A COMPUTER-AIDED DESIGN SYSTEM
(FBAR) TO SOLVE FOUR-BAR
COUPLER POSITION PROBLEMS

By

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ABSTRACT

A computer-aided design system (FBAR) has been developed which is capable of solving four-bar coupler position problems. This system can handle theoretically any number of positions of the coupler link and allows the designer to exercise his judgement in the design process by making use of the computer and the graphical display.

The theory is based on a multifactor optimization of two dependent design variables (errors in the coupler point coordinates and in the coupler link orientation) and by imposing constraints to ensure that a proper four-bar mechanism is obtained.

At present the synthesis program of the system is run on a CDC 6400 computer in a timesharing mode and the graphical analysis program is run on a PDP11/34 mini-computer. The final aim would be to make it a single system through a satellite graphics approach.

FBAR, the software system, has been tested for all types of the four-bar mechanisms (i.e., crank-rocker, double-crank and double-rockers) with the number of prescribed positions of the coupler link varying from three to nine.

ACKNOWLEDGEMENTS

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Financial assistance from the Natural Sciences and Engineering Research Council Canada is gratefully acknowledged.

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CHAPTER I

INTRODUCTION

1.1 Mechanisms

A mechanism is a device to transform one motion into another. If the device also transmits substantial forces, then it is known as a machine. A mechanism may be defined as a combination of rigid bodies connected in such a way that they move relative to each other with constrained motions. The motion may be transformed from either uniform to uniform or from uniform to non-uniform motion. Circular gears, chains, belts comprise most of uniform motion converters. Noncircular gears, cams and linkages belong to non-uniform motion converters.

A mechanism whose links have plane motions all parallel to the same plane is known as a planar mechanism. The motion of all particles of all links in a plane mechanism can be shown in one plane. Plane motion can be considered to be a combination of translation and rotation. If a line drawn through any machine member remains parallel to itself during the motion, then the motion is defined as translation, where as rotation occurs when such a line changes its direction during the motion.

The four-bar linkage is the most versatile of all mechanisms. It consists of four rigid members: the frame, which is stationary and to which are pivoted the crank and follower. The crank and follower are connected by means of the coupler. These members are connected by four Revolute pairs R_1, R_2, R_3 and R_4 whose axes are parallel (Figure 1.1.1). The input link is known as the crank and the output link is known as the follower.

The four-bar mechanism is very widely used.' It is the simplest possible lower-paired plane mechanism. Many mechanisms whose physical forms are not the four-bar are equivalent to four-bars in some aspects of their motions. Several important more complex mechanisms have four-bars as elements. The four-bar mechanism and its equivalents appear in some of the oldest as well as the most modern machines, in small instruments and in some of the heavy mechanical equipments. A few examples of applications of the four-bar mechanism are given below.

One of the most common uses for the four-bar mechanism is the conversion of rotary to oscillatory motion. Figure 1.1.2 shows a lawn sprinkler with a four-bar mechanism O_2ABO_4. Crank 2 is rotated by a small water operated motor. Links 4, 4' and the sprinkler tube oscillate as one rigid body about an axis through O_4 perpendicular to the paper.

Another application of the four-bar mechanism is the use of the coupler curve. Figure 1.1.3 shows the use of a four-bar in materials-handling equipment. Here point C on the coupler of the four-bar linkage O_AABO_B describes the path C as the crank 2 rotates through 360°. This motion is communicated to the transport member 5 by means of parallelogram linkages; member 5 moves horizontally for the line segment

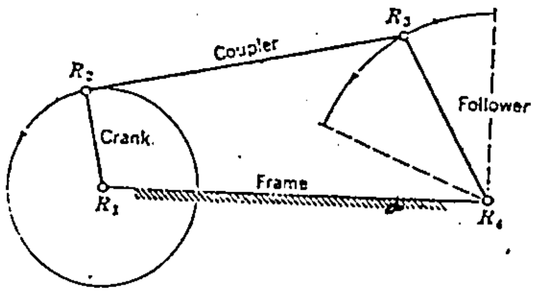

Figure 1.1.1 Four-bar linkage [1].

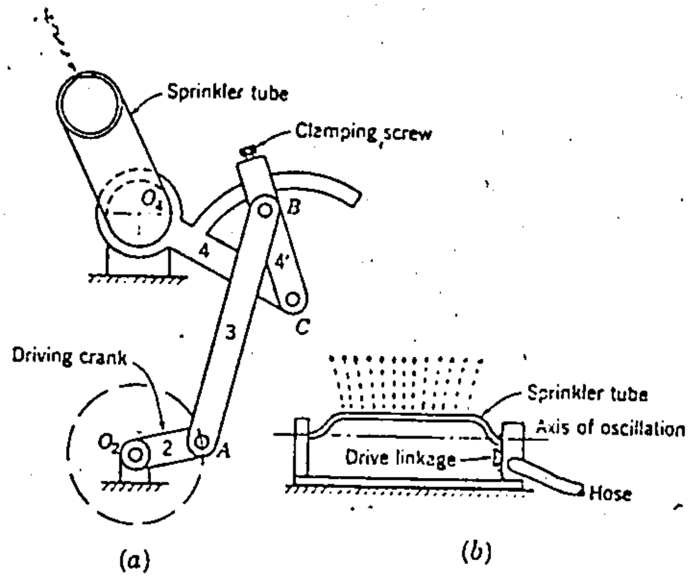

Figure 1.1.2 Application of the 4-bar mechanism in a lawn-sprinkler oscillator. [2]

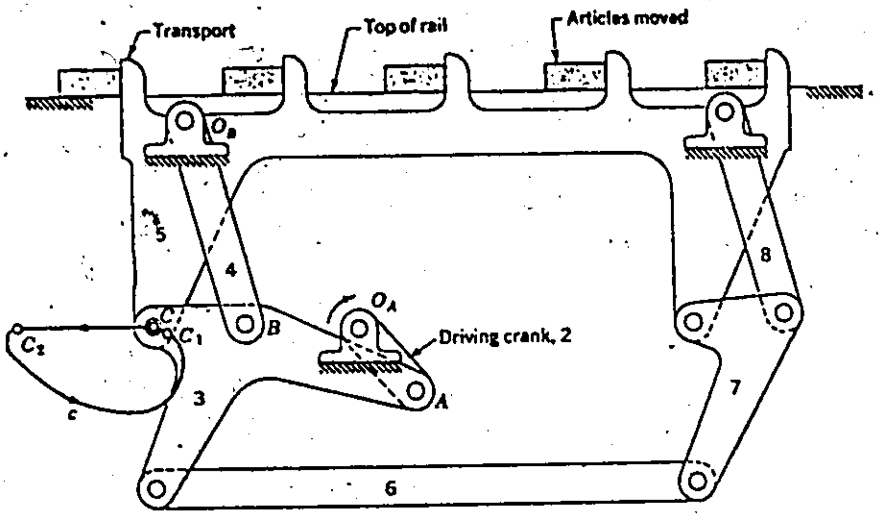

Figure 1.1.3 Transport mechanism. *(From C. W. Ham, E. J. Crane, and W. L. Rogers, "Mechanics of Machinery," 4th ed., p. 439, McGraw-Hill Book Company, New York, 1958.)* [1].

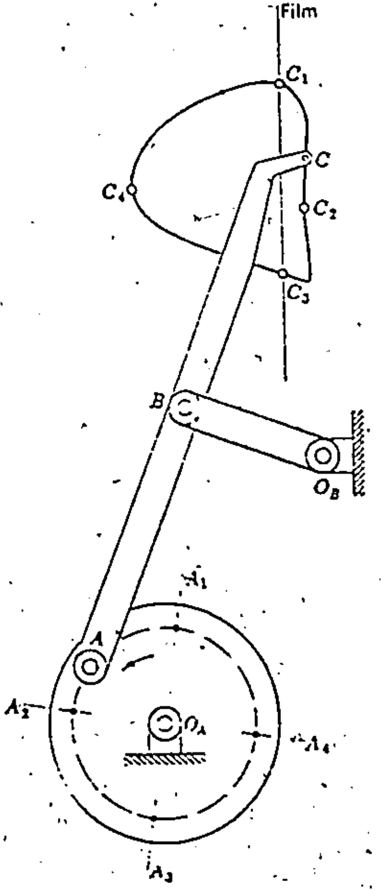

Figure 1.1.4 Film feed. *(From "Die Wissenschaftliche und Angewandte Photographie," ed. by Kurt Michel, vol. 3, Harald Weise, "Die Kinematographische Kamera," p. 202, Springer-Verlag OHG, Vienna, 1955.)* [1].

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C_1 C_2 and then drops out of the way, to reappear later at the right, rising nearly vertically before moving to the left. A similar mechanism is used for the film transport in some motion-picture cameras (Figure 1.1.4).

An examination of the different typewriters on the market will reveal a great variety in the linkages activating the typebars. However most of them use one or more four-bar mechanisms as essential elements in the linkage. Figure 1.1.5 shows a typical example.

