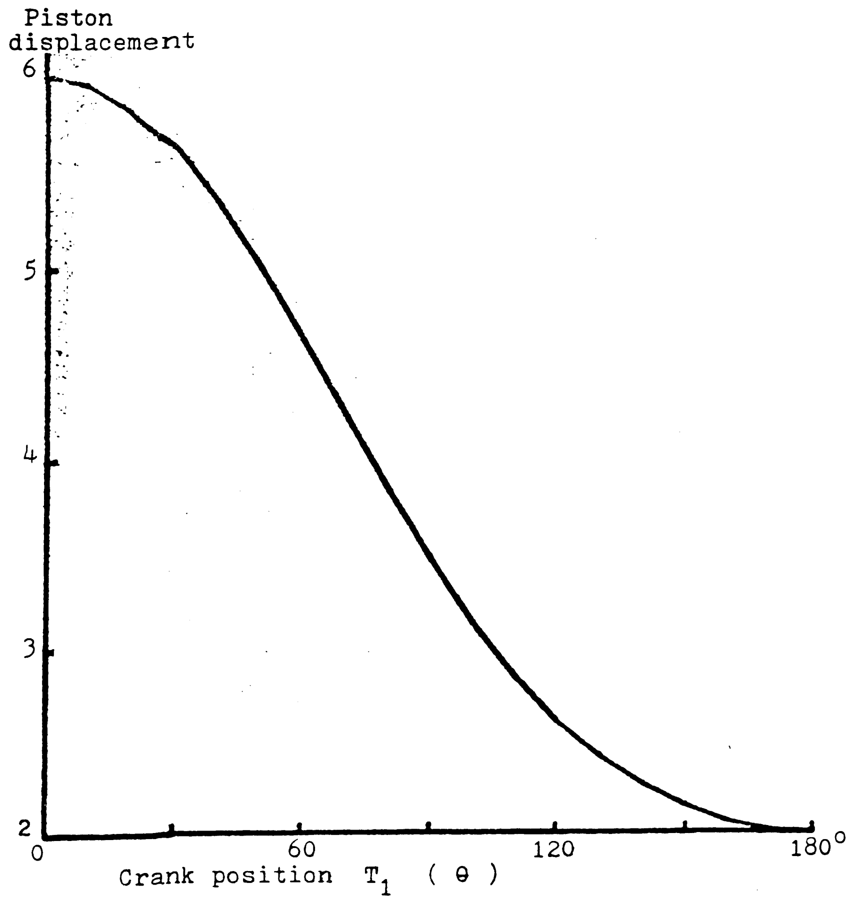
$= -2 \times 50 \times 500/\pi$

$v_{avg} = -15915$ mm/s (15.915 m/s)

to the left. (ans)

c) $\Delta x = 0$ $v_{avg} = 0$ (ans)

1.11 a) Angles θ and T_2 and slider location x are tabulated and plotted below



1.11 (cont'd.)

θ (T1°)	T2°	X2 (in)
0	0	6
30	14.4775121859	5.60503415378
60	25.6589062733	4.60555127546
90	30	3.46410161514
120	25.6589062733	2.60555127546
150	14.4775121859	2.14093253864
180	1.278976924E-12	2
210	-14.4775121859	2.14093253864
240	-25.6589062733	2.60555127546
270	-30	3.46410161514
300	-25.6589062733	4.60555127546
330	-14.4775121859	5.60503415378
360	-3.836930773E-12	6

b) For 30° crank rotation, the time interval is

(1 min/100 rev)x(1 rev/360°)x(60 s/min)x30° = 0.05 s/interval

For $30 \le \theta \le 60°$

v_{avg} = (4.60555 - 5.60503)/.05

= 19.99 in/s to the left (ans)

c) For the next interval

v_{avg} = (3.46410 - 4.60555)/.05

= 22.83 in/s to the left (ans)

1.12 through 1.20 The longest link is shorter than the sum of the other three, forming a mechanism in each case.

1.12 $L_{max} + L_{min} = 5 + 1.5 > L_a + L_b = 2 + 2$
The linkage is a non-Grashof (triple rocker) mechanism. See sketch.

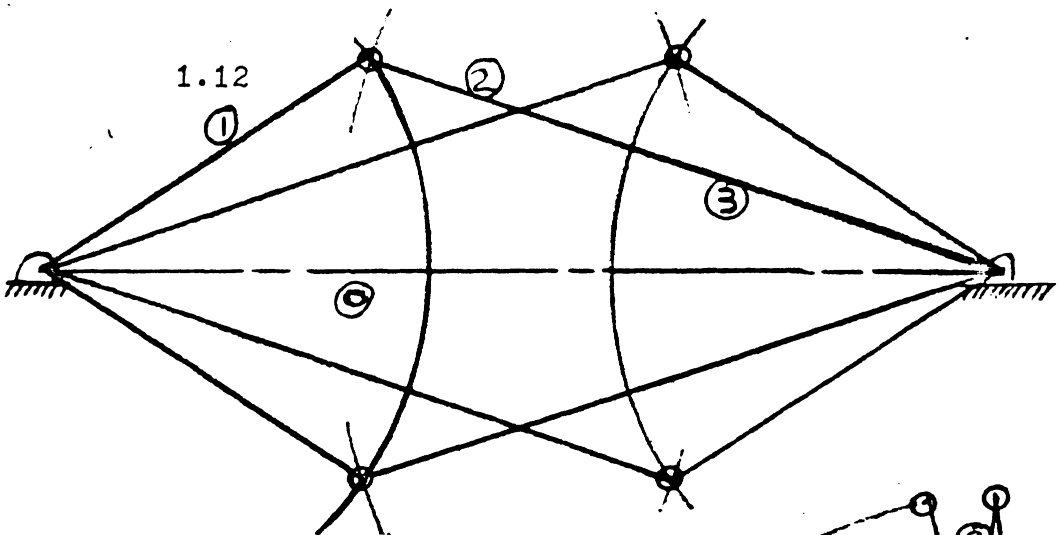
1.13 Fixed link shortest. Try drag link.
$|L_1 - L_2| + L_0 < L_3 < L_1 + L_2 - L_0$ is not satisfied. Linkage is a triple rocker. 3.5 + 1 > 1.5 + 2; $L_{max} + L_{min} > L_a + L_b$. (Non-Grashof). See sketch.

1.14 Fixed link shortest.
$|L_1 - L_2| + L_0 < L_3 < L_1 + L_2 - L_0$ is satisfied. Linkage is a drag link.

1.15 Fixed link is shortest, but drag link inequality is not satisfied since $|L_1 - L_2| + L_0 = L_3$. Motion is indefinite (a change point mechanism).

1.16 Fixed link is shortest, but drag link inequality is not satisfied since $L_3 = L_1 + L_2 - L_0$. Motion is indefinite (a change point mechanism).

1.12



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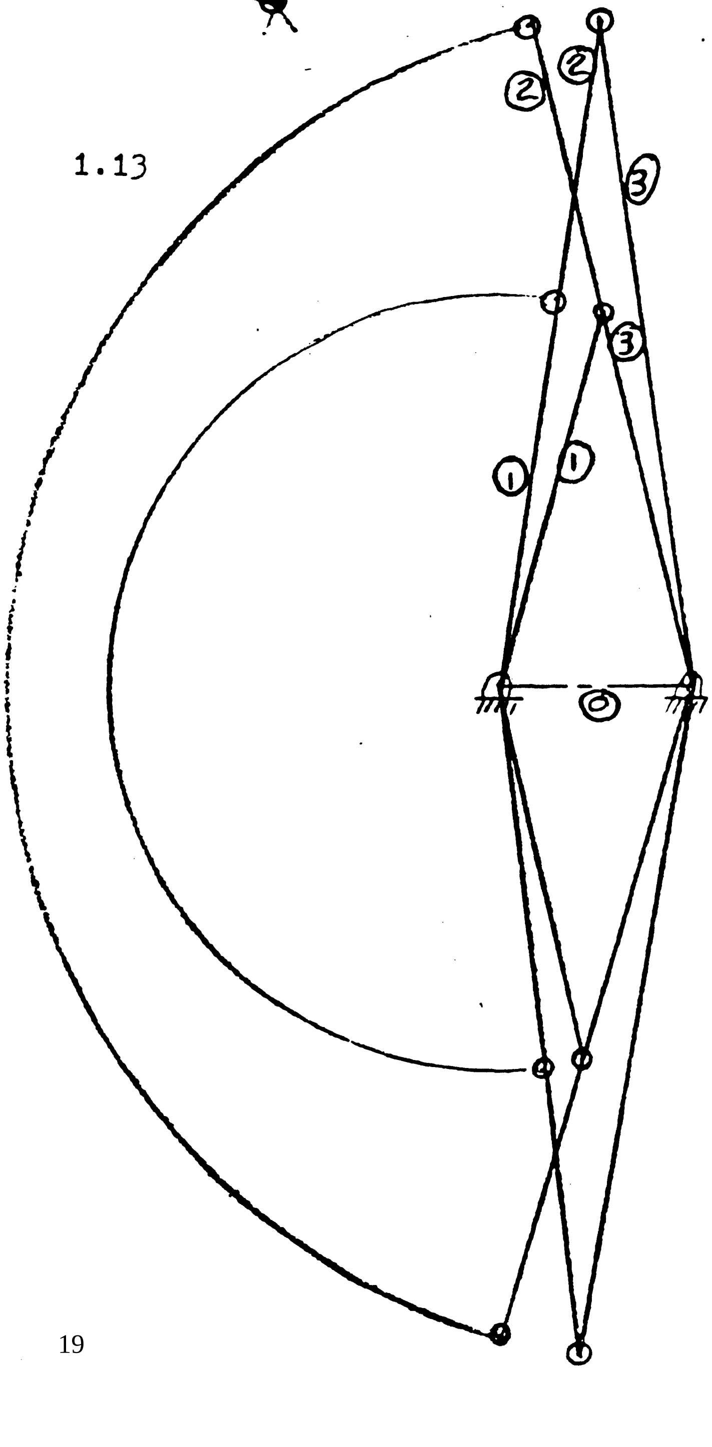
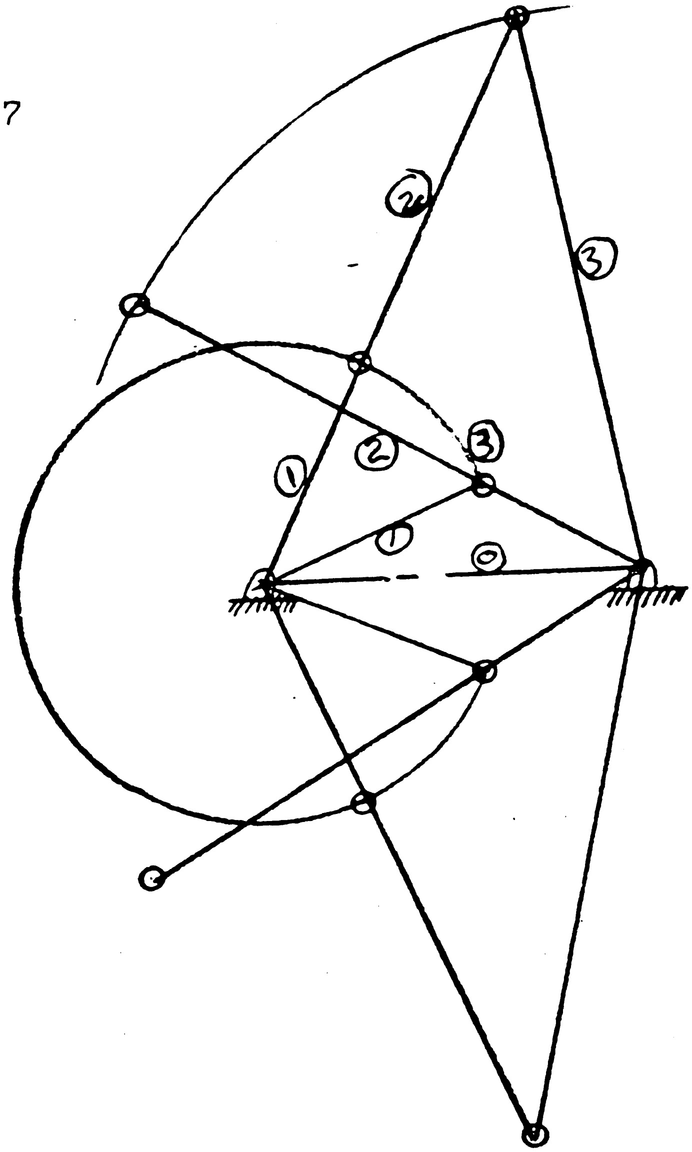
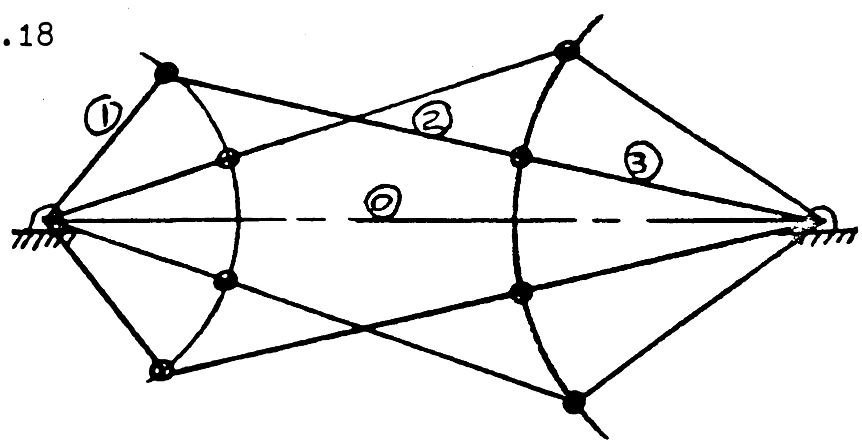


1.17



1.18



1.17 Crank is shortest, but crank-rocker inequality is not satisfied since $L_1 + |L_2 - L_3| > L_0$. Linkage is a triple rocker. See sketch. $3 + 1.25 > 2 + 2$; $L_{max} + L_{min} > L_a + L_b$ (Non-Grashof).