Much ingenuity has been displayed in developing mechanisms for toys. One of the interesting problems has been the devising of a realistic, yet simple walking mechanism for mechanical toy animals. Figure 1.1.6 shows one such mechanism. Crank 2 is driven by a conventional spring motor and gear train. The rear leg (link 5) of the toy is pivoted on the frame and caused to oscillate. Crank 2, frame 1, connecting rod 4, and rear leg 5 form one four-bar mechanism. The foreleg, link 3, is given a more complicated motion. The upper end of the leg is slotted and guided by a pin fixed to the frame. A point on the forefoot is thus given a roughly elliptical path.

Figure 1.1.7 shows a forklift truck in which the fork is guided by a four-bar linkage. This design eliminates the mast used in many lift trucks, providing for maneuverability of the truck in areas of low head room.

In engineering practice most problems of linkage design can be categorized into three types.

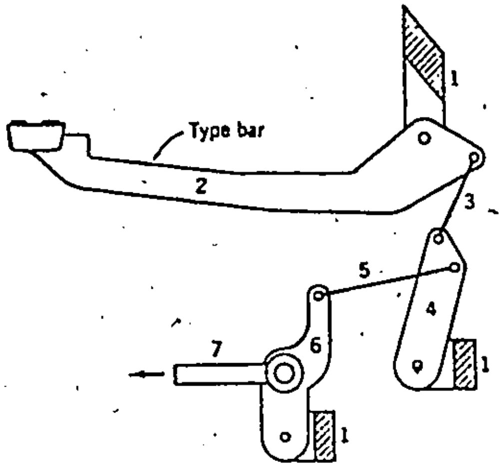

Figure 1.1.5 A typewriter linkage. Two 4-bar mechanisms in series. [3].

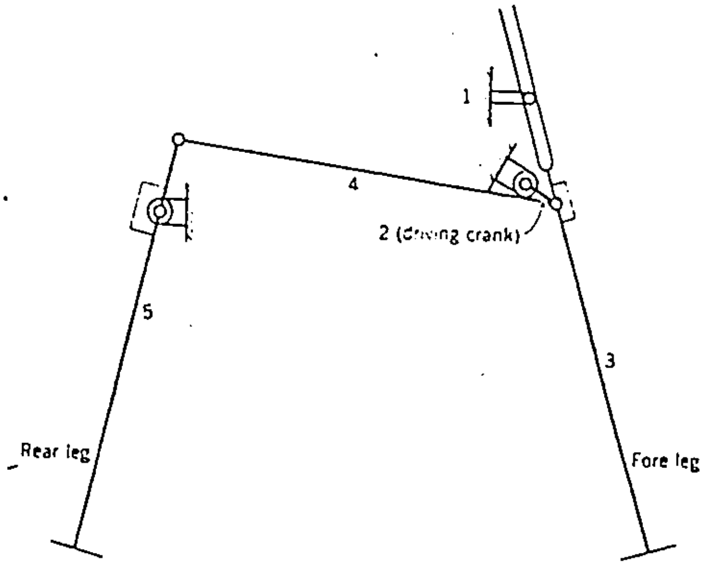

Figure 1.1.6 A toy-walking mechanism. Two 4-bar mechanisms in parallel. [3].

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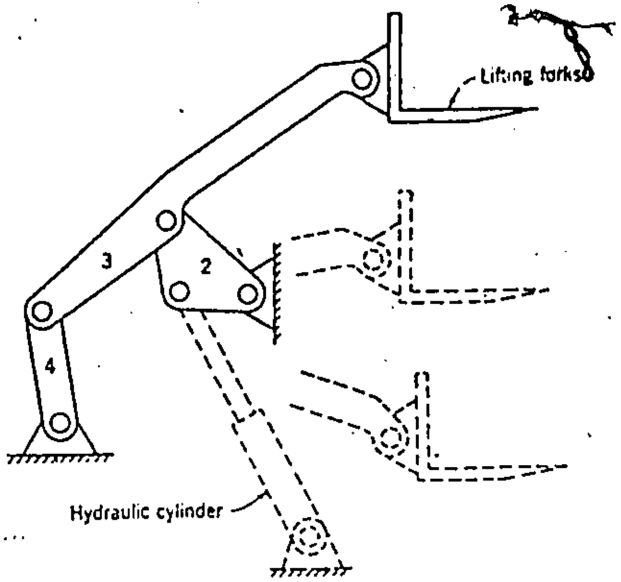

Figure 1.1.7 Mechanism of fork-lift truck without mast. [2].

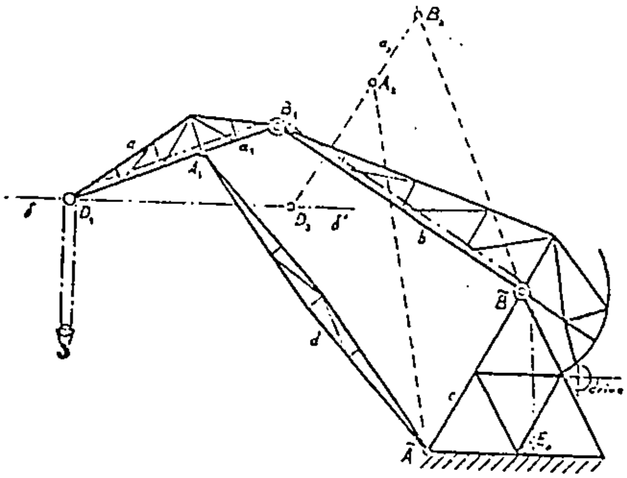

Figure 1.1.8 Out-rigger a of a jib-crane operating as a double rocker in two finitely near positions a_1 and a_2 [3].

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1. Coordination of Input and Output Motion:

Crank-rocker and double-crank mechanisms are used to coordinate input and output crank angles. Slider-crank mechanisms are used to coordinate angular motion with linear displacements. The outgrowth of this type of problem is the function generators. The motion of the output link is a mathematical function of the input motion.

2. Point Tracing:

This type of problem involves the design of a linkage where the coupler point traces out a specified path.

3. Link Guiding or Position Generator:

Here a linkage is designed to guide a moving plane through a series of specified positions.

Figure 1.1.8 illustrates the mechanism of a jib crane. The coupler AB of the double-rocker in the jib-crane $\overline{A}A\ B\overline{B}$, moves from position A_1B_1 to position A_2B_2 while point D on $\overline{a}$ describes the horizontal line $\delta\delta'$ or at least approaches it as closely as possible when $\overline{a}$ is moved from position A_1B_1 to A_2B_2. In order to fulfill this requirement (D accurately following straight line $\delta\delta'$) there would have to be many more intermediate positions $A_3B_3, A_4B_4, \ldots\ldots$ with $D_3, D_4 \ldots$ taken along $\delta\delta'$.

Figure 1.1.9 shows a thread feeder mechanism of a central spool sewing machine. The eye of the thread lever passes through points S_1, S_2 and S_3 while corresponding angles

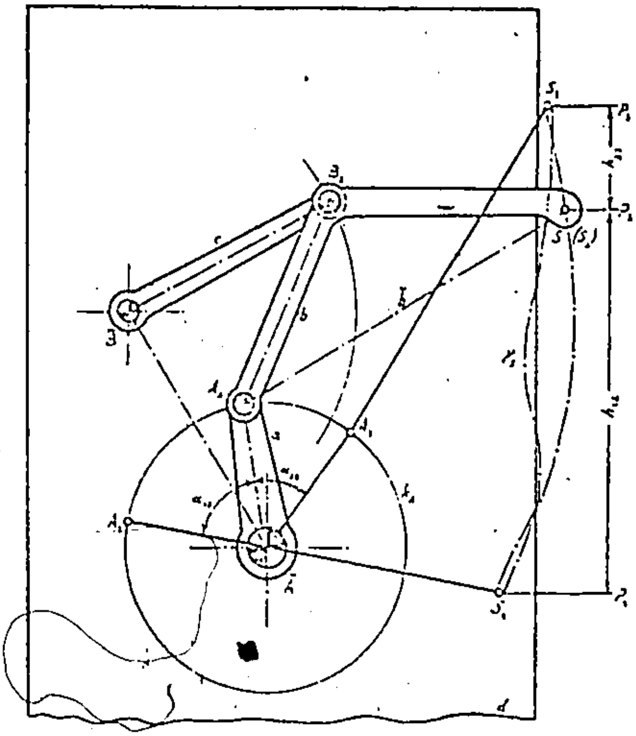

Figure 1.1.9 Three link positions of coupler AB of a 'threadfeeder mechanism for a sewing machine' corresponding to given co-ordinated angles of rotation α_{12}, α_{23} of the driving crank [3].

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$\alpha_{12} = A_1\bar{A}A_2$ and $\alpha_{23} = A_2\bar{A}A_3$ are turned. The crank positions $\bar{A}A_1, \bar{A}A_2$ and $\bar{A}A_3$ are so chosen about the driving shaft axis A in the machine head so that:

$$\measuredangle A_1\bar{A}A_2 = \alpha_{12} \quad \text{and} \quad \measuredangle A_2\bar{A}A_3 = \alpha_{23}$$

are fixed. Then some coupler length is chosen for the lengths from the crank pin A to the eye S. Three finitely separated positions of the coupler plane b, described by $\bar{b} = \overline{AS}$ are given by $\overline{A_1S_1}$, $\overline{A_2S_2}$ and $\overline{A_3S_3}$ in which A passes through points A_1, A_2 and A_3 on the crank circle.

It is required to find a four-bar linkage $\bar{A}AB\bar{B}$ which will move $\overline{AS} = \bar{b}$ of the coupler plane b through $\overline{A_1S_1}$, $\overline{A_2S_2}$ and $\overline{A_3S_3}$.

Another example of link guiding is the design of a car window mechanism. One of the more complex body hardware mechanisms present on all automobiles is the window regulator. Positive control over the window motion must result from a linkage exhibiting certain desirable characteristics and within definite space limitations (Figure 1.1.10). As shown in Figure 1.1.11, points F and G must stay within certain space limitations imposed by door hinges, door latches, sheet metal parts, and to accomplish this, the mechanism must fit within the available space. The basic design for this is shown in Figure 1.1.12 with the four-bar linkage CABD. The driver arm (CAP) is attached directly to the sector gear which is moved by the pinion gear on the crank handle shaft. The equalizer link (RAB) controls the front part of the window. Since pivot P

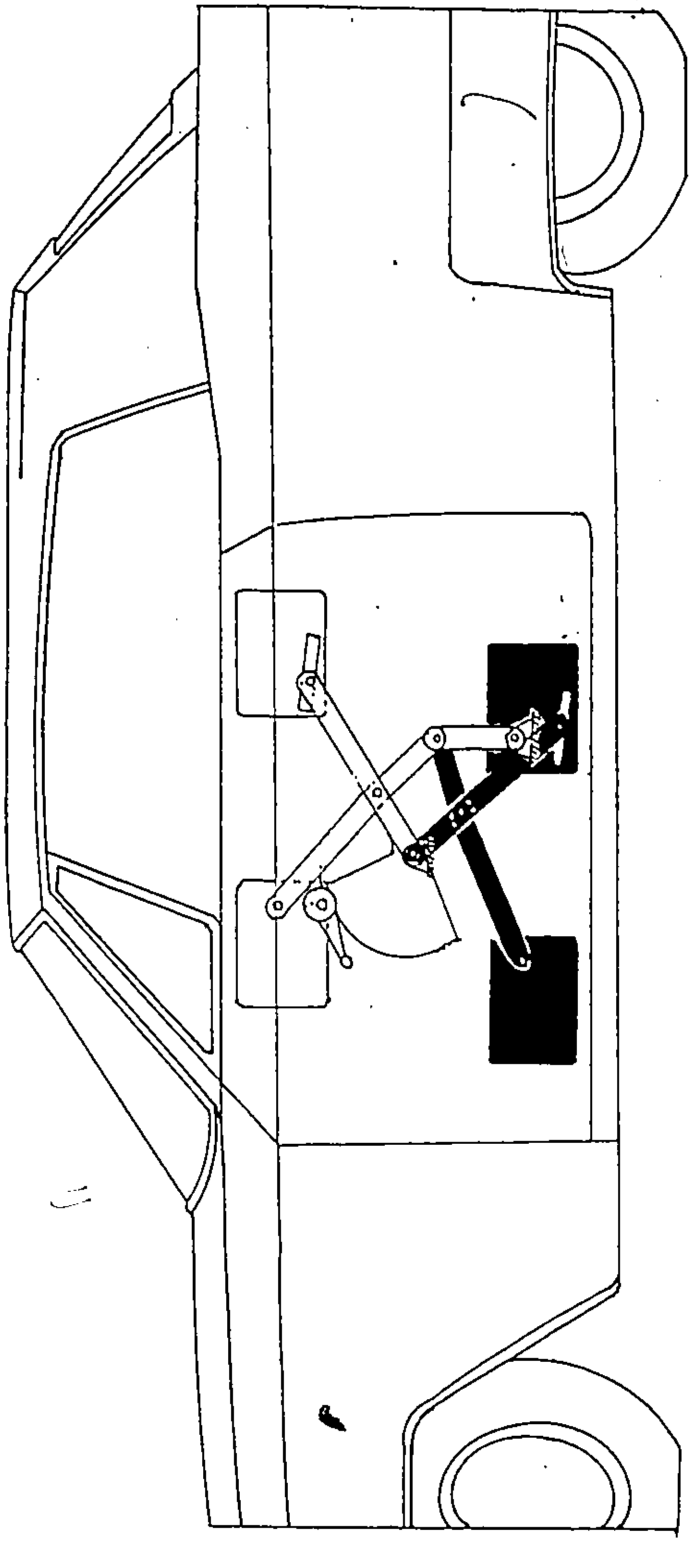


Figure 1.1.10 Car window mechanism [4].

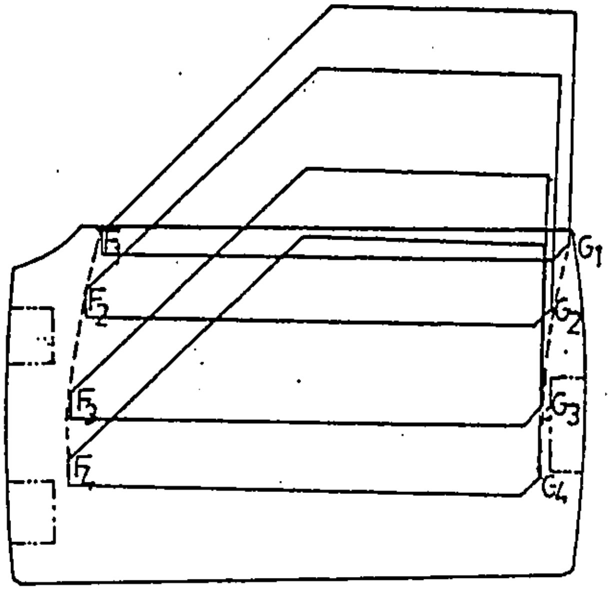


Figure 1.1.11 Four positions of the window [4].

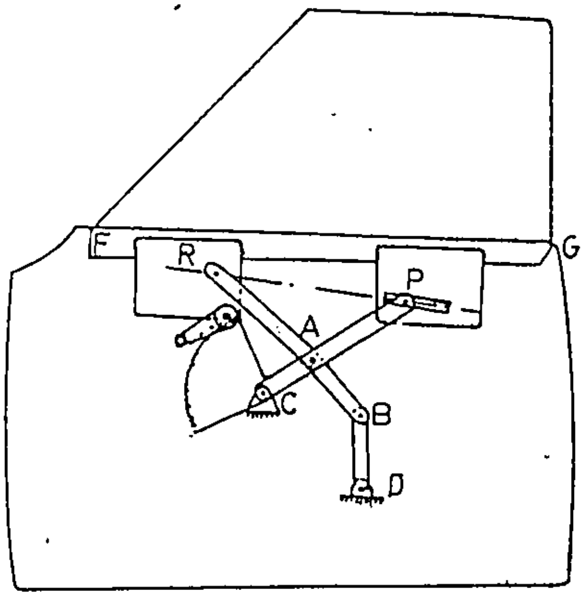


Figure 1.1.12 Basic design for the car window mechanism [4].

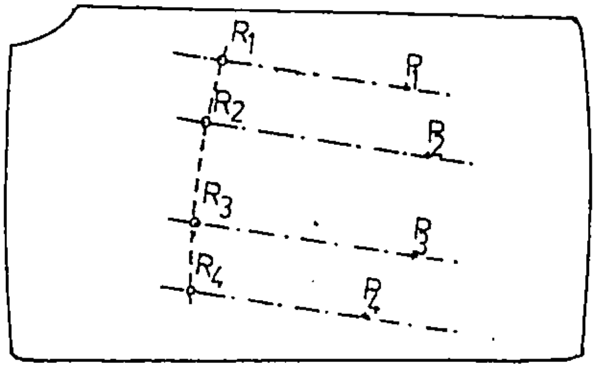


Figure 1.1.13 Design positions of the window [4].

travels in an arc, its pivot must be a sliding joint. Four positions of the window are prescribed and must be held for smooth operation (Figure 1.1.13). These are the window positions to be satisfied by the four-bar regulators. The points R_1 and R_4 define the window up and window down limits and must be precise.

All these are problems of link guiding through various positions and can be synthesized and analyzed by the method presented here.

1.2 A Review of Methods of Synthesis

In the pre-computer era, kinematic analysis and synthesis was accomplished primarily by intuitive and graphical techniques. The computer offers a tremendous advantage to the mechanism designer by accomplishing tedious calculations quickly and offer very attractive alternatives to the classical techniques. One of the difficulties that has arisen is the inability of the designer to keep up with the computer which can spew literally reams of computer output, which needs to be further analyzed. Computer graphics offers a timely solution for this input, output problem.