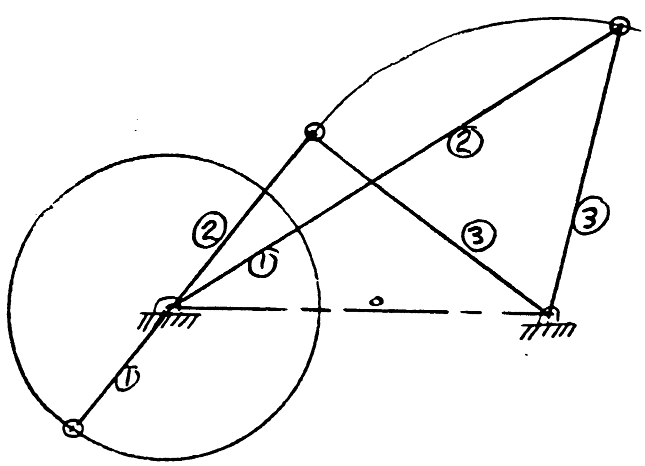
1.18 Crank is shortest, but crank rocker inequality is not satisfied since $L_0 > L_2 - L_1 + L_3$. Linkage is a triple rocker. $4 + 1 > 2 + 1.5$ $L_{max} + L_{min} > L_a + L_b$ (Non-Grashof). See sketch.

1.19 We may eliminate the drag link since the fixed link is not shortest. Trying the crank rocker criteria we find

$L_1 + |L_2 - L_3| = L_0 = L_2 - L_1 + L_3$. The motion is indefinite (a change point mechanism).

1.20 The crank is shortest. The inequality

$L_1 + |L_2 - L_3| < L_0 < L_2 - L_1 + L_3$ is satisfied. The linkage is a crank rocker. See sketch.



1.21 $L_{max} + L_{min} < L_a + L_b$ $15 + 5 < 15 + 10$ and the fixed link is shortest. The mechanism is a drag link.

1.22 $L_{max} + L_{min} < L_a + L_b$ $16 + 7 < 15 + 10$ and the crank is shortest. The mechanism is a crank rocker.

1.23 In the crank rocker, link 1 is shortest and $L_{max} + L_{min} < L_a + L_b$ from which $300 + 100 < 280 + L_2$ or $L_2 + 100 < 280 + 300$. Thus, $120 < L_2 < 480$.

1.24 Grashof linkages include the first four.

a) For the crank rocker

$L_1 + |L_2 - L_3| < L_0 < L_2 - L_1 + L_3$

$100 + |280 - 360| < L_0 < 280 - 100 + 360$

$180 < L_0 < 540$ mm. L_1 is shortest.

1.24 b) For the drag link

$|L_1 - L_2| + L_0 < L_3 < L_1 + L_2 - L_0$

$|100 - 280| + L_0 < 360 < 100 + 280 - L_0$

$L_0 < 180$ and $L_0 < 20$ $\quad L_0$ is shortest

$\underline{0 < L_0 < 20 \text{ mm.}}$

c) For the double rocker, L_2 is shortest. (<u>none</u>)

d) Change point mechanism

$L_{max} + L_{min} = L_a + L_b$

For L_0 largest:

$L_0 + 100 = 280 + 360$ $\quad \underline{L_0 = 540}$; or

for L_0 intermediate:

$360 + 100 = L_0 + 280$ $\quad \underline{L_0 = 180}$; or

for L_0 smallest

$360 + L_0 = 100 + 280$ $\quad \underline{L_0 = 20}$ mm.

e) Grashof linkages: A, B, C and D above

$\underline{0 < L_0 \le 20}$ and $\underline{180 \le L_0 \le 540}$ mm.

f) Triple rocker (non-Grashof)

$L_{max} + L_{min} > L_a + L_b$

For L_0 largest $L_0 + 100 > 280 + 360$ $\quad L_0 > 540$

For L_0 intermediate (i.e. $100 \le L_0 \le 360$)

$360 + 100 > L_0 + 280$ $\quad 180 > L_0 \ge 100$

For L_0 smallest (i.e. $0 < L_0 \le 100$)

$360 + L_0 > 100 + 280$ $\quad 100 \ge L_0 > 20$

Also, $L_{max} < L_{min} + L_a + L_b$

$L_0 < 100 + 280 + 360$ $\quad L_0 < 740$

Combining:

$\underline{20 < L_0 < 180}$ and $\underline{540 < L_0 < 740}$ mm

1.25 (see 1.24)

Grashof linkages: $L_{max} + L_{min} \le L_a + L_b$

If L_1 is shortest $0 < L_1 \le 40$)

$60 + L_1 \le 40 + 40$; $\underline{0 < L_1 < 20}$: crank rocker

If $L_1 = 20$, the result is a change point linkage

If L_1 is intermediate

$60 + 40 \le L_1 + 40$ $\quad \underline{L_1 = 60}$ change point

If L_1 is largest; i.e. $60 \le L_1 < 40 + 40 + 60$

$L_1 + 40 \le 40 + 60$ $\quad L_1 = 60$ change point

1.25 (cont'd.)

Combining results:

a) CR: $0 < L_1 < 20$

b) DL: none

c) DR: L_2 shortest: none

d) $L_1 = 20$ and $L_1 = 60$ (CP)

e) Grashof: $0 < L_1 \leq 20$ and $L_1 = 60$

f) TR: $L_{max} + L_{min} > L_a + L_b$

For L_1 largest (i.e. $60 \leq L_1 < 60 + 40 + 40$)

$L_1 + 40 > 60 + 40$

$60 < L_1 < 140$

For L_1 intermediate (i.e. $40 \leq L_1 \leq 60$)

$60 + 40 > L_1 + 40$

$40 \leq L_1 < 60$

For L_1 smallest (i.e. $0 \leq L_1 \leq 40$)

$60 + L_1 > 40 + 40$

$20 < L_1 \leq 40$

Combining: $20 < L_1 < 60$ and $60 < L_1 < 140$ mm (ans)

1.26 a) A crank rocker is impossible since the crank is not shortest (ans).

b) Drag link: L_0 is shortest and $L_{max} + L_{min} < L_a + L_b$

If L_2 is intermediate:

$250 + 50 < L_2 + 200 \quad 100 < L_2 \leq 250$

If L_2 is largest:

$L_2 + 50 < 200 + 250 \quad 250 \leq L_2 < 400$

Combining: $100 < L_2 < 400$ (ans)

c) Double rocker L_2 is shortest and

$250 + L_2 < 50 + 200$: impossible (ans)

d) Change point: $L_{max} + L_{min} = L_a + L_b$

If L_2 is largest

$L_2 + 50 = 200 + 250 \quad L_2 = 400$

If L_2 is smallest

$250 + L_2 = 50 + 200$ impossible

If L_2 is intermediate

$250 + 50 = L_2 + 200 \quad L_2 = 100$

$L_2 = 100$ or 400 (ans)

1.26 (cont'd.)

e) Grashof: combining a through d:

$100 \le L_2 \le 400$ (ans)

f) Triple rocker:

$L_{max} + L_{min} > L_a + L_b$

If L_2 is largest

$L_2 + 50 > 200 + 250 \quad L_2 > 400$

If L_2 is intermediate

$250 + 50 > L_2 + 200 \quad 100 > L_2 \ge 50$ impossible

If L_2 is smallest

$250 + L_2 > 50 + 200 \quad 50 \ge L_2 > 0$

Also, $L_2 < L_0 + L_1 + L_3 \quad L_2 < 50 + 200 + 250$

Combining the results,

$0 < L_2 < 100$ and $400 < L_2 < 500$ (ans)

1.27 a) Crank rocker: L_1 is not shortest, but if L_3 shortest:

$L_{max} + L_{min} < L_a + L_b$

$220 + L_3 < 120 + 80$ impossible (ans)

b) Drag link: L_0 is not shortest impossible (ans)

c) Double rocker: L_2 shortest

$L_{max} + L_{min} < L_a + L_b$ If L_3 longest:

$L_3 + 80 < 120 + 220 \therefore 220 \le L_3 < 260$

If L_3 intermediate, $220 + 80 < 120 + L_3$

$180 < L_3 \le 220$. Thus:

$180 < L_3 < 260$ (ans)

d) Change point:

$L_{max} + L_{min} = L_a + L_b$

$L_3 + 80 = 120 + 220 \quad L_3 = 260$

$220 + L_3 = 80 + 120$ impossible

$220 + 80 = 120 + L_3 \quad L_3 = 180$

Thus, $L_3 = 180$ and 260 (ans)

e) Grashof linkage: Combining a through d:

$180 \le L_3 \le 260$ (ans)

1.27 (cont'd.)

f) Triple rocker:

$L_{max} + L_{min} > L_a + L_b$. and $L_{max} < L_{min} + L_a + L_b$ if $L_3 = L_{max}$:

$L_3 + 80 > 120 + 220 \Rightarrow L_3 > 260$ and $L_3 < 80 + 120 + 220 \Rightarrow L_3 < 420$

$220 + L_3 > 80 + 120 \Rightarrow L_3 > -20$ and $220 < L_3 + 120 + 80 \Rightarrow L_3 > 20$ if min

$220 + 80 > L_3 + 120 \Rightarrow 180 > L_3 \geq 80$ if L_3 intermediate

Combining: $20 < L_3 < 180$ and $260 < L_3 < 420$ (ans)

1.28 a) Crank rocker: L_1 shortest and $L_{max} + L_{min} < L_a + L_b$. If L_0 longest:

$L_0/L_1 \geq 1.5$ $\quad L_0/L_1 + 1 < 1.2 + 1.5$ $\quad 1.5 \leq L_0/L_1 < 1.7$

If L_0 intermediate:

$1.5 + 1 < L_0/L_1 + 1.2$ $\quad 1.3 < L_0/L_1 \leq 1.5$. Thus:

$1.3 < L_0/L_1 < 1.7$ (ans)

b) Drag link: L_0 is L_{min}

$1.5 + L_0/L_1 < 1 + 1.2$ $\quad 0 < L_0/L_1 < 0.7$ (ans)

c) Double rocker: L_2 is L_{min} none (ans)

d) Change point:

If $L_0 = L_{min}$: $1.5 + L_0/L_1 = 1 + 1.2$ $\quad L_0/L_1 = 0.7$

If L_0 intermediate: $1.5 + 1 = L_0/L_1 + 1.2$ $\quad L_0/L_1 = 1.3$

If $L_0 = L_{max}$: $L_0/L_1 + 1 = 1.5 + 1.2$ $\quad L_0/L_1 = 1.7$

$L_0/L_1 = 0.7$ or 1.3 or 1.7 (ans)

e) Grashof: combine above:

$0 < L_0/L_1 \leq 0.7$ and $1.3 \leq L_0/L_1 \leq 1.7$ (ans)

f) Triple rocker: If $L_0 = L_{max}$ $\quad L_0/L_1 < 1 + 1.2 + 1.5$

$L_0/L_1 < 3.7$ $\quad L_0/L_1 + 1 > 1.2 + 1.5$ $\quad L_0/L_1 > 1.7$

If $L_0 = L_{min}$ $\quad 1.5 + L_0/L_1 > 1 + 1.2$ $\quad 0.7 < L_0/L_1 \leq 1$

If L_0 intermediate: $1 + 1.5 > L_0/L_1 + 1.2$ $\quad 1.3 > L_0/L_1 \geq 1$

Combining: $0.7 < L_0/L_1 < 1.3$ and $1.7 < L_0/L_1 < 3.7$ (ans)

1.29 To form a mechanism, if $L_2 = L_{max}$

$L_2/L_1 < 1 + 2.2 + 1.7$ $\quad L_2/L_1 < 4.9$, and if

$L_2/L_1 + 1 > 2.2 + 1.7$ (i.e. $L_2/L_1 > 2.9$) it is a triple rocker.

For a change point, $L_2/L_1 + 1 = 2.2 + 1.7$ $\quad L_2/L_1 = 2.9$

For a crank rocker, $L_2/L_1 + 1 < 2.2 + 1.7$ $\quad 1.7 \leq L_2/L_1 < 2.9$

Suppose L_2/L_1 is intermediate. For a triple rocker:

$2.2 + 1 > L_2/L_1 + 1.7$ $\quad 1.5 > L_2/L_1 \geq 1$. For a change point,

$2.2 + 1 = L_2/L_1 + 1.7$ $\quad L_2/L_1 = 1.5$. For a crank rocker,

$1 + 2.2 < L_2/L_1 + 1.7$ $\quad 1.5 < L_2/L_1 \leq 1.7$. Suppose $L_2/L_1 = L_{min}$

For a triple rocker, $2.2 + L_2/L_1 > 1 + 1.7$ $\quad 1 \geq L_2/L_1 > 0.5$.

For a change point, $L_2/L_1 = 0.5$

For a double rocker, $L_2/L_1 < 0.5$

Summary:

a) Crank rocker: $1.5 < L_2/L_1 < 2.9$

b) Drag link: none

c) Double rocker: $0 < L_2/L_1 < 0.5$

d) Change point: $L_2/L_1 = 0.5$ or 1.5 or 2.9

e) Grashof: $0 < L_2/L_1 \leq 0.5$ and $1.5 \leq L_2/L_1 \leq 2.9$

f) Triple rocker: $0.5 < L_2/L_1 < 1.5$ and $2.9 < L_2/L_1 < 4.9$

1.30 a) For a crank rocker, $L_1 + |L_2 - L_3| < L_0 < L_2 - L_1 + L_3$ and the driver L_1 is shortest.