Some of the traditional and more recent methods will now be reviewed.

Two Positions of a Plane:

A_1B_1 and A_2B_2 are the required positions of the coupler plane (Figure 1.2.1). A number of different four-bar linkages

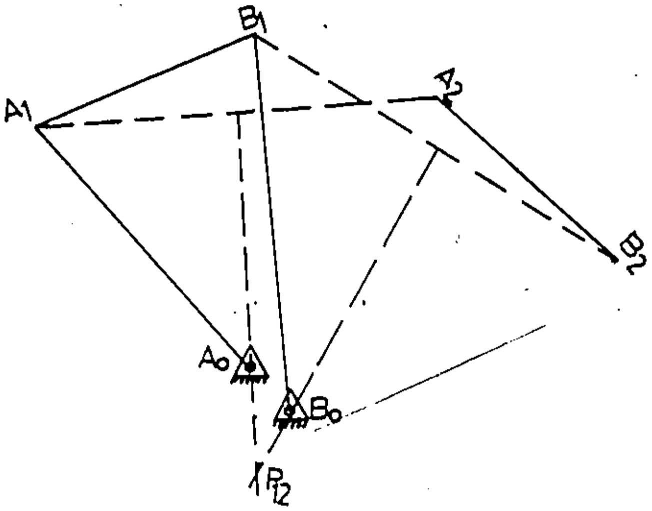


Figure 1.2.1 Two positions of a plane.

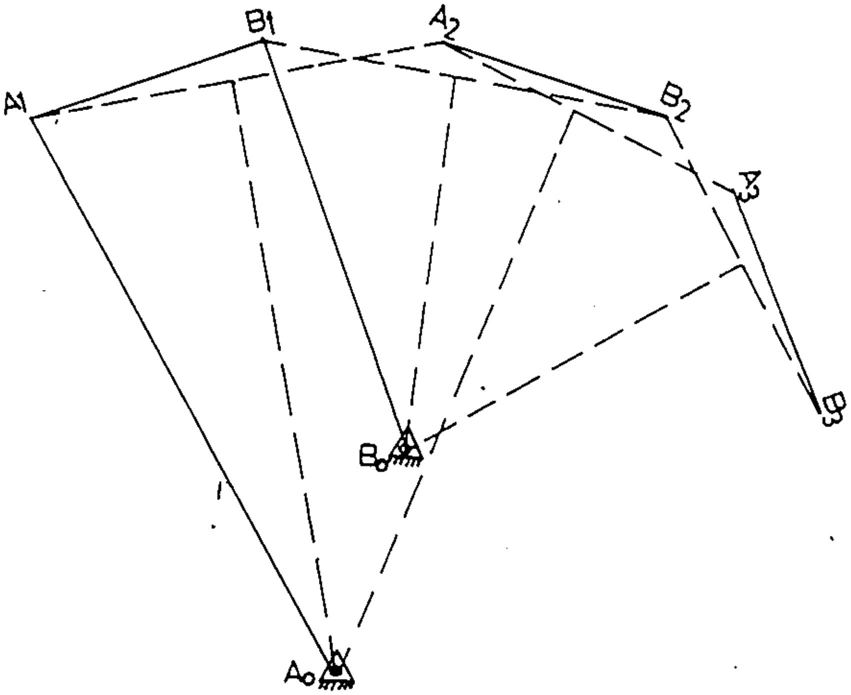


Figure 1.2.2 Three positions of a plane.

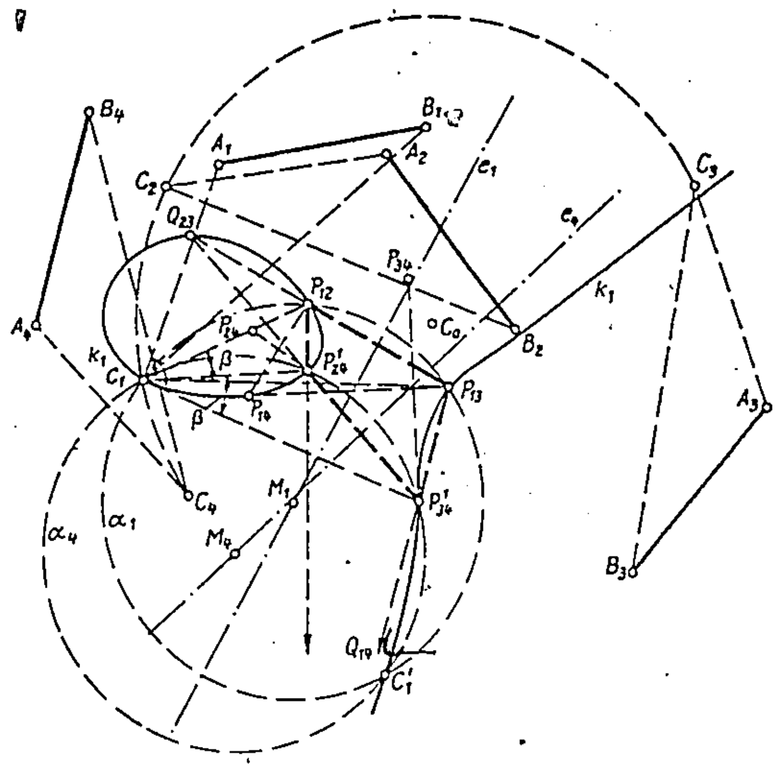
can easily be designed to do this by arbitrarily selecting the crank centers on the perpendicular bisectors of A_1A_2 and B_1B_2 respectively. There are an infinite number of choices for the linkage, and therefore one must select a mechanism that has good space requirements, i.e., no dead positions and a good transmission angle. Another solution is to extend the link AB and pin joint it at the pole P_{12} so that the problem is solved by a single link.

Three Positions of a Plane:

A_1B_1, A_2B_2 and A_3B_3 are the three required positions of the coupler plane (Figure 1.2.8). There is only one solution to this problem using the poles. The centers A_o and B_o must be placed at the intersection of the bisectors of A_1A_2; A_2A_3 and B_1B_2;B_2B_3 respectively. We must ensure that there is no discontinuity in the motion and the linkage should be satisfactory. If a discontinuity occurs, we can select a series of points along AB or AB extended or on a line at some angle to AB and construct the center-point curve. Now we can choose alternative points for crank centers along this curve by trial and error until a solution is found.

Four Positions of a Plane:

As the plane moves through three successive positions in turn, any point on the plane assumes three corresponding positions and it is always possible to draw a circle through three such point-positions. When there are four positions, however this is no longer generally the case, although there



Construction of the circle-point curve k_1.

Figure 1.2.3 Four positions of a plane [5].

still remain an infinite number of points moving with the plane into four successive locations, which happen to lie on some circle. The locus of these points form a circle point curve and may be found. The centers of all the circular arcs traced by the points in the circle point curve likewise lie on a curve, called the center-point curve.

In Figure 1.2.3 the four positions of a plane E are established by the four positions A_1B_1,A_2B_2,A_3B_3 and A_4B_4 of a given line AB of the plane. Associated with these four positions, there are six poles, P_{12}, P_{13}, P_{14}, P_{23}, P_{24} and P_{34} and these poles can be located from the intersections of the corresponding perpendicular bisectors. For example P_{12} lies at the intersection of perpendicular bisectors drawn to the lines A_1A_2 and B_1B_2.

The graphical construction of the circle-point curve is based upon a theorem of Burmester [6] which states that all points of this curve subtend either equal or complementary angles on the opposite sides of the "opposing pole quadrangle". An opposing-pole quadrangle is formed by two poles and the two mirror images of "opposing" poles. An opposing pole is defined as one neither of whose subscript members are the same as the diagonally placed pole. The circle-point curve can be drawn in any of the four positions of the plane E. The center-point curve is unlike the circle-point curve in that it is attached to the fixed reference plane rather than to the moving plane E. The center-point curve stays in its one position for all four positions of the plane. Its construction is similar to that for the circle point curve, but the difference is that only poles and no image poles are involved.

The technical significance of these curves arises from the fact that in linkage mechanisms the fixed pivots are center points (located on the center-point curve) and the crank pins are circle points (located on the circle-point curve). The graphical construction for the location of center-points and the circle-points are not described here as they are to be found in any standard book on kinematic synthesis.

Five Positions of a Plane:

When five positions of a plane are prescribed, there remain only four specific points of the plane, whose five homologous positions lie on a circle. These four points may all be real, all imaginary, or pairs may be imaginary. They are generally known as "Burmester points". They may be discovered by taking two differnet groups of four from the five given plane positions and laying out the center-point curves for each group, and then finding the points of intersection of these curves. For this purpose there are, of course, five different center-point curves which could be constructed; but they will only intersect one another in the same and at most, four Burmester points.

Freudenstein and Sandor [7] developed a computer program which gives the location of Burmester points in an efficient manner for five positions. An excellent algebraic development of Burmester theory has been given by Cherkudinov [8] and is described also in a joint text by Artobolevskii, Levitskii and Cherkudinov [8]. These references contain an equation for the location of the Burmester points in Cartesian coordinates which is well suited for computation.

More than Five Positions of a Plane:

Sarkisyan, Gupta and Roth [9] extended the theory of algebraic method to problems consisting of more than five finitely separated positions in a least squares minimum error sense. Prasad and Bagci [10] developed a variational method to synthesize four-bar mechanisms to guide rigid bodies. Bagci and In-Ping Jack Lee [11] synthesized four-bar mechanisms up to 11 specified positions of coupler plane via the linear superposition technique.

Synthesizing a four-bar linkage as a mathematical programming problem was first presented by Fox and Willmert [12]. The objective was to synthesize a four-bar linkage whose coupler point will generate, as closely as possible, a given curve, and whose crank rotation will be as close as possible to desired values. Varma [13] investigated all possible types of four-bar linkages, up to ten specified positions of coupler plane, as a mathematical programming problem.

The best known effort to date on interactive computer-aided design of planar linkages was accomplished in a pioneering effort by Kaufman et al. [14]. KINSYN, a well known system, has been programmed on a customized in-house minicomputer. It has synthesis capabilities up to 5 finitely spaced positions of coupler plane, based on Burmester theory.

Erdman and Gustafson [15] developed a computer-aided design system, called LINCAGES: Linkage Interactive Computer Analysis and Graphically Enhanced Synthesis Package. This is the first such system to be generally available over telephone lines in a time sharing mode and to be designed to make optimal use of graphical output from either a teletype or graphics CRT. Synthesis programs were based on Burmester theory and the complex number method and were used to synthesize four-bar mechanisms up to five specified positions of the coupler plane.

Smith and Reed [16] developed a computer-aided design system to synthesize multiloop two-degree of freedom plane mechanisms to guide a cutting tool along a prescribed path using several multi-dimensional, constrained optimization algorithms. A Satellite Graphics approach to hardware allocation has been adopted.

1.3 Ojectives

The objective of this work is to develop a computer-aided design system employing computer graphics to synthesize and analyze four-bar mechanisms, whose coupler plane is required to pass through a number of specified positions.

The designer can interactively communicate with the computer and input data, synthesize the mechanism and graphically analyze the motion characteristics with options on the CRT. The computer, the designer and the graphics output are strategically used to maximize the utility of each.

The problem is presented here as a mathematical programming problem and is formulated as a multifactor optimization problem in two dependent design variables. Constraints are imposed on the design variables which force the result to be a four-bar mechanism of desired type, restrict the location of pivots and the link lengths.

The displacement of a rigid body can be represented by the displacement of a line on that body, and a line can be located on a plane by specifying the coordinates of any point on the line, and its inclination with any reference axis. For the present work we assume a line on the coupler link at some inclination as representing a rigid body. A rigid body which has to pass through a series of positions, must satisfy the point coordinates and the angular positions at all the accuracy positions specified.

The structural error is the combination of the two errors, 1. the distance between the actual point and the desired point, and 2. the angular deviation of the line from the desired position.

$$\text{Minimize} \qquad U = \sum_{j=1}^{\gamma} U_j \tag{1.3.1}$$

subject to p inequality constraints

$$\phi_i\ (x_1, x_2, \ldots, x_n) \geq 0\ ,\ i=1,p \tag{1.3.2}$$

and q equality constraints

$$\psi_K(x_1, x_2, \ldots, x_n) = 0 \quad K=1,q \tag{1.3.3}$$

where γ is the number of dependent design variables
p is the number of inequality constraints
q is the number of equality constraints
n is the number of independent design varibles.

$$\text{In our case } U = U_1 + U_2 \tag{1.3.4}$$

suitable functions have been chosen for utilities U_1 and U_2.

$$U_1 = U_1(Y_1) \tag{1.3.5}$$

$$U_2 = U_2(Y_2) \tag{1.3.6}$$

The proper choice is explained later.

There are many techniques for the solution of this type of problem. Subroutines from "OPTISEP" [17] -- a designers optimization subroutine package -- have been used. All types of problems such as crank-rocker, double crank and double-rocker were tried.

The synthesized mechanism can be analyzed on the CRT for static display in various positions or real time animation of the mechanism with the coupler driving through various positions and the coupler point tracing the coupler path. Options like clockwise or counter-clockwise rotation of the crank in crank-rocker and double-crank mechanisms and the option of a particular phase in double-rocker mechanisms are provided. Messages pertaining to the type of mechanism, number of positions being synthesized, extreme positions in double-rockers, maximum and minimum errors and angular deviations are seen on the screen.

The program is developed in Fortran language. At present the synthesis program is run in a time sharing mode on a CDC 6400 computer and the analysis program is run on a PDP-11/34 mini-computer along with a GT-46 graphics terminal. The final aim is to make a single system through the satellite graphics approach.

CHAPTER 2

COMPUTER-AIDED DESIGN
AND COMPUTER GRAPHICS

2.1 Introduction

Over the last decade or so, much exciting research has been done in the area of computer-aided design. Computer-aided design connotes a close interaction between man and the computer through the use of visual displays, typewriter keyboards, special computer languages and other man-computer interfaces. The man is able to converse with the computer and to receive a direct response from it.

Computer-aided design enables the designer to test a hypothesis rapidly, to see its effect and to modify the hypothesis in a multi-pass optimization process. Figure 2.1.1 shows a simplified representation of the design process. The design activities of recognition and definition are viewed as managerial tasks and are therefore assigned totally to the designer. Conceptualization is almost entirely "mind oriented" and is viewed primarily as a designer oriented task. We normally utilize past experience as an initial starting point for the conceptualization of new designs.

We then synthesize and analyze the model and compare its characteristics with the specifications or design goals. We can then alter the design to improve its performance until

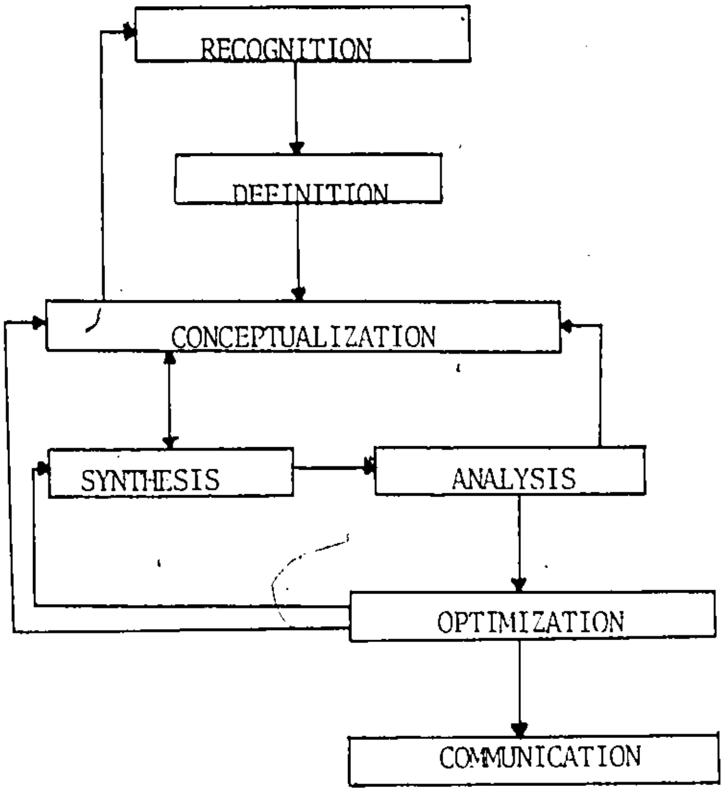


Figure 2.1.1 The iterative design process.

it is satisfactory. Characteristically, each time a pass is made through the design loop, the design approaches closer to the optimum. It is exactly for this purpose that computer-aided design holds forth the most promise.

The computer, by permitting the designer to rapidly view the results, enables him to introduce the desired changes much more quickly. This close man-computer dialog has benefits beyond what might be expected, simply due to the more rapid input and output. We may immediately see and correct any gross errors in the drawing or input statement. We can monitor the progress of a problem solution and terminate the run or modify the input data as required. We can make subjective decisions at critical branch points which guide the computer in a continuation of the problem solution. The graphical display will present data which cannot be readily understood or interpreted in a computer output listing.