Thus, $400 < L_0$ $\quad 400 + |600 - 750| < L_0 < 600 - 400 + 750$

$550 < L_0 < 950$ mm

b) For drag link, fixed link is shortest. Thus $L_0 < 400$ and

$|L_1 - L_2| + L_0 < L_3 < L_1 + L_2 - L_0$

$|400 - 600| + L_0 < 750 < 400 + 600 - L_0$

$200 + L_0 < 750 < 1000 - L_0$

$L_0 < 550$ $\quad L_0 < 250$

$0 < L_0 < 250$ mm

c) For double rocker, coupler shortest. ans none

d) For change point $L_{max} + L_{min} = L_a + L_b$ $\quad L_0 \geq 750$

If $L_0 = L_{max}$, $L_0 + 400 = 600 + 750$; $L_0 = 950$

If $L_0 \leq 400$ (min) $\quad 750 + L_0 = 600 + 400$ $\quad L_0 = 250$

If $400 < L_0 < 750$ $\quad 400 + 750 = 600 + L_0$ $\quad L_0 = 550$ mm

1.30 (cont'd.)

e) Grashof mechanism:

$L_{max} + L_{min} \le L_a + L_b$ includes all above

$0 < L_0 \le 250$ and $550 \le L_0 \le 950$ mm

f) Non-Grashof (triple rocker):

$L_{max} + L_{min} > L_a + L_b$

If $L_0 \ge 750$, L_0 is max

$L_0 + 400 > 600 + 750$

$L_0 > 950$

If L_0 intermediate, $400 < L_0 < 750$

$750 + 400 > L_0 + 600$

$550 > L_0 > 400$

If L_0 min, $0 < L_0 \le 400$

$750 + L_0 > 400 + 600$

$400 \ge L_0 > 250$

Also, $L_{max} < L_{min} + L_a + L_b$

$L_0 < 400 + 600 + 750$

$L_0 < 1750$

$\therefore$ $250 < L_0 < 550$ and $950 < L_0 < 1750$

1.31 Crank rocker: L_1 is shortest ($L_1 = L_{min}$)

$L_3/L_1 > 1$ and $L_2/L_1 > 1$ (1 and 2)

If $L_3 = L_{max}$,

$L_3/L_1 + 1 < L_2/L_1 + 2$ $L_3/L_1 < L_2/L_1 + 1$ (3)

If L_3 and L_2 are intermediate:

$2 + 1 < L_3/L_1 + L_2/L_1$

$L_3/L_1 > 3 - L_2/L_1$ (4)

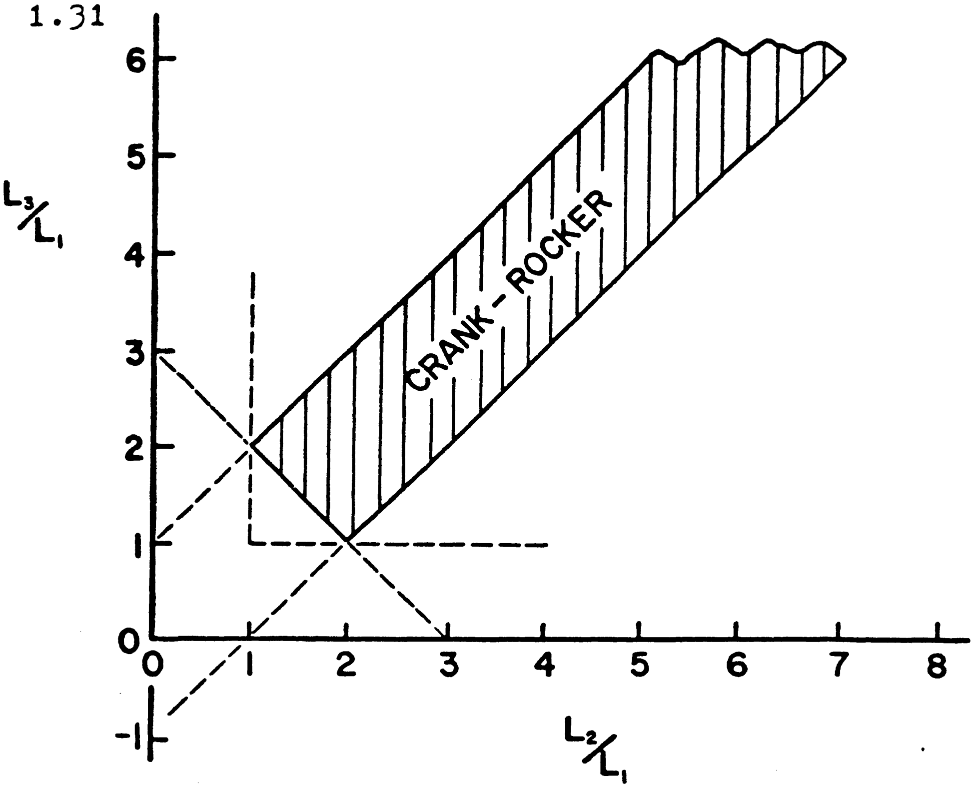
If L_3 is intermediate and $L_2 = L_{max}$:

$L_2/L_1 + 1 < L_3/L_1 + 2$

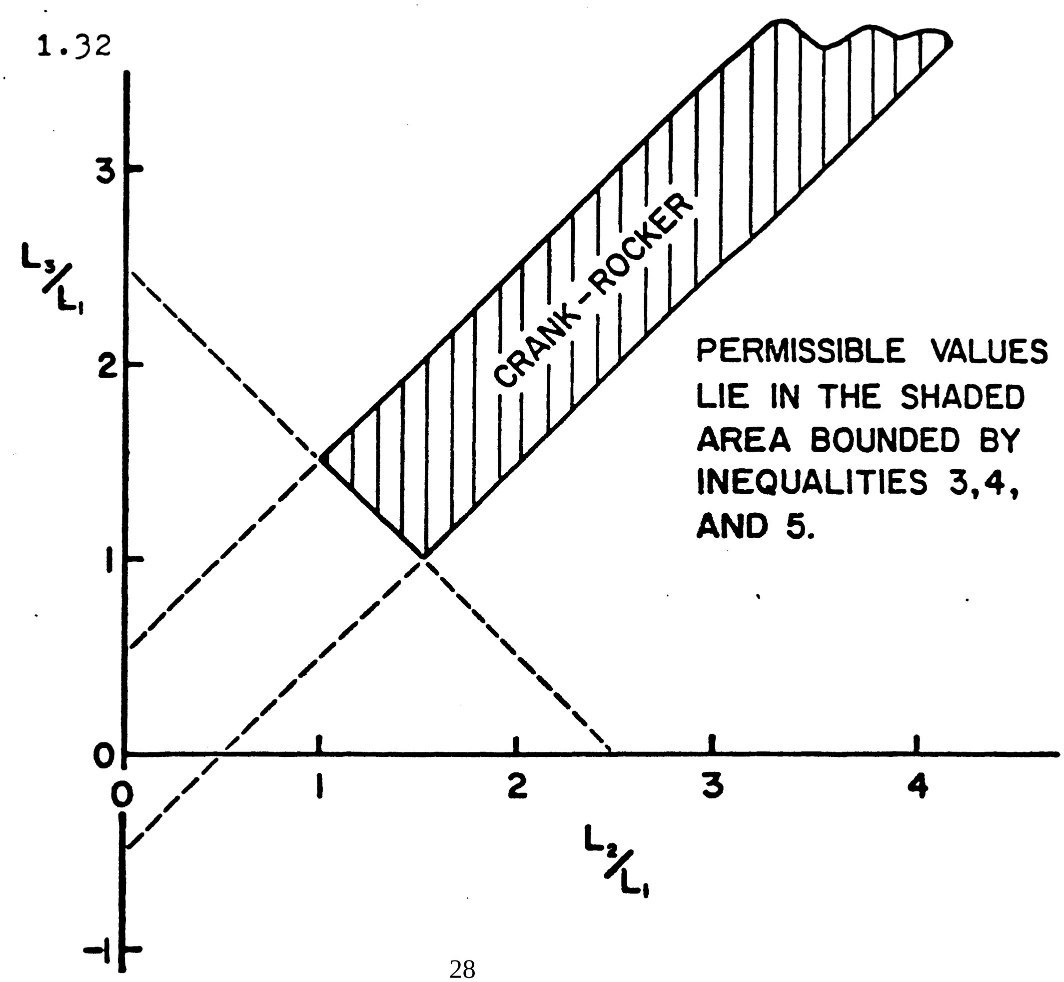
$L_3/L_1 > L_2/L_1 - 1$ (5)

Permissible values for the crank rocker lie in the region bounded by inequalities 3, 4 and 5 (1 and 2 are redundant). See figure.

1.31


6
5
L_3/L_1
4
3
2
1
0
-1
0
1
2
3
4
5
6
7
8
L_2/L_1
CRANK - ROCKER

1.32


3
L_3/L_1
2
1
0
-1
0
1
2
3
4
L_2/L_1
CRANK - ROCKER
PERMISSIBLE VALUES
LIE IN THE SHADED
AREA BOUNDED BY
INEQUALITIES 3,4,
AND 5.

1.32 L_1 is shortest for a crank rocker

$L_3/L_1 > 1$ (1) and $L_2/L_1 > 1$ (2)

If $L_3 = L_{max}$

$L_3/L_1 + 1 < L_2/L_1 + 1.5 \quad L_3/L_1 < L_2/L_1 + 0.5$ (3)

If $L_0 = L_{max}$

$1.5 + 1 < L_2/L_1 + L_3/L_1$

$L_3/L_1 > 2.5 - L_2/L_1$ (4)

If $L_2 = L_{max}$

$L_2/L_1 + 1 < L_3/L_1 + 1.5$

$L_3/L_1 > L_2/L_1 - 0.5$ (5) See figure.

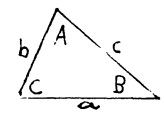
1.33 The linkage satisfies the Grashof criteria for a crank-rocker. Theoretically, the driven crank will rock back and forth as the drive crank rotates through 360°. However, the linkage nearly satisfies the change-point criteria. It is likely that the linkage will jam (lock) as the transmission angle approaches 0° or 180°.

1.34 The program corresponds to the flowchart of text Figure 1.17. It is tested for ten sets of values. Results are as follows:

FOUR BAR LINKAGE
IN MILLIMETERS

LO	L1	L2	L3	COMMENT
50	600	400	500	DRAG LINK
100	300	250	50	CHANGE POINT
300	100	150	200	TRIPLE ROCKER
150	100	250	500	NOT A MECHANISM
150	100	250	200	CHANGE POINT
500	900	300	400	TRIPLE ROCKER
700	350	560	600	CRANK ROCKER
300	100	400	800	NOT A MECHANISM
550	400	100	300	DOUBLE ROCKER
40	500	300	495	DRAG LINK

1.35 From the Grashof criterion for a crank rocker linkage, if $L_2 = L_{max}$
$140 + 100 < 120 + L_3$ or $120 < L_3$



If $L_3 = L_{max}$

$L_3 + 100 < 120 + 140$ or $L_3 < 160$

Thus, $120 < L_3 < 160$ mm without limiting ϕ. if ϕ_{min} or ϕ_{max} is specified, we may use the law of sines and the cosine law to find L_3. This may be programmed as a triangle solution.
$\phi_{min}=45^o$, side $a=L_0-L_1=20$, $b=L_2=140$. No triangle satisfies the input data. No value of L_3 satisfies the criteria.

1.36 See above problem.

From the Grashof criteria for a crank rocker, if $L_3 = L_{max}$,

$L_3 + 50 < 200 + 210 \quad L_3 < 360$

If $L_0 = L_{max} \quad 210 + 50 < 200 + L_3 \quad 60 < L_3$

$60 < L_3 < 360$ without limiting ϕ.

Let: $\phi_{min} = 45^o$; side $a = L_0 - L_1 = 210 - 50 = 160$

$b = L_2 = 200$ Triangle solution yields

$c = L_3 = 216.25$ mm (ans)

Let

$a = L_0 + L_1 = 210 + 50 = 260$, $b = L_2 = 200$

$c = L_3 = 216.25$ from which $77.20^o = \phi_{max}$ which is acceptable.
(Other solutions possible.)

1.37 If $L_3 = L_{max}$, $L_3 + 110 < 150 + 150$

$L_3 < 190$ If $L_{max} = 150$

$150 + 110 < L_3 + 150 \quad 110 < L_3$

Thus $110 < L_3 < 190$ to satisfy Grashof criteria (without limiting ϕ)

Let

$a = L_0 - L_1 = 150 - 110 = 40$; $b = L_2 = 150$ $\angle A = 45^o$.

No value of L_3 satisfies the criteria. (ans)

1.38 If $L_2 = L_{max}$

$1.5 + 1 < 1.2 + L_0/L_1 \quad 1.3 < L_0/L_1$

If $L_0 = L_{max} \quad L_0/L_1 + 1 < 1.2 + 1.5 \quad L_0/L_1 < 1.7$

Thus, $1.3 < L_0/L_1 < 1.7$ satisfies the Grashof criteria.

Let

$a = L_2/L_1 = 1.5$; $b = L_3/L_1 = 1.2$; $\angle C = 45^o$ from which
$c = 1.0698 = (L_0-L_1)/L_1 \quad L_0/L_1 = 2.0698$

which does not satisfy the crank rocker criteria.

No value of L_0/L_1 satisfies the criteria. (ans)

1.39 Let

$a = (L_0-L_1)/L_1 = 3.2 - 1 = 2.2$

$b = L_3/L_2 = 1.7 \quad <A = \phi_{min} = 45^o$ From which:

$c = L_2/L_1 = 3.045$ (ans)

Let

$a = (L_0+L_1)/L_1 = 3.2 + 1 = 4.2$

$b = L_3/L_2 = 1.7 \quad c = 3.045$

$<A = 121.95^o = \phi_{max}$ which is acceptable.

Grashof criteria L_1 is shortest;

$L_{max} + L_{min} < L_a + L_b \quad 3.2 + 1 < 3.045 + 1.7$ is satisfied for the crank rocker. Other solutions are possible.

1.40 Values must satisfy the Grashof criterion (see prob. 1.31).

Let $a = (L_0-L_1)/L_1 = 2 - 1 = 1$;

$b = L_2/L_1$; $LA = \phi_{min} = 45^o$

No combinations of L_3/L_1 and L_2/L_1 satisfy all criteria (without relaxing the transmission angle limitation). (ans)

1.41 First, checking the Grashof criteria for a crank rocker with $L_0/L_1 = 4$, if $L_0 = L_{max}$

$4 + 1 < (L_2+L_3)/L_1 \quad 5 < (L_2+L_3)/L_1$

If $L_2 = L_{max}$

$L_2/L_1 + 1 < 4 + L_3/L_1 \quad (L_2-L_3)/L_1 < 3$

If $L_3 = L_{max}$

$L_3/L_1 + 1 < 4 + L_2/L_1 \quad (L_3-L_2)/L_1 < 3$

The following triangle solutions are based on the requirement that $\phi_{min} = 45^o$

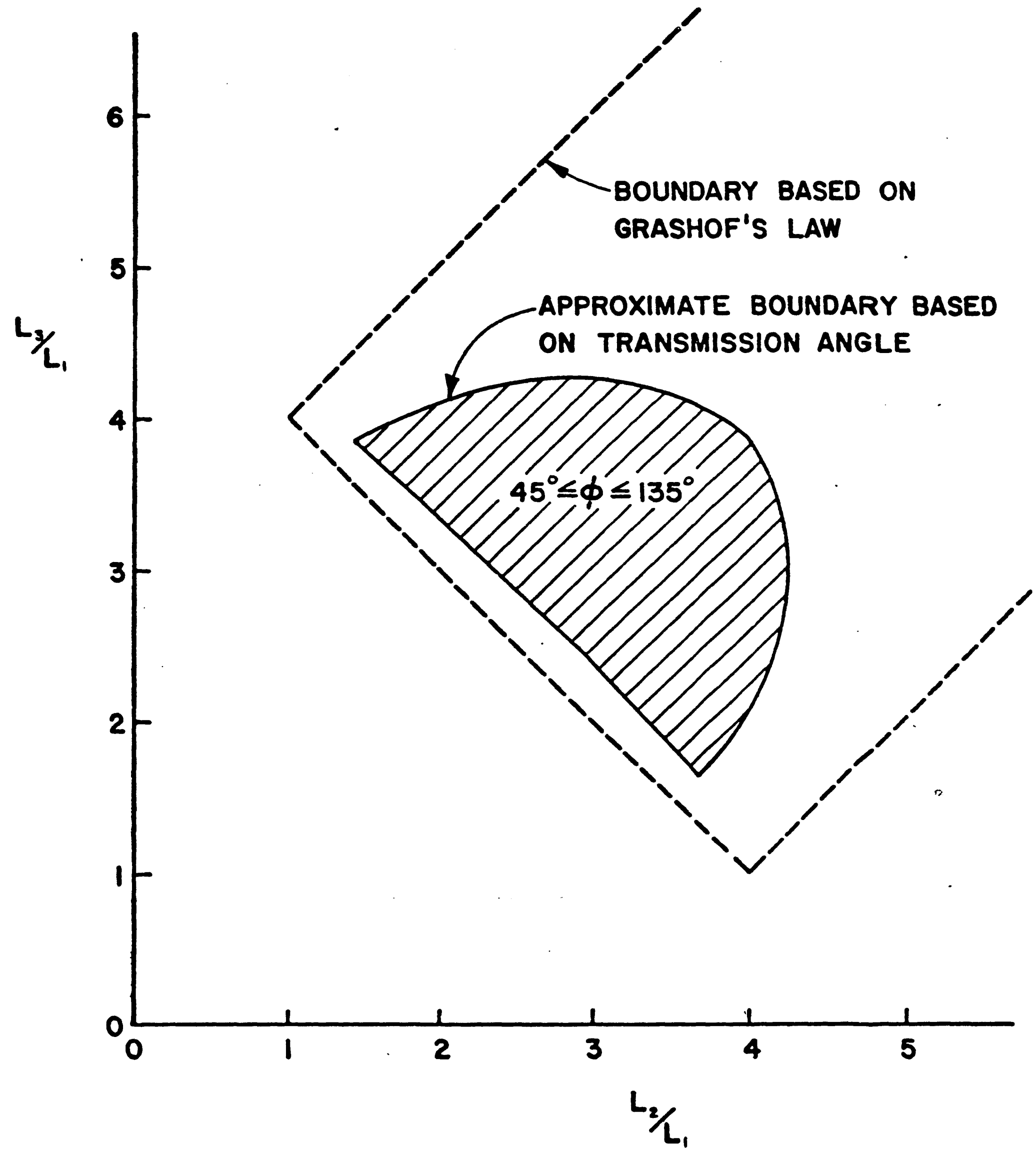
L_3/L_2 is determined from 2 sides and one angle (columns 1-4). Then, the configuration is checked for ϕ_{max} using the three known sides (columns 2, 4 and 5). Then, L_3/L_1 is computed based on $\phi_{max} = 135^o$ (columns 8-11)

ϕ_{min} is checked (columns 9, 11, 12, 13 and 14) See figure.

1	2	3	4	5	6	7
$\frac{L_0-L_1}{L_1}$	$\frac{L_2}{L_1}$	ϕ_{min}^o	$\frac{L_3}{L_1}$	$\frac{L_0+L_1}{L_1}$	ϕ_{max}^o	Acceptable?
3	1.5	45°	3.867	5	132.22°	Yes
3	2	45°	4.060	5	106.15	Yes
3	3	45°	4.243	5	85.48	Yes
3	4	45°	3,823	5	79.36	Yes
3	4.5	45°	none	5	--	No
3	5	45°	none	5	--	No
3	4.22	45°	3.294	5	82.44	Yes

8	9	10	11	12	13	14
$\frac{L_0+L_1}{L_1}$	$\frac{L_2}{L_1}$	ϕ_{max}^o	$\frac{L_3}{L_1}$	$\frac{L_0-L_1}{L_1}$	ϕ_{min}^o	Acceptable?
5	1.5	135°	3.826	3	46.59°	Yes
5	2	135	3.382	3	61.58	Yes
5	3	135	2.406	3	66.36	Yes
5	3.5	135	1.870	3	58.97	Yes
5	4	135	1.295	3	33.11	No
5	3.7	135	1.645	3	52.59	Yes
5	4	108.2	2	3	46.56	Yes

1.41


BOUNDARY BASED ON GRASHOF'S LAW
APPROXIMATE BOUNDARY BASED ON TRANSMISSION ANGLE
45°≤φ≤135°
L3/L1
L2/L1
0
1
2
3
4
5
6

1.42 through 1.47: As shown in problem 1.51, extreme values of transmission angle occur when the crank is perpendicular to the slider path. Thus,

$$\sin \phi_{\substack{max \\ min}} = \frac{R \pm E}{L}$$

for crank length R, connecting rod length L and offset E.

1.42 $L_{min} = \frac{R}{\sin\phi_{max}} = \frac{100}{\sin 45^o} = \underline{141.42 \text{ mm}}$ (ans)

1.43 $L_{min} = \frac{R + E}{\sin\phi_{max}} = \frac{500 + 100}{\sin 45^o} = \underline{848.53 \text{ mm}}$ (ans)

1.44 $L_{min} = \frac{400 + 200}{\sin 45^o} = \underline{848.53 \text{ mm}}$ (ans)

1.45 $L_{min} = \frac{300 + 50}{\sin 45^o} = \underline{494.97 \text{ mm}}$ (ans)

1.46 $R + E_{max} = L \sin \phi_{max}$

$E_{max} = L \sin\phi_{max} - R = L(\sin 45^o - 0.5) = \underline{0.207\ L}$ (ans)

1.47 $E_{max} = L \sin\phi_{max} - R = L(\sin 45^o - 0.25) = \underline{0.4571\ L}$ (ans)

1.48 There are many possible solutions. Let the linkage have a forward-to-return-stroke ratio of 1:1. The limiting positions are shown in the figure (O_1BCO_3 and $O_1B'C'O_3$). $B'O_1BC'C$ is a straight line with $CO_1 = L_2 + L_1$ and $C'O_1 = L_2 - L_1$. Thus $CC' = 2L_1$ forming isosceles triangle O_3CC' with angles γ, $90^o - \gamma/2$ and $90^o - \gamma/2$. From the law of sines,

$$\frac{\sin \gamma}{2L_1} = \frac{\sin(90-\gamma/2)}{L_3} = \frac{\cos(\gamma/2)}{L_3} \qquad \text{(a)}$$

Since one link length may be selected arbitrarily, let $L_1 = 1$. Then, from (a),

$$L_3 = 2 \cos(\gamma/2)/\sin \gamma \qquad \text{(b)}$$

For $O_1O_3 = L_0$ and $L_1 = 1$, we have from the cosine law:

$$(L_0 - 1)^2 = L_2^2 + L_3^2 - 2L_2L_3 \cos \phi_{min} \qquad \text{(c)}$$

from which

$$\cos \phi_{min} = \frac{L_2^2 + L_3^2 - (L_0 - 1)^2}{2L_2L_3} \qquad \text{(d)}$$

1.48 (cont'd.)

Similarly,

$$\cos\phi_{max} = \frac{L_2^2 + L_3^2 - (L_0+1)^2}{2L_2L_3} \qquad (e)$$

If we specify that $\phi_{max} - 90^o = 90^o + \phi_{min}$, then

$$\phi_{max} = 180^o - \phi_{min} \text{ and } \cos\phi_{max} = -\cos\phi_{min} \qquad (f)$$

Using Eq. (f) in (d) and (e)

$$L_2^2 + L_3^2 - (L_0+1)^2 = -L_2^2 - L_3^2 + (L_0-1)^2$$

from which

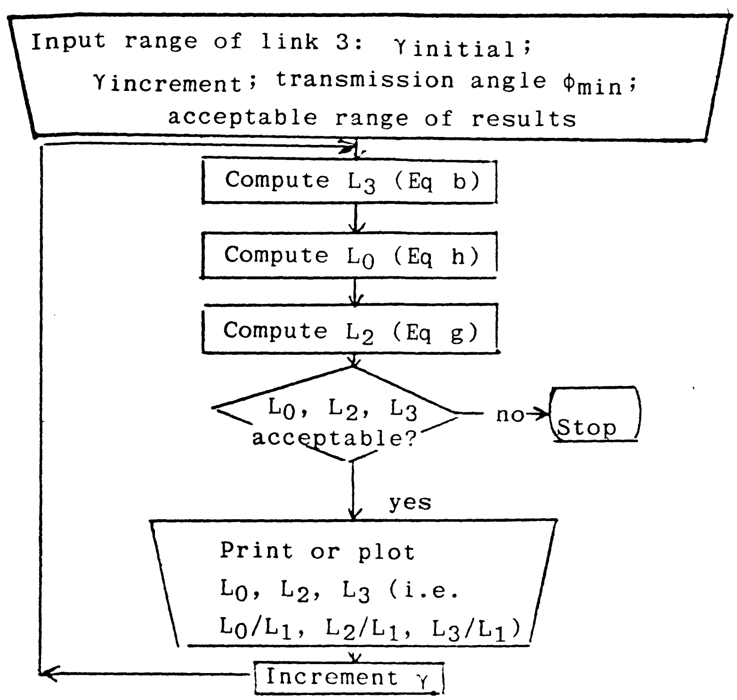
$$L_2 = [L_0^2 + 1 - L_3^2]^{1/2} \qquad (g)$$

Substituting Eq. (g) in (d)

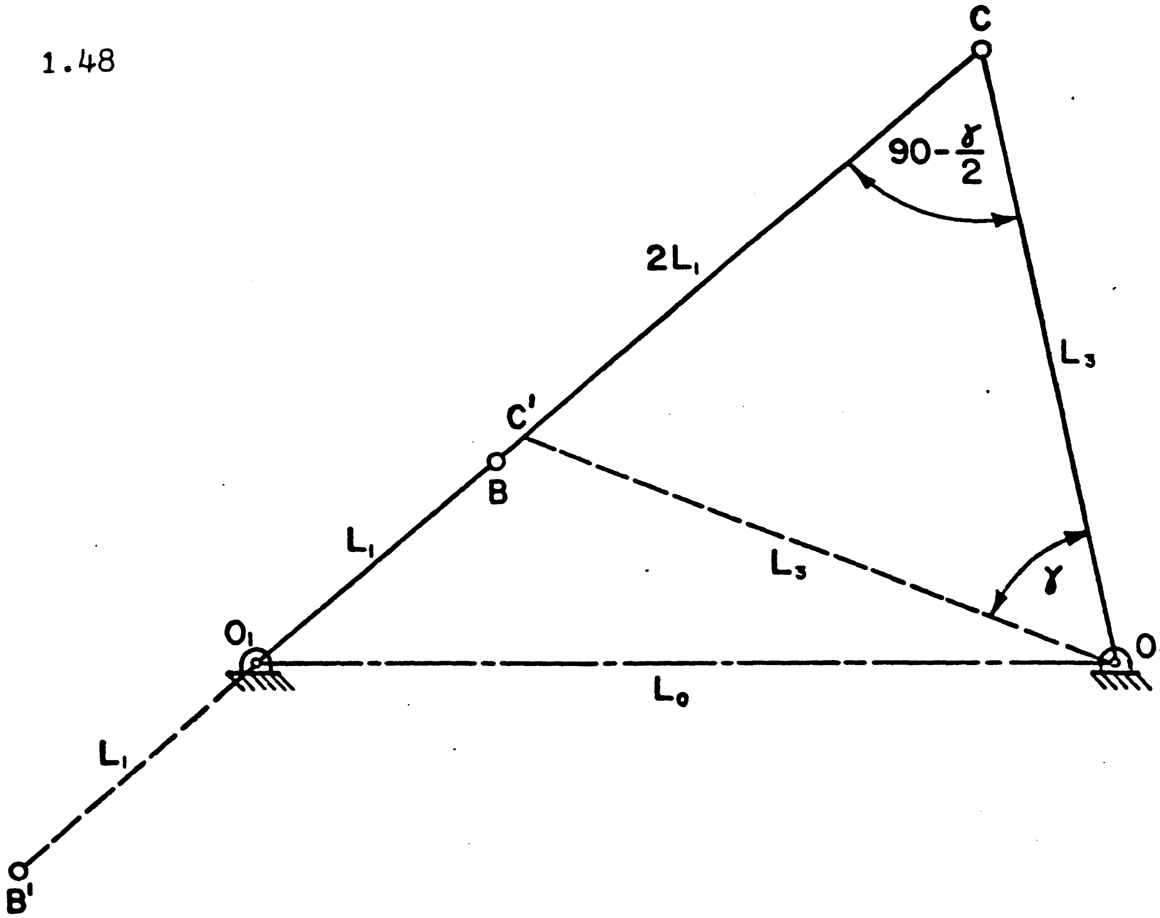
$$\cos\phi_{min} = \frac{L_0^2 + 1 - L_3^2 + L_3^2 - (L_0-1)^2}{2L_3\sqrt{L_0^2 + 1 - L_3^2}}$$

from which

$$L_0 = [\frac{L_3^2(1-L_3^2)\cos^2\phi_{min}}{1 - L_3^2\cos^2\phi_{min}}]^{1/2} \qquad (h)$$



1.48



```
100 PRINT "OPTIMIZE FOLLOWER RANGE"
110 P=PI*5/18
112 P1=180*P/PI
115 PRINT "MINIMUM TRANSMISSION ANGLE (DEGREES) = ",P1
116 P1=180*P/PI
118 PRINT "RANGE(DEGREES)     L0/L1              L2/L1              L3/L1"
120 FOR G=PI*30/180 TO PI STEP PI*2.5/180
130 L3=2*COS(G/2)/SIN(G)
140 L0=(L3↑2*(1-L3↑2)*COS(P)↑2/(1-L3↑2*COS(P)↑2))↑0.5
150 L2=(L0↑2+1-L3↑2)↑0.5
160 G1=180*G/PI
170 P1=180*P/PI
220 PRINT G1,L0,L2,L3
230 NEXT G
240 END
```