2.2 Graphics System

The graphical computer-aided design system consists of the man, the hardware and the programming. (Figure 2.2.1). The hardware consists of a computer, a display driven by the computer and input devices which permit the man to give instructions and data to the computer. The programming consists of the basic systems programs of the computer, time-sharing programs if that mode of operation is used, applications programs which permit the solution of specific problems, and the graphics interface programs which permit the computer

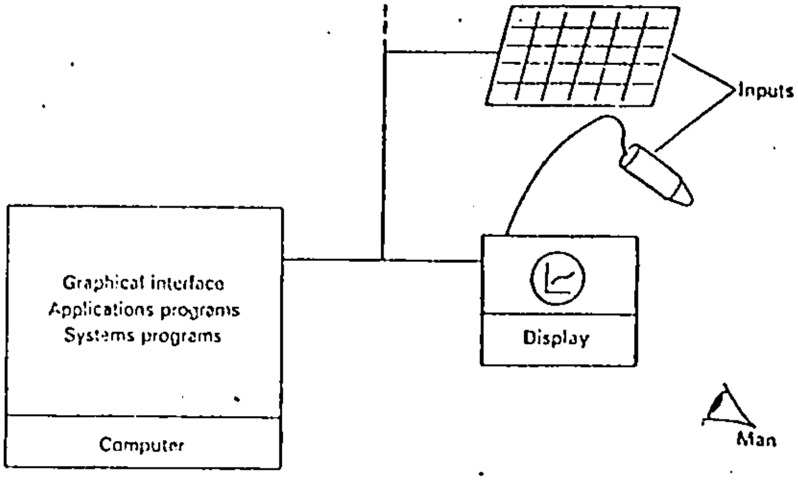


Figure 2.2.1 The man–computer graphics system. [18].

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to communicate with the display.

The graphics system used for the present work consists of a PDP11/34 minicomputer, a teletype, a floppy disk, system disks, a GT46 graphics terminal (refresher type), a HP7221A plotter and a CALCOMP565 plotter. The schematic diagram is shown in Figure 2.2.2 and a photograph of the equipment is shown in Figure 2.2.3. The proposed hardware configuration includes a CDC6400 computer connected through a communications link. This configuration is referred to as a satellite graphics system where the primary computer and the support minicomputer are connected by means of a communication link. The data from the designer is transmitted to the primary computer for synthesis and the results are transmitted to the minicomputer for designer evaluation. This is necessary because the execution time for the synthesis program on the minicomputer is longer than one hour. As there is no facility of the communication-link at the present, the synthesis and analysis programs are run separately.

The graphics display subsystem consists of a VT 11 display processor, a display screen with a light pen and a line frequency clock. The display processor is interfaced to a PDP-11 UNIBUS. The display screen provides a basic 9 1/4 inch by 9 1/4 inch viewing area. The screen can be treated as a coordinate grid with a horizontal x-axis and a vertical y-axis. There are 1024 logical positions on each axis resulting in 1048576 individually addressable positions on the screen. The viewing area capacity is 73 characters

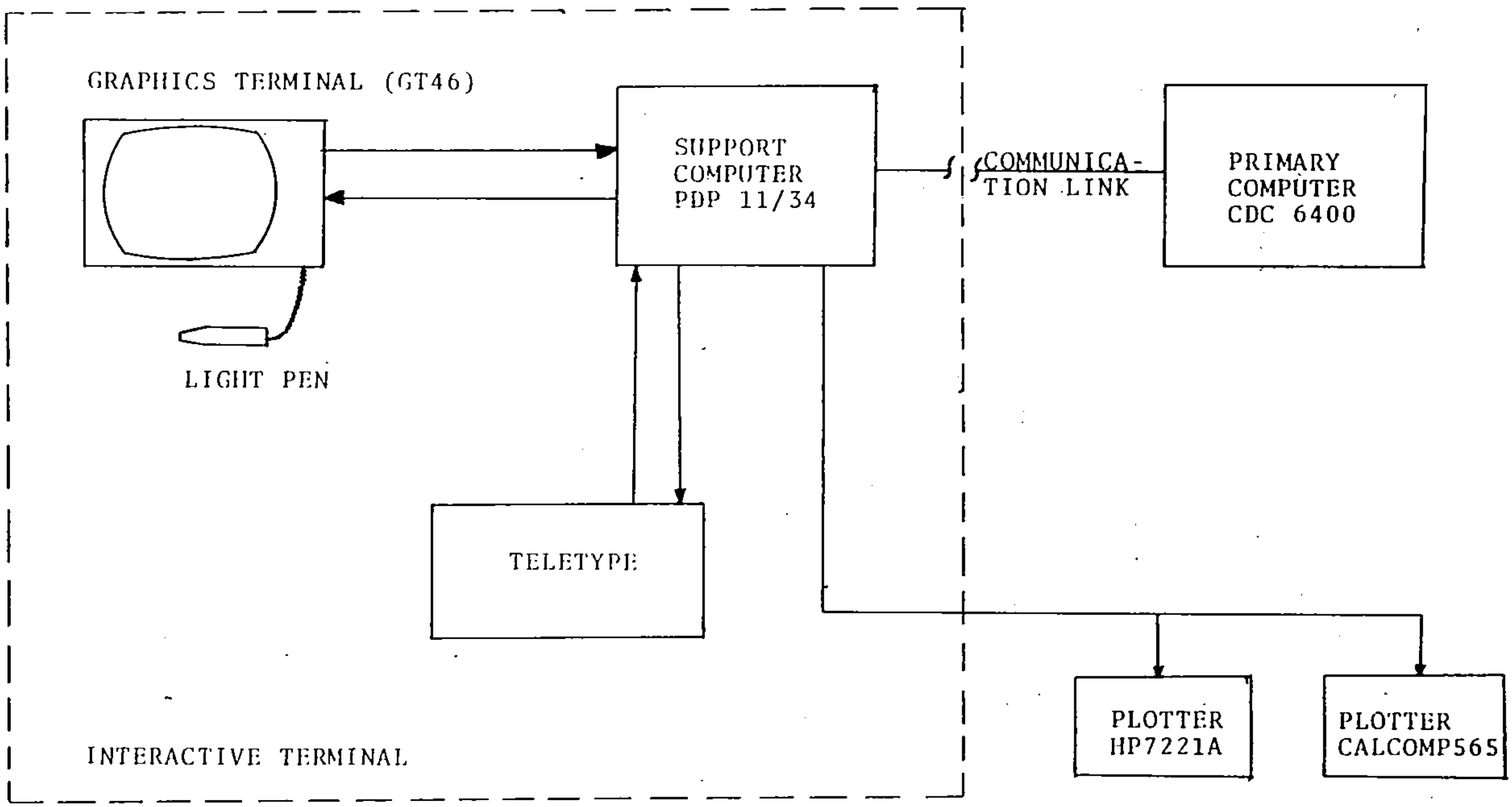


Figure 2.2.2 Hardware system arrangement.

Figure 2.2.3 The designer and the computer environment.

per line and 31 lines per screen. Positions begin at (x=0, y=0) in the bottom left corner and extend to (x=1023, y=1023) at the top right corner of the screen.

The software support is provided as a set of FORTRAN-callable subroutines and can perform the following basic graphics functions by issuing simple CALL statements.

(a) Display points, vectors, text and graph data.
(b) Scale the display screen to any coordinate system.
(c) Control portions of the display screen independently by means of the sub-picture facility.
(d) Facilitate light pen interaction.
(e) Display an entire array of data with one subroutine call.

The graphics output program for the present work is developed utilizing these basic graphic functions and the configurations that can be seen on the screen are explained in Chapter 5.

CHAPTER 3

ANALYSIS OF FOUR-BAR AND PROBLEM FORMULATION

3.1 Grashof Criterion

The relationship between the link lengths turns out to be very important from the point of view of establishing whether the crank (link $O_A A$) and the follower (link $O_B B$) are capable of a complete rotation (Figure 3.1.1). Links which are capable of rotating through 360° are called cranks; if they can only oscillate, they are called rockers.

Let us identify the length of the longest link as ℓ, the length of the shortest link as s, and the lengths of the other two links as p and q. The following relations, stated without proof are valid:

1. A Grashof four-bar is one in which the sum of the lengths of the longest and the shortest links is less than the sum of the lengths of the other two links, that is $\ell + s < p + q$.

Thus:

(a), (b) Two different crank-rocker mechanisms are possible. In each case the shortest link will be the crank, the frame being either adjacent link.

(c) One double-crank mechanism results when the shortest link is the frame.

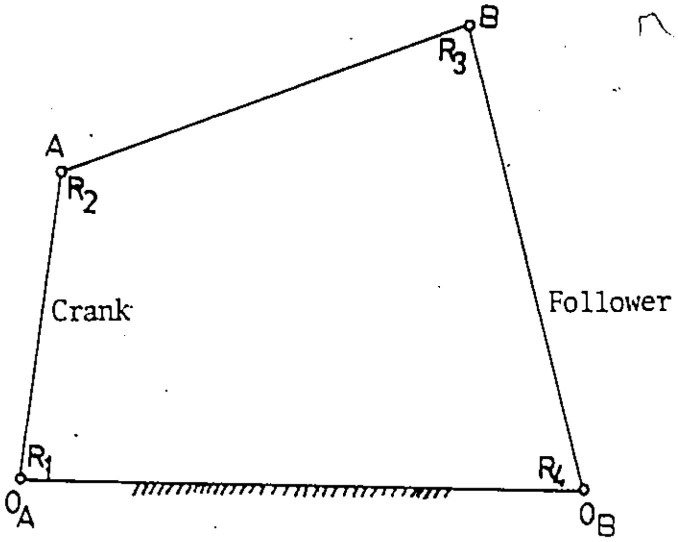


Figure 3.1.1 Four-bar mechanism.

(d) One double-rocker mechanism is formed when the link opposite to the frame (coupler) is the shortest.

2. If the sum of lengths of the longest and the shortest link is greater than the sum of the lengths of the other two links, that is $\ell + s > p + q$ only double-rocker mechanisms result depending upon, whether the longest link is the frame, the crank, the coupler or the follower.

3. If $\ell + s = p + q$, the four possible mechanisms are like those of (1), all however, suffering from a condition known as change point; that is the center lines of all the links become collinear, whence the cranks may change direction of rotation unless given guidance.

For our present work we shall classify the mechanisms into seven different types:

Type 1: $\ell + s < p + q$ with the crank as the shortest link
CRANK-ROCKER

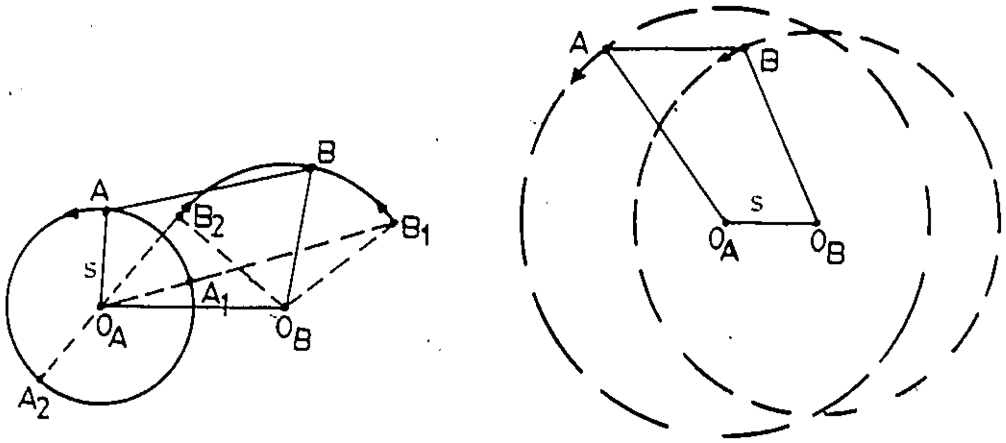
Type 2: $\ell + s < p + q$ with the frame as the shortest link
DOUBLE-CRANK

Type 3: $\ell + s < p + q$ with the coupler as the shortest link
DOUBLE-ROCKER TYPE 3

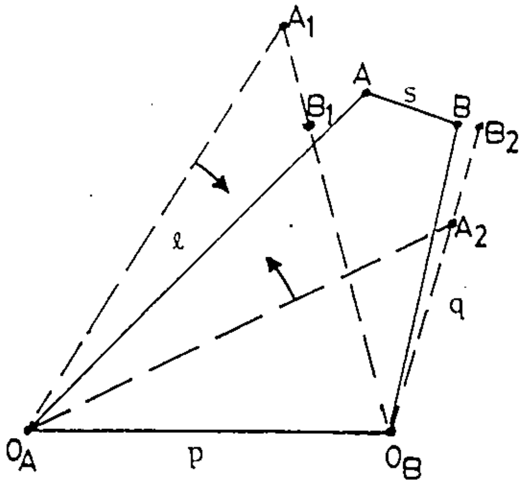
Type 4 $\ell + s > p + q$ with the input link as the longest link
DOUBLE-ROCKER TYPE 4

Type 5: $\ell + s > p + q$ with the coupler as the longest link
DOUBLE-ROCKER TYPE 5

Type 6: $\ell + s > p + q$ with the follower as the longest link
DOUBLE-ROCKER TYPE 6

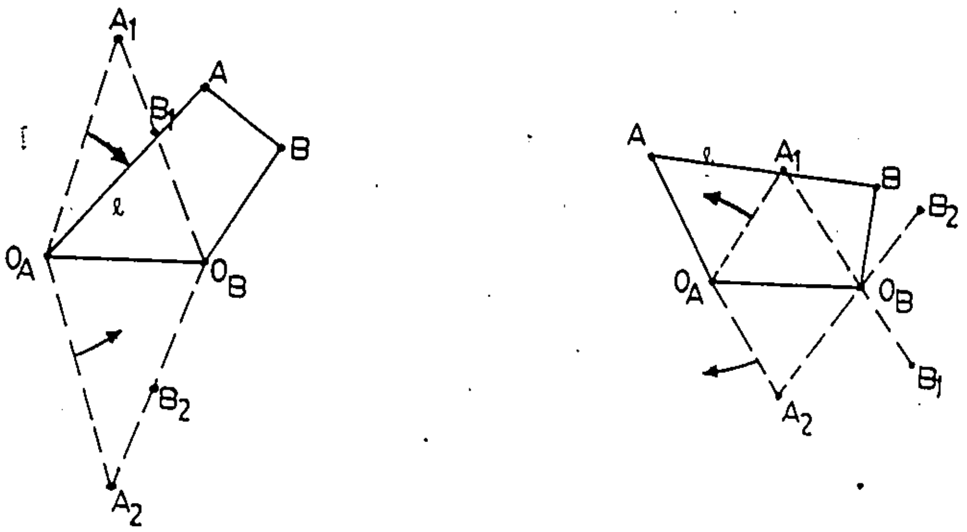


(a) Crank-rocker (b) Double-crank



(c) Double-rocker type 3

Figure 3.1.2 Grashof four-bar mechanisms ($\ell + s < p + q$).



(a) Double-rocker type 4

(b) Double-rocker type 5

(c) Double-rocker type 6

(d) Double-rocker type 7

Figure 3.1.3 Non-Grashof four-bar mechanisms ($\ell + s > p + q$).

Type 7: $\ell + s > p + q$ with the frame as the longest link

DOUBLE-ROCKER TYPE 7

Figures 3.1.2 and 3.1.3 show all possible types of four-bar mechanisms (Grashof and non-Grashof four-bar mechanisms).

3.2 Output Angle as a Function of Crank Angle

For a four-bar mechanism the degree of freedom is one. In other words, given the crank angle and knowing the link lengths one can derive the mathematical relationship between the follower angle and the crank angle. But the follower angle also depends upon the initial closure of the mechanism. Hence we introduce a parameter "ICASE" to identify the initial closure (Figure 3.2.1).

In the double-rocker mechanisms one has to identify the two branches of the input-output curve (Figure 3.2.2). Irrespective of the initial closure of the mechanism, there will be two different follower angles for a given input angle (Figure 3.2.3). Hence it becomes necessary to introduce another parameter "IPATH" to differentiate between the two phases of the mechanism. We assume that for phase 1 the value of IPATH is equal to +1 and for phase 2, the value of IPATH is equal to -1.

3.3 Design Variables

The set of design variables which uniquely define

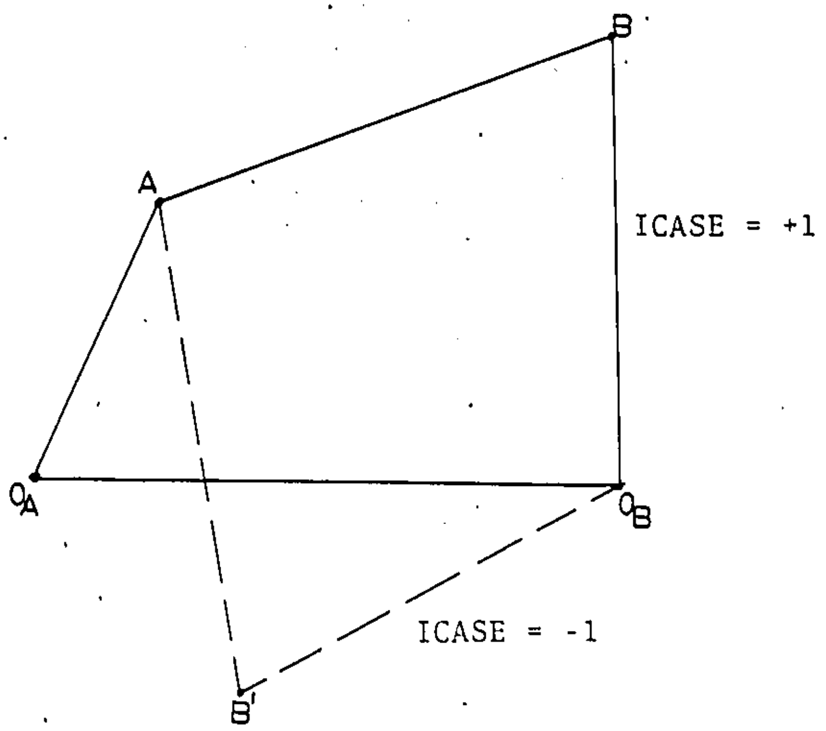


Figure 3.2.1 Configurations for closure of the four-bar mechanism.