OPTIMIZE FOLLOWER RANGE

MINIMUM TRANSMISSION ANGLE (DEGREES) = 50

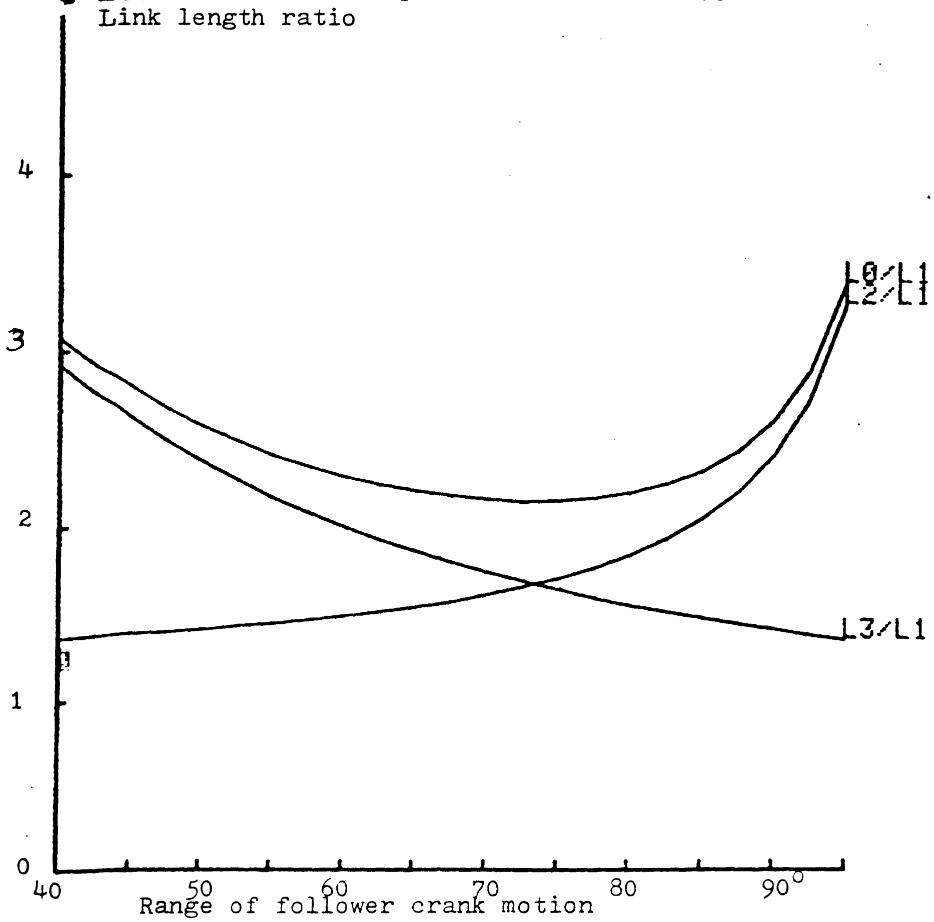
RANGE(DEGREES)	L0/L1	L2/L1	L3/L1
30	4.07716844983	1.64167577129	3.86370330516
32.5	3.81091585711	1.65903139821	3.57361084755
35	3.58848196589	1.67874632662	3.32550952342
37.5	3.40179920804	1.70114125105	3.11100567274
40	3.24496838841	1.72661161566	2.92380440016
42.5	3.11366278701	1.75564963511	2.75909229819
45	3.00474636219	1.78887494709	2.61312592975
47.5	2.91603439699	1.82707815646	2.48295026422
50	2.8461578179	1.87128415594	2.36620158315
52.5	2.79451426114	1.92284672843	2.26096669916
55	2.76130750096	1.98359440983	2.1656805702
57.5	2.74769908453	2.0560639006	2.07905062367
60	2.75613255463	2.14389054261	2
62.5	2.79096444356	2.25249786395	1.92762441832
65	2.85970726987	2.39040014607	1.8611589967
67.5	2.97563829177	2.5718853852	1.79995244627
70	3.16388596242	2.8232193776	1.74344679562
72.5	3.47809714994	3.19955203198	1.69116131077
75	4.05934988833	3.84446682174	1.6426796317
77.5	5.47536536389	5.33171400381	1.59763939913
80	1.413811038E+7	1.413811038E+7	1.55572382686

1.49 An optional program and a plot of link length ratios for a minimum transmission angle of 40°.

```
LIST
80 D=32
90 PAGE
92 A=40
93 B=95
94 C=0
95 E=5
100 WINDOW A,B,C,E
101 VIEWPORT 0,80,0,90
102 AXIS 5,1,40,0
103 HOME
110 PRINT "OPTIMIZE FOLLOWER RANGE"
120 P=PI*40/180
130 P1=180*P/PI
140 PRINT "MINIMUM TRANSMISSION ANGLE (DEGREES) = ",P1
145 PRINT "FOLLOWER RANGE:",A,"TO",B,"L/L1:",C,"TO",E
150 P1=180*P/PI
180 X1=0
190 Y0=0
200 Y2=0
210 Y3=0
215 FOR G=PI*30/180 TO PI*95/180 STEP PI*2.5/180
220 L3=2*COS(G/2)/SIN(G)
230 L0=(L3↑2*(1-L3↑2)*COS(P)↑2/(1-L3↑2*COS(P)↑2))↑0.5
240 L2=(L0↑2+1-L3↑2)↑0.5
250 G1=180*G/PI
260 P1=180*P/PI
270 MOVE @D:X1,Y0
280 DRAW @D:G1,L0
290 MOVE @D:X1,Y2
300 DRAW @D:G1,L2
310 MOVE @D:X1,Y3
320 DRAW G1,L3
330 GOSUB 360
340 NEXT G
345 MOVE X1,Y0
346 PRINT "L0/L1"
347 MOVE X1,Y2
348 PRINT "L2/L1"
349 MOVE X1,Y3
350 PRINT "L3/L1"
351 END
360 X1=G1
370 Y0=L0
380 Y2=L2
390 Y3=L3
400 RETURN
```

1.49

OPTIMIZE FOLLOWER RANGE
MINIMUM TRANSMISSION ANGLE (DEGREES) = 40
FOLLOWER RANGE: 40 TO 95
L/L1: 0 TO 5



1.49 See listing and output. The program prints values of L_0, L_2 and L_3 where $L_1 = 1$ for a given value of ϕ_{min} (P) and a series of values of follower range γ (G). Computation continues until one of the variables is no longer real. The solution is the largest value of γ which produces a reasonable configuration (e.g., we could require $L_0 < 5$, etc.).

1.50

Using the cosine law

$$L_0^2 + L_1^2 - 2L_0L_1 \cos\theta_1 = L_2^2 + L_3^2 - 2L_2L_3 \cos\phi$$

Differentiating with respect to θ_1,

$$2L_0L_1 \sin\theta_1 = 2L_2L_3 \sin\phi \frac{d\phi}{d\theta_1}$$

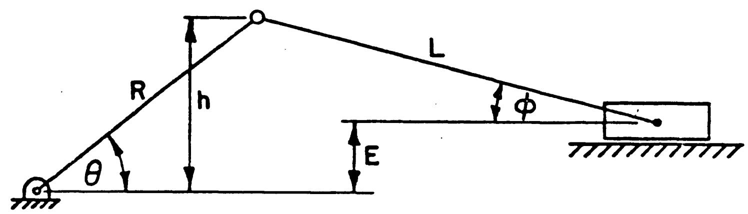
from which

$$\frac{d\phi}{d\theta_1} = \frac{L_0L_1 \sin\theta_1}{L_2L_3 \sin\phi}$$

$\frac{d\phi}{d\theta_1} = 0$ implies $\sin\theta_1 = 0$

or $\theta_1 = 0$ or 180° for extreme values of ϕ_1.

1.51



$$h = R \sin\theta = L \sin\phi + E$$

Differentiating with respect to θ:

$R \cos\theta = L \cos\phi \frac{d\phi}{d\theta}$ from which

$\frac{d\phi}{d\theta} = \frac{R \cos\theta}{L \cos\phi}$ $\quad \frac{d\phi}{d\theta} = 0$ (for $\cos\phi \neq 0$)

implies $\cos\theta = 0$ or $\theta = \pm 90^\circ$ for extreme values of ϕ.

1.52 a) $L_{max} + L_{min} < L_a + L_b \quad 18 + 7 < 17 + 9$

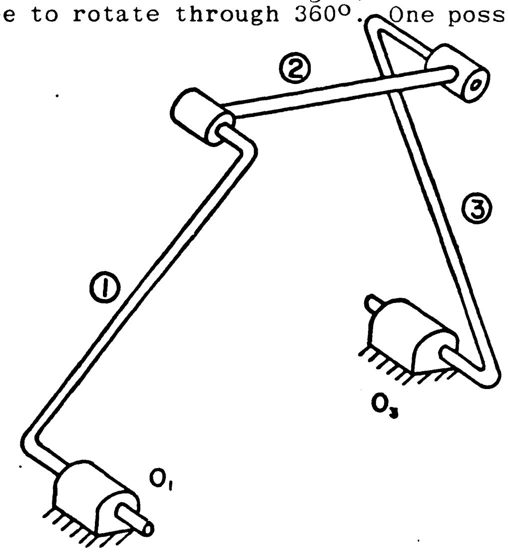
The linkage theoretically acts as a crank rocker.

b) $\cos\phi_{min} = [L_2^2 + L_3^2 - (L_0 - L_1)^2]/(2L_2L_3) \quad \phi_{min} = 35.5^\circ$

$\cos\phi_{max} = [L_2^2 + L_3^2 - (L_0 + L_1)^2]/(2L_2L_3) \quad \phi_{max} = 146.4^\circ$

c) Values of transmission angle are not in the generally accepted range. The linkage will not operate properly unless special provisions are made to prevent jamming.

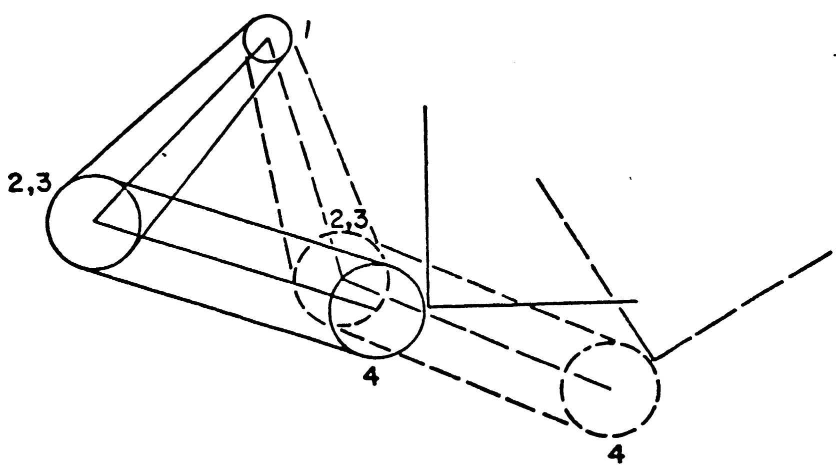
1.53 In a double rocker linkage (of the first kind) the coupler must be free to rotate through 360°. One possible configuration is shown.



1.54 Referring to the figure, let the upper arm rotate through an angle $\theta_1 = 60°$ counterclockwise. This is equivalent to a 60° clockwise rotation of pulley 1 relative to the arm. Pulley 2 rotates

$$\theta_2 = \frac{r_1}{r_2}\ \theta_1 = \frac{50}{100} \times 60 = 30°$$

clockwise relative to the arm. Thus, adding arm rotation, the total rotation of pulleys 2 and 3 is 30° counterclockwise, while the total rotation of pulley 1 is zero. Since pulleys 3 and 4 are equal, rotation of the lower arm is offset by equal relative motion. Thus, lower arm rotation causes no additional rotation, but the straight edges have rotated by an angle $\theta_1/2$. <u>The machine will not operate properly</u>. (ans)



1.55 Let BC = DE. BE = CD. Size factor DA/DF = 2. Thus, tracing point F falls at midpoint of BE, and CA/CB = 2. Copy traced by A is twice the size of pattern traced by F. Lengths DE and DC are arbitrary, but large enough to allow F to trace the entire pattern.

1.56 Let BC = DE and BE = CD. Part to pattern size ratio = 1.10 = AF/DF where D traces the pattern and A reproduces it 10% larger. Thus, AB/BC = 1.10 and fixed point F is located by the proportion BF/EF = 1.10 since triangles ABF and DEF are similar. BE and DE are arbitrary, but must be large enough for D to trace the entire pattern.

1.57 Let BC = DE and BE = CD. Let AB/AC = 0.40. Point A traces the pattern and point F (on line AD) is the drawing tool. Lengths must be adequate to trace the entire pattern.

1.58 a) $Q = ANd \tan\phi$

$$Q = \frac{(120 \text{ ft}^3/\text{hr})(1 \text{ hr}/60 \text{ min})(1728 \text{ in}^3/\text{ft}^3)}{600 \text{ rev/min}}$$

$= 5.76 \text{ in}^3/\text{rev}$

where A, N, d and ϕ are arbitrary. E.g., let $A = .5 \text{ in}^2$, $N = 6$ cyl, $\phi = 30^\circ$.

Then, $d = \dfrac{Q}{AN \tan\phi} = 3.33$ in

b) Stroke length $L = d \tan\phi = 1.92$ in

Stroke time t = (1 min/600 rev)(60 sec/min)(1 rev/2 strokes) = 0.05 sec/stroke.

$v_{(avg)} = \dfrac{L}{t} = 38.5$ in/sec

1.59 a) $Q = ANd \tan\phi$

$$Q = \frac{0.01 \text{ m}^3}{\text{s}} \times \frac{1\text{s}}{300 \text{ rad}} \times \frac{2\pi \text{rad}}{\text{rev}} = 2.094\times10^{-4} \text{ m}^3/\text{rev}$$

Let $\phi = 30^\circ$, N = 6 cylinders, $A = (d/6)^2$

Then, $2.094\times10^{-4} = (d/6)^2 \times 6 \times d \times \tan 30^\circ$

$d^3 = 2.094\times10^{-4} \times 36/(6 \tan 30^\circ)$

$d = 0.1296$ m $\quad A = 4.665\times10^{-4} \text{ m}^2$

$d = 129.6$ mm $\quad A = 466.5 \text{ mm}^2$

b) Stroke length $L = d \tan\phi = 74.8$ mm

Stroke time $t = \dfrac{1\text{s}}{300 \text{ rad}} \times \dfrac{2\pi \text{rad}}{\text{rev}} = 2.094\times10^{-2}$ s

$V_{avg} = \dfrac{L}{t} = \dfrac{74.8 \text{ mm}}{2.094\times10^{-2} \text{ s}} = 3573$ mm/s (ans)

There are many possible solutions.

1.60 $v = (n/60)(L_2-L_1) = 2\pi\omega(L_2-L_1)$
from which
$L_2 - L_1 = v/(2\pi\omega) = 0.1/(2\pi \times 65) = .000245$
One solution would be two right hand single threads where the leads are $L_1 = 2$ mm, $L_2 = 2.000245$ mm.

1.61 $v = (n/60)(L_2-L_1)$
from which
$L_2 - L_1 = 60\ v/n = 60 \times 0.0005/60$
$= 0.0005$ in
One solution would be two right hand single threads where the leads are $L_1 = 0.05$ (20 threads/in) and $L_2 = 0.0505$ (19.8 threads/in would approximate this value).

1.62 There are many possible solutions, e.g. a linkage with the same dimensions as in the feed mechanism--example problem, but employing a single thread power screw with 10 threads per inch.

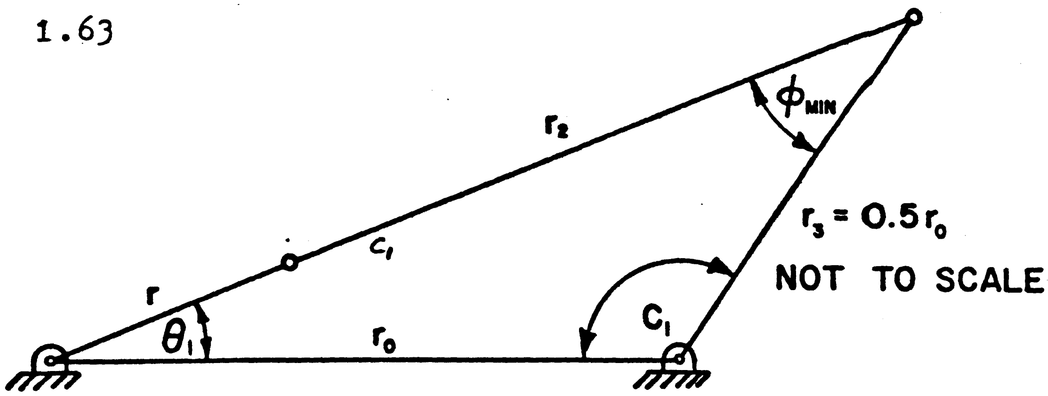
1.63 There are many possible solutions. Consider using a power screw with a lead L = 15mm. Screw pitch would be 5mm if a triple thread screw is used. Feed per ratchet pitch is 0.100mm = L/N = 15/N from which N ≐ 150 ratchet teeth. Let the fixed link have a radius r_o and let $r_3/r_o = 0.5$. See sketch. For a transmission angle of $\phi_{min} = 45^o$ (between links 2 and 3) the triangle solution yields

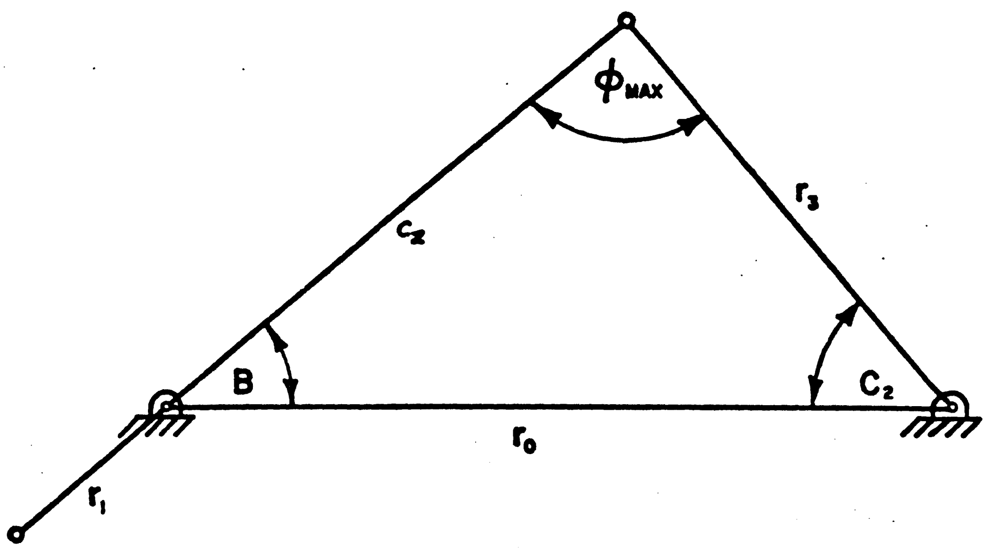
$c_1 = r_1 + r_2 = 1.289\ r_o$
$\theta_1 = 20.7^o$
$\angle C_1 = 114.3^o$ (extended position).
For the fixed position,
$\angle C_2$ is determined by the feed of 3mm divided by the lead:
$(3/15) \times 360 = 72^o = \Delta C$
from which
$\angle C_2 = 114.3 - 72^o = 42.3^o$
The triangle solution yields:
$c_2 = r_2 - r_1 = 0.7144\ r_o$; $\angle B = 28.1^o$
$\phi_{max} = 109.6^o$(which is acceptable).
Using $r_2 - r_1 + r_1 + r_2 = (0.7144 + 1.289)r_o = 2.0034\ r_o$
or $r_2 = 1.002\ r_o$ and $r_1 = 0.287\ r_o$ (maximum value)

These values would have to be changed slightly to account for tolerances in the actual linkage. Crank length r_1 must be adjustable to provide the range of feeds. If we try $r_1(min) = 0.090\ r_o$, then for the extended position,

$c_1 = r_1 + r_2 = 1.002\ r_o + 0.090\ r_o = 1.092\ r_o$
$\phi_{min} = 66.1^o$, $\theta_1 = 27.2^o$ and $\angle C_1 = 86.7^o$. For the flexed position,
$c_2 = r_2 - r_1 = 1.002\ r_o - 0.090\ r_o = 0.912\ r_o$
$\phi_{max} = 84.9^o$; $B = 29.9^o$; $\angle C_2 = 65.3^o$; $\Delta C = C_1 - C_2 = 21.4^o$
21.4 L/360 $\text{Feed}_{(min)} = 21.4\ L/360 = 21.4 \times 15/360 = 0.89$ mm
which is satisfactory (less than the required minimum).

1.63





1.64 $n_2/n_1 = \omega_2/\omega_1 = \cos\phi$ to $1/\cos\phi$ where $\phi = 20^o$.

Thus, $n_2 = 939.7$ to 1064.2 RPM.

1.65 $\omega_2/\omega_1 = \cos\phi$ to $1/\cos\phi$

$n_2 = 1000 \cos 15^o$ to $1000/\cos 15^o$

$n_2 = 965.9$ to 1035.3 RPM

1.66 $0.98 \le \omega_2/\omega_1 \le 1.02$

$0.98 = \cos\phi$ yields $= 11^o28'$

$1.02 = 1/\cos\phi$ yields $\phi = 11^o22'$ or 11.36^o. Thus, permissible misalignment is 11.36^o.

1.67 $\pm 3\%$ variation requires $0.97 \le \omega_2/\omega_1 \le 1.03$

Also, $\cos\phi \le \omega_2/\omega_1 \le 1/\cos\phi$

$\arccos 0.97 = 14.07^o$; $\arccos (1/1.03) = 13.86^o$

Permissible misalignment is 13.86^o.

1.68 For 10 in. stroke, $L_3 = 10/2 = 5$ in. Other dimensions are arbitrary within certain ranges. Thus, there are many solutions. $L_4 > L_3$, say $L_4 = 8$ in. L_0 is shortest, say $L_0 = 2$ in. Let $L_1 = 4.5$ in. The drag link inequality requires that

$$|L_1 - L_2| + L_0 < L_3 < L_1 + L_2 - L_0 \text{ from which}$$

$$2.5 < L_2 < 7.5.$$

Values of L_2 between 2.5 and 7.5 are tried as in the figure. In trial 7, with $L_2 = 6.75$ in., we find $\angle BO_1B' = 121.5^o$ between limiting positions. For this value, the forward to return time ratio is

$$\frac{360^o - 121.5^o}{121.5^o} = 1.96$$

which is close enough to the required value.

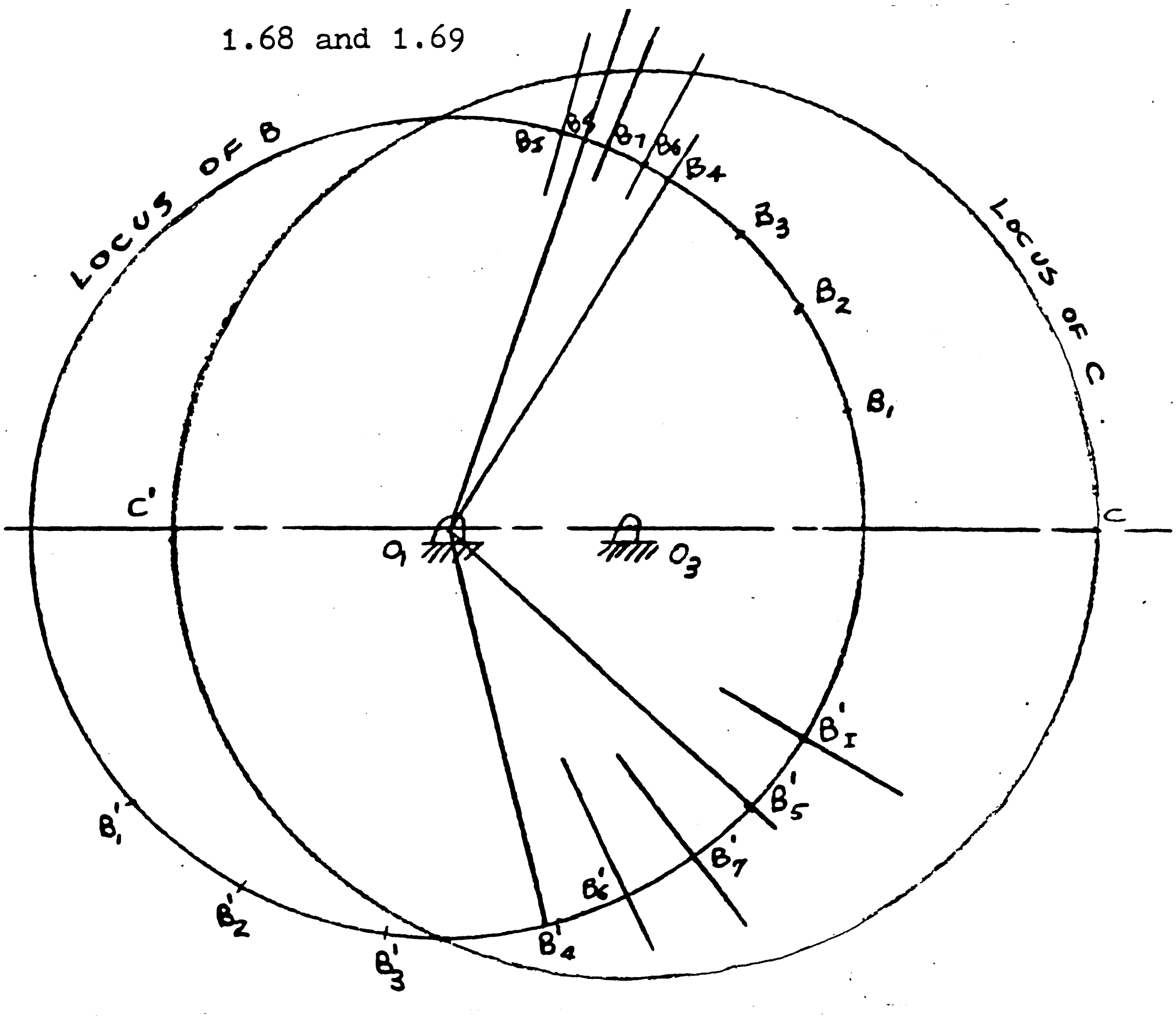
1.69 See figure. There are many solutions. As an example, use the same dimensions as in Prob. 1.68 except for L_2. Trial I with $L_2 = 7.25$ produces $\angle BO_1B' = 106.5^o$. The forward to return ratio is

$$\frac{360^o - 106.5^o}{106.5^o} = 2.45, \text{ close enough to the required value.}$$

1.68 and 1.69

	Trial	L_2	BO_1B'	Ratio
1.68	1	3		
	2	4		
	3	5		
	4	6	135^o	
	5	7	114^o	
	6	6.5	126^o	
	7	6.75	121.5^o	$\frac{238.5}{121.5} = 1.96$
1.69	I	7.25	106.5^o	$\frac{253.5}{106.5} = 2.45$

1.68 and 1.69



LOCUS OF B
LOCUS OF C
B5
B4
B7
B6
B3
B2
B1
C'
C
O1
O3
B'1
B'5
B'7
B'6
B'4
B'1
B'2
B'3

1.70 L_3 = stroke/2 = 75mm. Other dimensions are arbitrary within limits. Referring to the solution to 1.68, we may use the same proportions, yielding $L_0 = 30$; $L_1 = 67.5$; $L_2 = 101.25$; and $L_4 = 120$mm.

1.71 Refer to the solution to Prob. 1.68. L_3 = stroke/2 = 100/2 = 50mm. Using the proportions of Prob. 1.68, $L_0 = 20$; $L_1 = 45$; $L_2 = 67.5$ and $L_4 = 80$ in.

1.72 For ratio of 1.5, set

$$\frac{360^\circ - \theta^\circ}{\theta^\circ} = 1.5 \text{ or } \theta = 144^\circ.$$

There are many solutions. For example, try a distance $O_1O_2 = 5$ in. Then, maximum drive crank length is $L_1(max) = O_1O_2 \cos\theta/2 = 1.55$ in. Then,

$$L_2 = O_2C = \frac{S(max)/2}{\sin(90^\circ - \frac{\theta}{2})} = 16.2 \text{ in.}$$

We will arbitrarily let $L_3 = 4$ in. The distance from O_1 to the path of D may be based on a horizontal position of CD at midstroke. Then, we have $L_2 - O_1O_2 = 11.2$ in., the distance from O_1 to the path of D. For minimum stroke, the crank must be adjustable to a length

$$L_1 \text{ (min)} = O_1O_2\{\frac{S(min)/2}{O_2C}\} = 0.75 \text{ in.}$$

The linkage must be checked to see that physical limits are not reached during operation.

1.73 See Prob. 1.72. Let $O_1O_2 = 7$ in and $L_3 = 4$ in.

$$\text{Ratio } 2.5 = \frac{360 - \theta}{\theta} \text{ whence } \theta = 103^\circ.$$

$$L_1 \text{ (max)} = O_1O_2 \cos\frac{\theta}{2} = 4.36. \text{ Then,}$$

$$L_2 = \frac{S(max)/2}{\sin(90 - \frac{\theta}{2})} = 8.03 \text{ in.}$$

If this design is used, link 2 must be estended beyond C and designed so that the slider clears pin C. (I.e., the actual configuration differs from the schematic.) For minimum stroke,

$$L_1 \text{ (min)} = O_1O_2 \frac{S(min)/2}{O_2C} = 2.18 \text{ in.}$$

Let the distance from O_2 to the path of D equal O_2C or 8.03 in.

1.74

For 1.5 to 1 ratio, $\angle BO_1B' = 360 \times 1/(1.5+1) = 144^o$ $\angle BO_1O_2 = 72^o$

$\angle BO_2O_1 = 90 - 72 = 18^o$

For 200 mm stroke, $2O_2C \sin BO_2O_1 = 200$ mm

$O_2C = 100/\sin 18^o = \underline{323.6 \text{ mm}}$

$O_1B/O_2O_1 = \sin 18^o$

If we let $O_2O_1 = \underline{200 \text{ mm}}$, $O_1B_{(max)} = 200 \sin 18^o = \underline{61.8 \text{ mm}}$

For minimum stroke, $2\ O_2C \sin BO_2O_1 = 100$ mm

$\sin BO_2O_1 = 100/(2\text{x}323.6)$ $\angle BO_2O_1 = 8.888^o$

$O_1B_{(min)} = 200 \sin 8.888^o = \underline{30.9 \text{ mm}}$

1.75 See above problem. $\angle BO_1O_2 = 72^o$

$\angle BO_2O_1 = 18^o$

For 280 mm stroke, $2\ O_2C \sin BO_2O_1 = 280$ mm

$O_2C = 280/(2 \sin 18^o) = \underline{453 \text{ mm}}$

Selecting $O_1O_2 = \underline{250 \text{ mm}}$,

$O_1B_{max} = O_1O_2 \sin BO_2O_1 = 250 \sin 18^o = \underline{77.25 \text{ mm}}$

For 180 mm stroke, $2\ O_2C \sin BO_2O_1 = 180$ mm

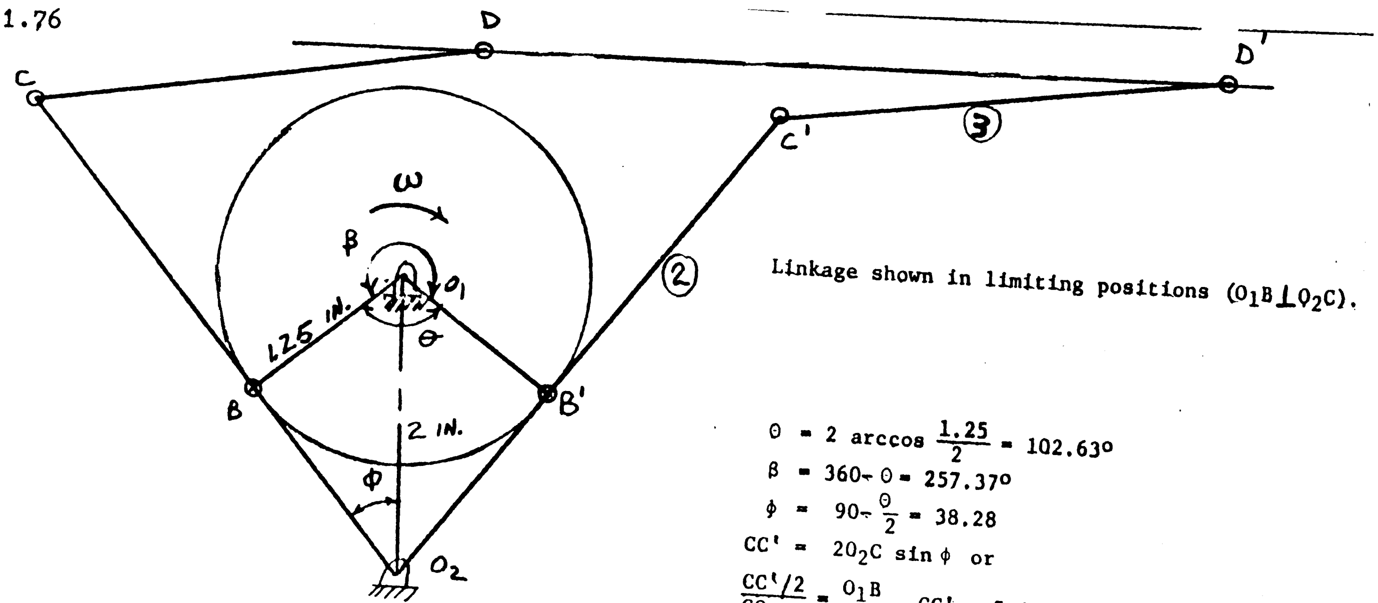
$\sin BO_2O_1 = 180/(2\text{x}453)$ $\angle BO_1O_2 = 11.46^o$

$O_1B_{(min)} = 250 \sin BO_1O_2 = 250 \sin 11.46^o = \underline{43.67 \text{ mm}}$

1.76 As link 1 rotates about a fixed point, link 2 rotates (oscillates) about a fixed point, link 3 has combined rotation (oscillation) and translation and link 4 translates. As the slider moves from left to right, link 1 turns through $\beta = 257.4^o$. See sketch. Link 1 turns through $\theta = 102.6^o$ as the slider returns. The ratio of β to θ which corresponds to the time ratio of forward to return strokes is 2.5 to 1. The stroke, given by DD' or CC' is 5 in. Values may be computed or measured directly from the sketch.

1.77 As link 1 rotates about O_1, link 2 has combined rotation (oscillation) and translation and link 3 translates. As the slider moves from left to right, link 1 turns through = 159.6^o; link 1 turns through $\theta = 200.4^o$ as the slider returns. See sketch. The ratio of to θ is 0.796 to 1. The stroke, CC', is 3.14 in. Values may be computed or measured directly from the sketch.

1.76



Linkage shown in limiting positions ($O_1B \perp O_2C$).

$\Theta = 2 \arccos \frac{1.25}{2} = 102.63°$

$\beta = 360 - \Theta = 257.37°$

$\phi = 90 - \frac{\Theta}{2} = 38.28$

$CC' = 2O_2C \sin\phi$ or

$\frac{CC'/2}{CO_2} = \frac{O_1B}{O_1O_2}$ $CC' = 5$ in.

1.77

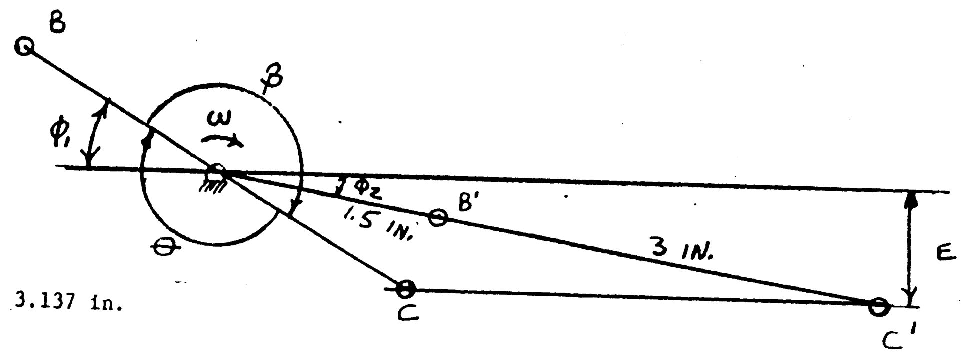
$\phi_1 = \arcsin \frac{E}{L-R} = 30°$

$\phi_2 = \arcsin \frac{E}{L+R} = 9.6°$

$\beta = 180 - \phi_1 + \phi_2 = 159.60°$

$\Theta = 360 - \beta = 200.40°$

$CC' = \sqrt{(L+R)^2 - E^2} - \sqrt{(L-R)^2 - E^2} = 3.137$ in.



1.78 Link 1 rotates about O_1 , link 2 rotates and translates, and link 3 translates.

ϕ_1 = arcsin(E/(L-R)) = arcsin(20/(120-60))=19.47^o

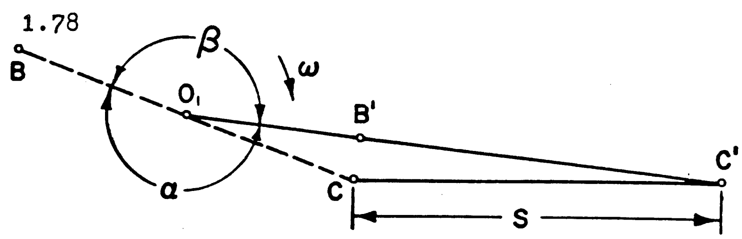
ϕ_2 = arcsin(E/(L+R)) = arcsin(20/(120+60))=6.38^o

$\beta = 120^o - \phi_1 + \phi_2 = 180^o - 19.47^o + 6.38^o = 166.91^o$ (left to right)

$\alpha = 180^o + \phi_1 - \phi_2 = 180^o + 19.47^o - 6.38^o = 193.09^o$ (right to left)

Stroke $S = ((L+R)^2 - E^2)^{\frac{1}{2}} - ((L-R)^2 - E^2)^{\frac{1}{2}}$

$= ((120+60)^2 - 20^2)^{\frac{1}{2}} - ((120^2-60)^2 - 20^2)^{\frac{1}{2}} = 122.32$mm.



1.79 $\phi_1 = \arcsin \frac{E}{L-R} = 7.65^o$

$\phi_2 = \arcsin \frac{E}{L+R} = 3.28^o$

$\alpha = 180 + \phi_1 - \phi_2 = 184.37^o$

$\beta = 180 - \phi_1 + \phi_2 = 175.63^o$

a) $\frac{\alpha}{\beta} = 1.05$

b) $S = [(L+R)^2 - E^2]^{\frac{1}{2}} - [(L-R)^2 - E^2]^{\frac{1}{2}} = 4.016$

1.80 ϕ_1 = arcsin[E/(L-R)] = arcsin[0.8/(5-2)] = 15.47°

ϕ_2 = arcsin[E/(L+R)] = arcsin[0.8/(5+2)] = 6.56°

$\alpha = 180^o + \phi_1 - \phi_2 = 180 + 15.47 - 6.56 = 188.9^o$

$\beta = 180^o - \phi_1 + \phi_2 = 180 - 15.47 + 6.56 = 171.1^o$

a) Time ratio = α/β = 188.9/171.1 = 1.104

b) Stroke $S = [(L+R)^2 - E^2]^{1/2} - [(L-R)^2 - E^2]^{1/2}$

$= [(5+2)^2 - 0.8^2]^{1/2} - [5-2)^2 - 0.8^2]^{1/2} = 4.063$

1.81 ϕ_1 = arcsin[E/(L-R)] = arcsin[0.65/(5-2)] = 12.51°

ϕ_2 = arcsin[E/(L+R)] = arcsin[0.65/(5+2)] = 5.33°

$\alpha = 180^o = \phi_1 - \phi_2 = 180 + 12.51 - 5.33 = 187.19^o$

$\beta = 180^o - \phi_1 + \phi_2 = 180 - 12.51 + 5.33 = 172.81^o$

a) Time ratio = α/β = 187.19/172.81 = 1.083

b) Stroke $S = [(L+R)^2 - E^2]^{1/2} - [(L-R)^2 - E^2]^{1/2}$

$= [(5+2)^2 - 0.65^2]^{1/2} - [(5-2)^2 - 0.65^2]^{1/2} = 4.041$

1.82 The linkage is plotted in various positions and the midpoint of the connecting rod is located as in the figure. Alternatively, a computer graphics program is used, plotting the linkage for increments of $T_1=\pi/9$ radians (see second figure). Then, the midpoint of the connecting rod is located by $X3=(X_1+X_2)/2$, $Y3=(Y1+Y2)/2$. It is plotted to the same scale (third figure). (For this plot, the eccentricity is assumed to be positive.)

1.83 A computer graphics program is used as described in problem 1.82. First, the linkage is shown in 18 positions. See figure. The coupler curve is then plotted. The scale inside the coordinate axes applies to problem 1.82, while the outside scale applies to problem 1.83. The proportions of the linkage are the same in both problems.

1.84 See Figure 1.41. When the one-way clutch is engaged, link 5 and the output shaft move as a unit. There are six links including the frame and seven one-degree-of-freedom pairs (point C represents two pairs). Degrees of freedom are given by

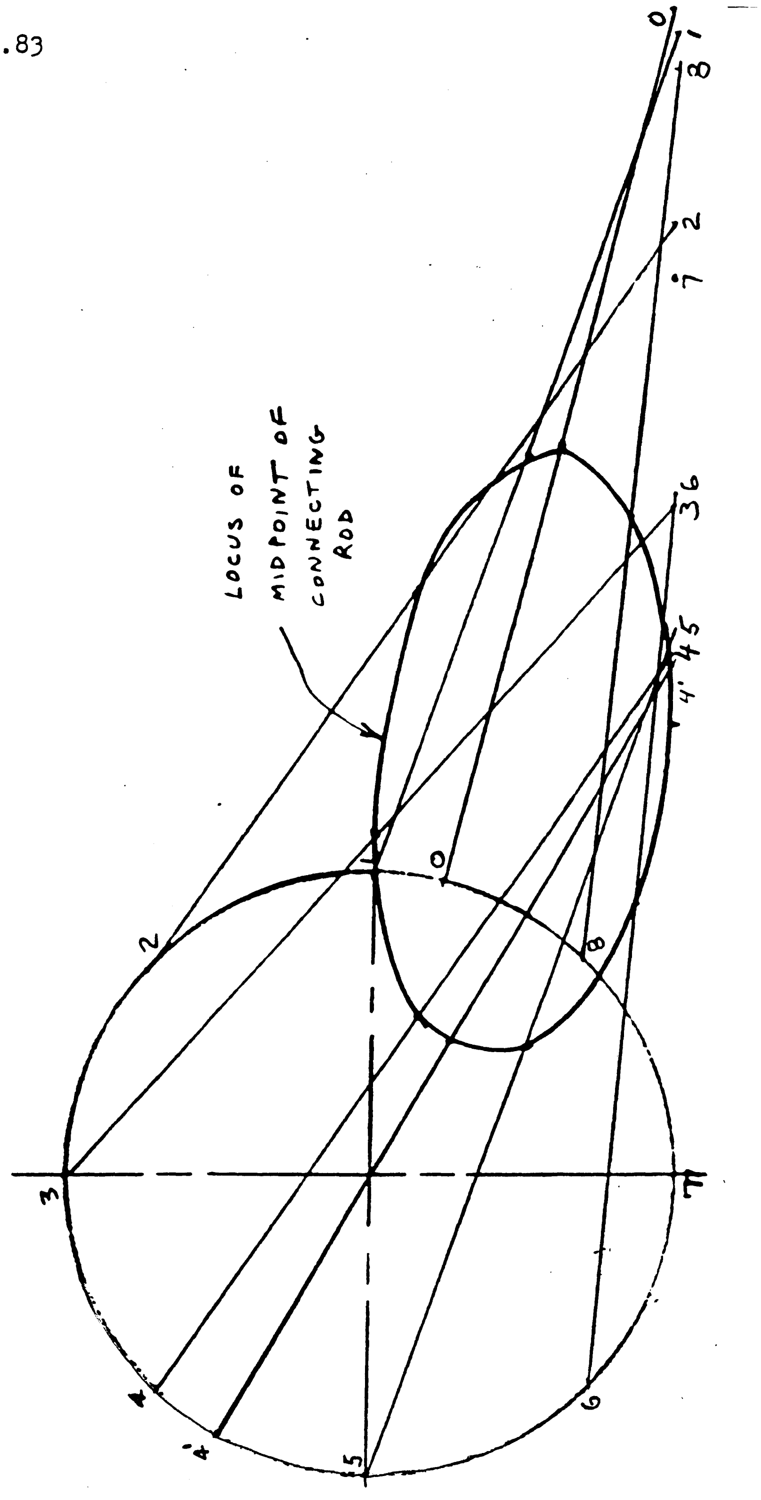
$$DF_{(planar)} = 3(n_L-1) - 2n_j$$
$$= 3(6-1) - 2(7) = 1$$

1.85 through 1.88

Driver L_1 shortest ($L_1<L_2$) and $L_1 + |L_2-L_3| < L_0 < L_2 - L_1 + L_3$

or $L_{max} + L_1 < L_a + L_b$

1.83

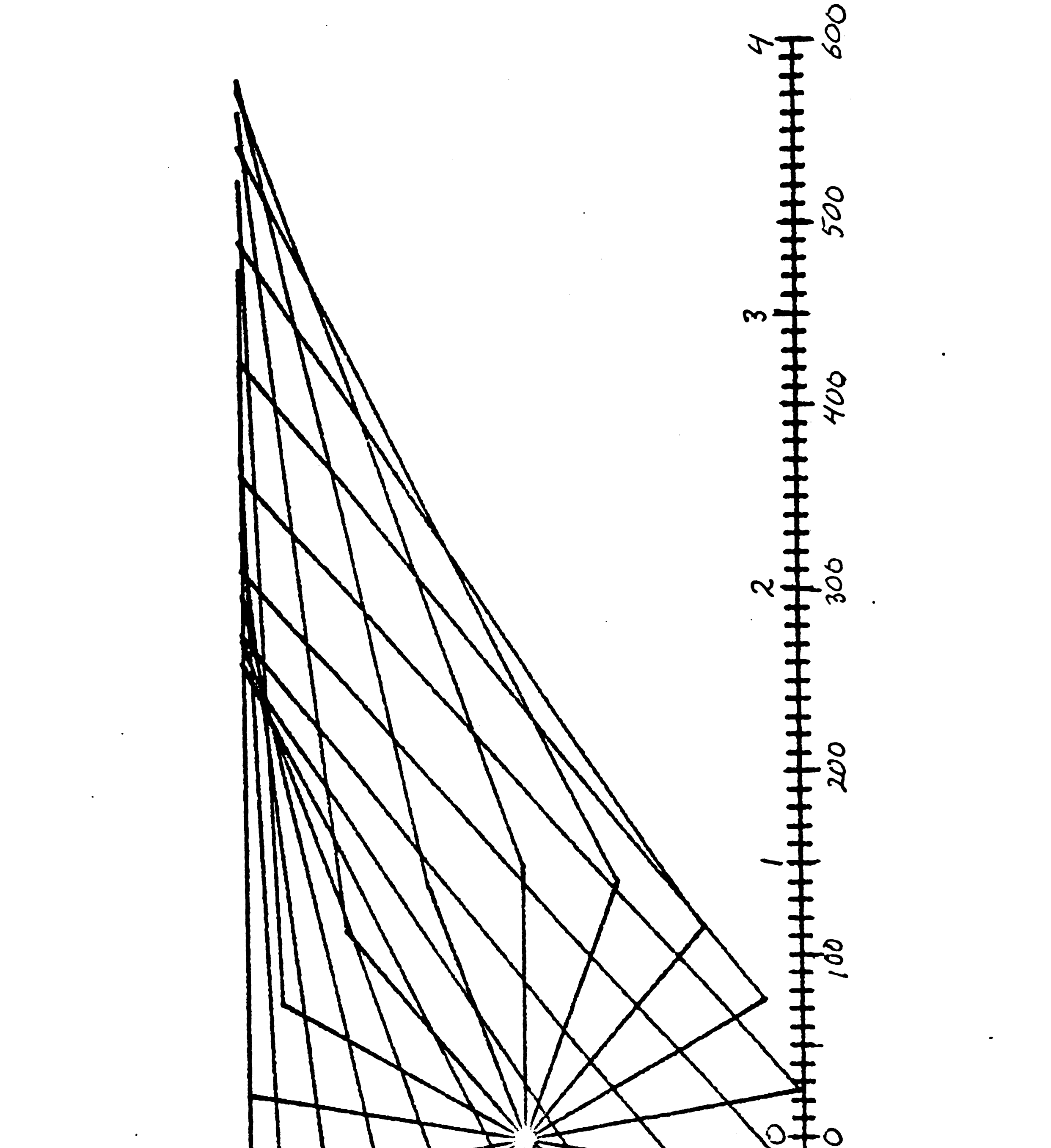


1.83 continued

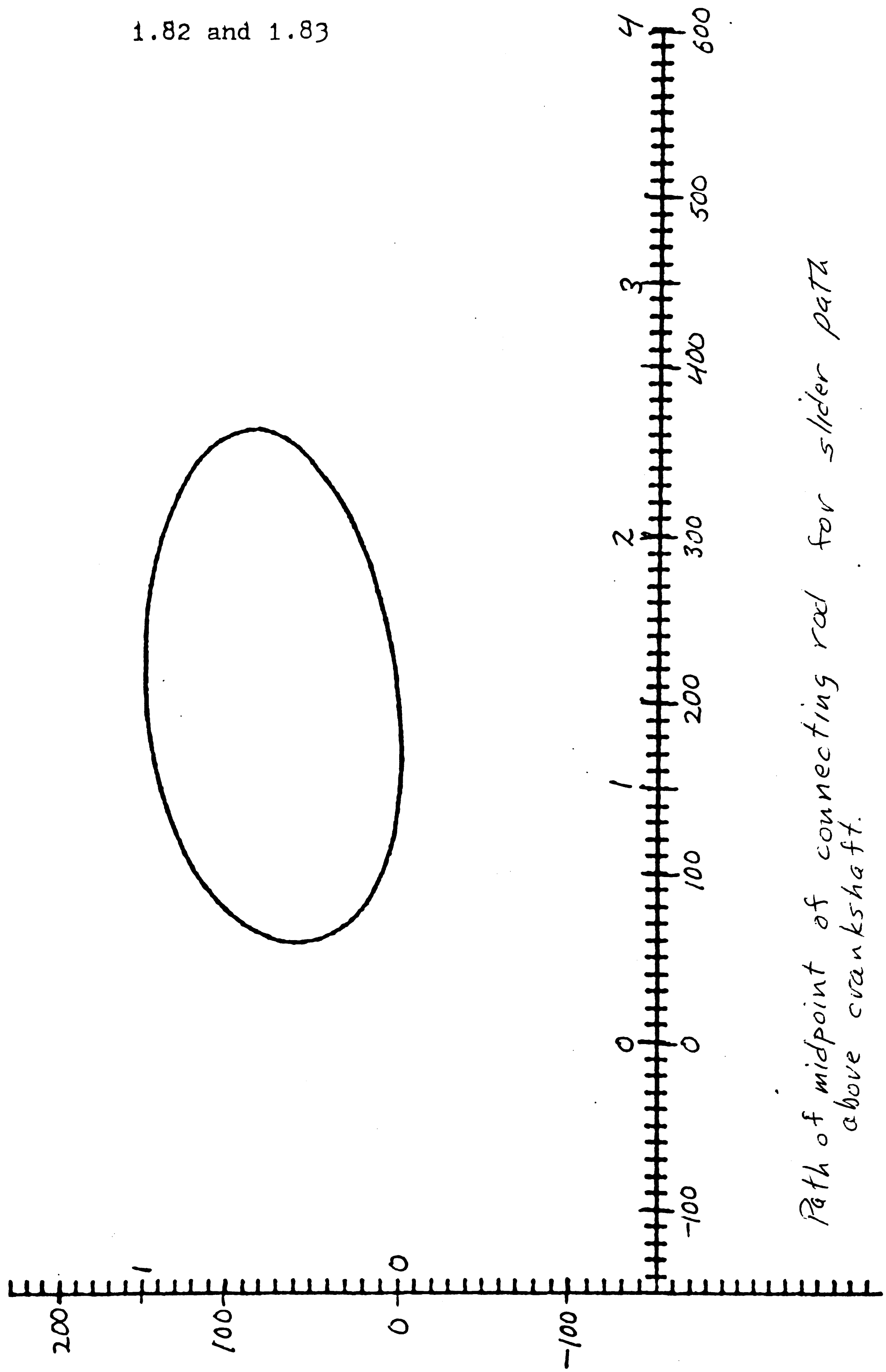
```
LIST
100 PAGE
101 PRINT "INPUT 32 FOR SCREEN 1 FOR PLOTTER"
105 INPUT D
110 PAGE
120 R=150
130 L=450
140 E=150
150 WINDOW -150,600,-288.46,288.46
160 VIEWPORT 0,130,0,100
170 FOR T1=0 TO 2*PI STEP PI/9
180 X1=R*COS(T1)
190 Y1=R*SIN(T1)
200 T2=ASN((Y1-E)/L)
210 X2=X1+L*COS(T2)
220 Y2=E
230 MOVE @D:0,0
240 DRAW @D:X1,Y1
250 DRAW @D:X2,Y2
260 NEXT T1
270 AXIS @D:10,10,-150,-150
280 HOME
290 END
```

```
LIST
100 PAGE
101 PRINT "INPUT 32 FOR SCREEN 1 FOR PLOTTER"
105 INPUT D
110 PAGE
120 R=150
130 L=450
140 E=150
150 WINDOW -150,600,-288.46,288.46
160 VIEWPORT 0,130,0,100
165 MOVE @D:362.1,75
170 FOR T1=0 TO 2*PI STEP PI/30
180 X1=R*COS(T1)
190 Y1=R*SIN(T1)
200 T2=ASN((Y1-E)/L)
210 X2=X1+L*COS(T2)
220 Y2=E
230 X3=(X1+X2)/2
240 Y3=(Y1+Y2)/2
250 DRAW @D:X3,Y3
260 NEXT T1
270 AXIS @D:10,10,-150,-150
280 HOME
290 END
```

1.82 and 1.83



1.82 and 1.83



Path of midpoint of connecting rod for slider path above crankshaft.

1.85 $50 < L_2$ and $0 < L_2$

$50 + |L_2 - 150| < 200 < L_2 - 50 + 150 \therefore$ $\underline{100 < L_2 < 300 \text{ mm}}$

.86 $50 < L_2$ and $50 + |L_2 - 150| < 210 < L_2 - 50 + 150$

$L_2 - 150 < 160 \qquad L_2 < 310 \qquad 110 < L_2$

$50 + 150 - L_2 < 210 \qquad -10 < L_2 \qquad \therefore$ $\underline{110 < L_2 < 310}$ mm

1.87 $45 < L_2$ and $45 + |L_2 - 150| < 200 < L_2 - 45 + 150$

$L_2 - 150 < 155 \qquad L_2 < 305 \qquad 45 + 150 - L_2 < 200 - 5 < L_2$

$200 + 45 - 150 < L_2 \qquad 95 < L_2 \qquad \therefore$ $\underline{95 < L_2 < 305}$ mm

1.88 $50 < L_2$ and $50 + |L_2 - 160| < 200 < L_2 - 50 + 160$

$L_2 - 160 < 150 \qquad L_2 < 310 \qquad 160 < L_2 < 150 \qquad 10 < L_2$

$200 < L_2 + 110 \qquad 90 < L_2 \qquad \therefore$ $\underline{90 < L_2 < 310}$ mm

1.89 through 1.92

$L_2^2 - 2L_2L_3 \cos 45^o + L_3^2 - (L_0 - L_1)^2 = 0$ for $\phi_{min} = 45^o$

$L_2^2 - 1.414\, L_3L_2 + L_3^2 - (L_0 - L_1)^2 = 0$

$L_2 = (1/2)(1.414\, L_3 \pm \sqrt{2L_3^2 - 4[L_1^2 - (L_0 - L_1)^2]}) =$

$0.707\, L_3 \pm \sqrt{-.5\, L_3^2 + (L_0 - L_1)^2}$

$\cos \phi_{max} = (L_2^2 + L_3^2 - (L_0 + L_1)^2)/(2L_2L_3)$

The root (L_2) which falls in the crank rocker range is selected.

1.89 $(200-50)^2 = L_2^2 + 150^2 - 2L_2 \times 150 \cos 45^o$

$L_2 = 0.707 \times 150 \pm \sqrt{-.5 \times 150^2 + (200-50)^2} =$ $\underline{212.13 \text{ mm}}$ (or 0)

$$\cos \phi_{max} = \frac{[212.13^2 + 150^2 - (200+50)^2)]}{2 \times 212.13 \times 150}$$

$\underline{\phi_{max} = 85.5^o}$

1.90 $L_2 = .707 \times 150 \pm \sqrt{-.5 \times 150^2 + (210-50)^2} =$ $\underline{225.84 \text{ mm}}$

(or -13.74 -- not possible)

$$\cos \phi_{max} = \frac{225.84^2 + 150^2 - (210+50)^2}{2 \times 225.84 \times 150} \qquad \underline{\phi_{max} = 85^o}$$

1.91 $L_2 = .707 \times 150 \pm \sqrt{-.5 \times 150^2 + (200-45)^2} =$ $\underline{219.08 \text{ mm}}$

(or -6.98 -- not possible)

$$\cos \phi_{max} = \frac{219.08^2 + 150^2 - (200+45)^2}{2 \times 219.08 \times 150} \qquad \underline{\phi_{max} = 80.83^o}$$