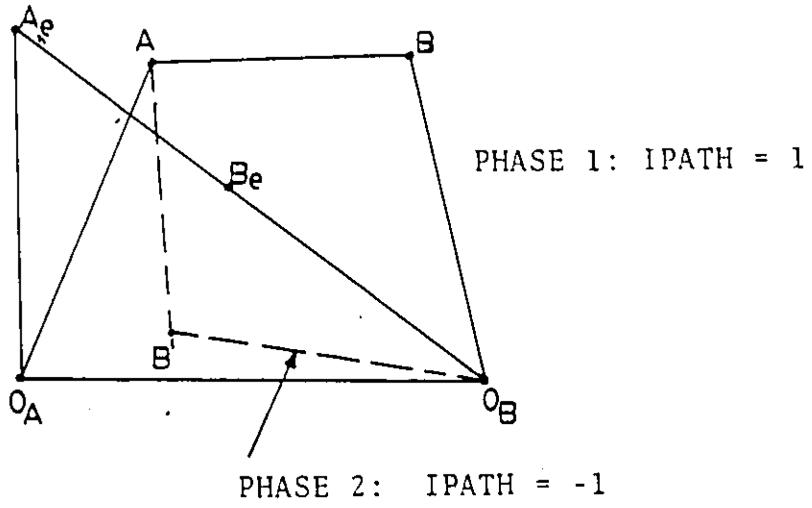


Figure 3.2.3 Configurations for the phases of double-rocker mechanisms.

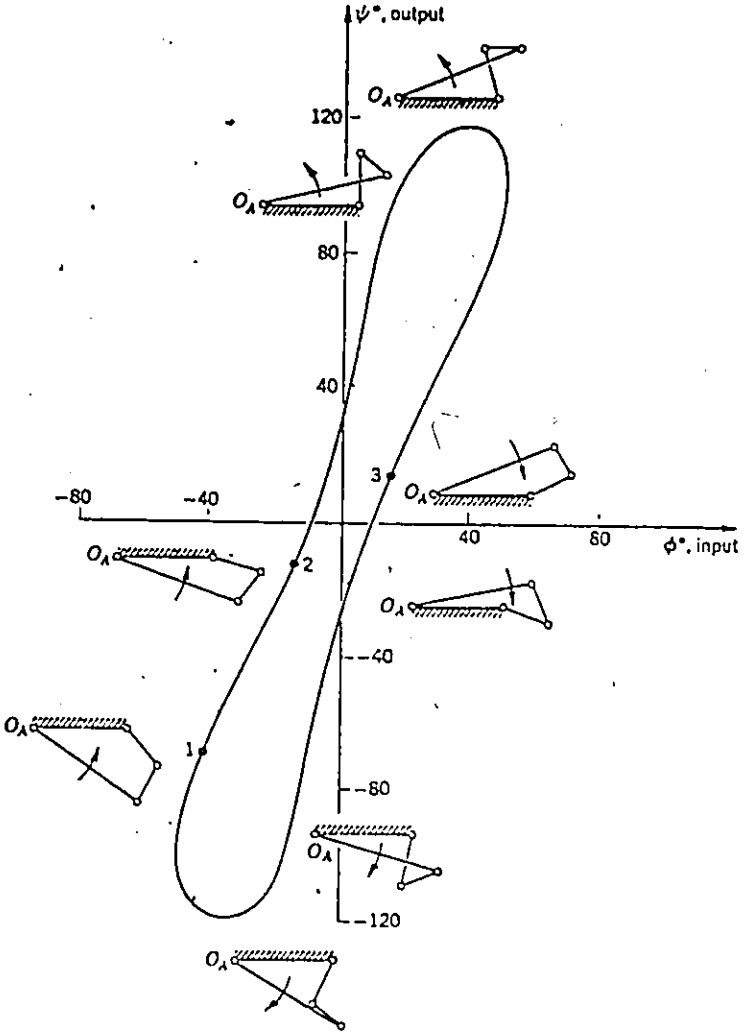


Figure 3.2.2 Input-output relationship for double-rocker mechanisms [1].

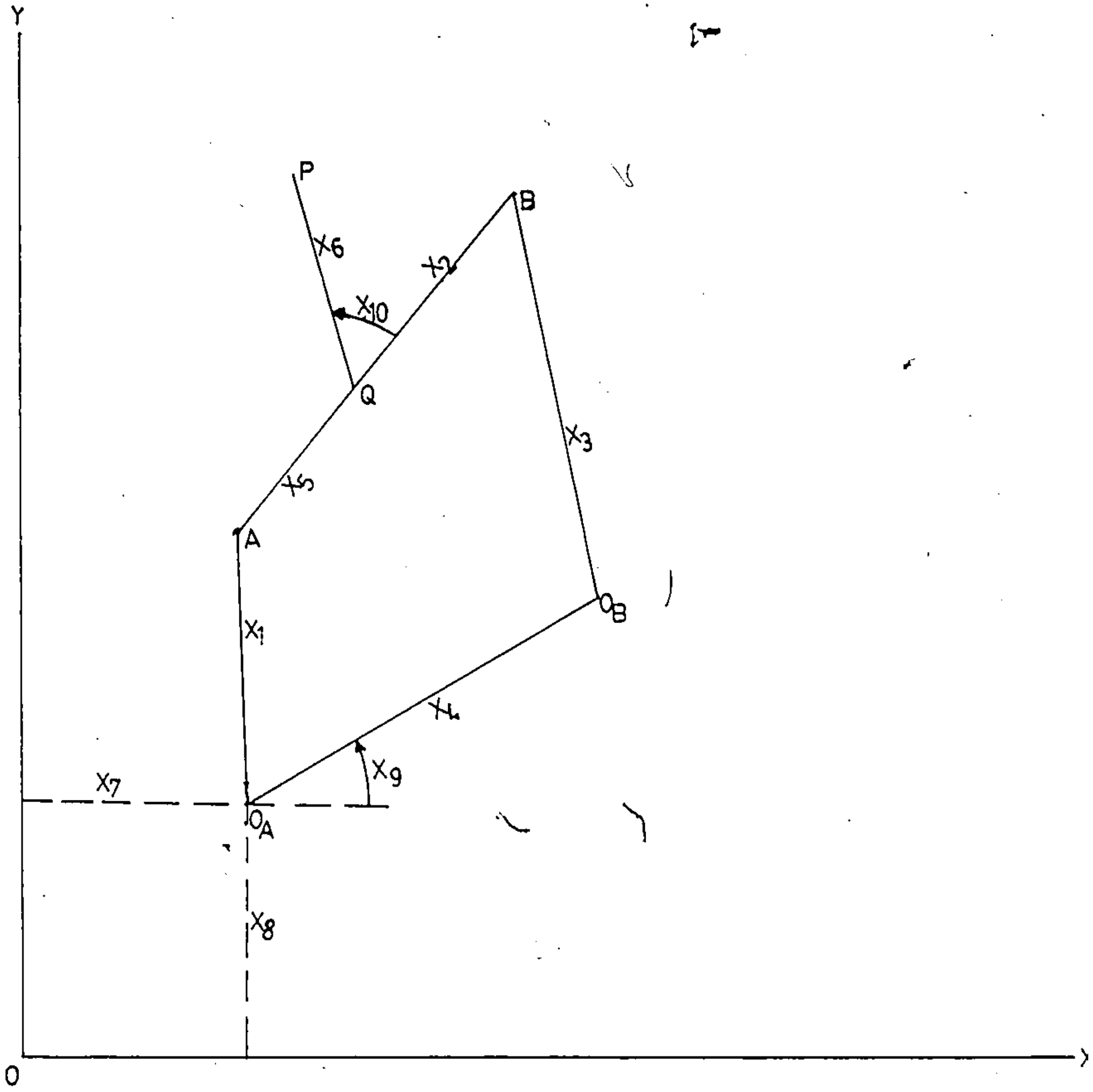


Figure 3.3.1 Design variables (specified crank input angles).

the planar four-bar mechanism are illustrated in Figure 3.3.1. x_1 , x_2, x_3 and x_4 are the link lengths of the crank, coupler, follower and the frame respectively. x_5, x_6 and x_{10} define the coupler point and the coupler link. The distances x_7 and x_8 are the coordinates of the pivot O_A. x_9 is the orientation of the frame with respect to the reference axis X .

The output angle ψ is a function of x_1, x_2, x_3, x_4 and the input crank angle ϕ. Once the output angle ψ is calculated, the coordinates of the coupler point and the angle that the link PQ makes with the Y axis is calculated. The details are given in Appendix A.

In many problems the designer wants the coupler link to pass through a number of positions without specifying particular input angles. In which case the crank input angles can also be made as independent design variables. For this type of formulation the number of independent design variables would be equal to 10 + the number of positions.

3.4 Structural Error

Structural error is the combination of the errors involved in the point coordinates and the angular deviation of the actual position of the plane from the desired position.

The error in point tracing can be expressed as

$$Y_1 = \sum_{i=1}^{N} \{(X_{D_i}-X_i)^2 + (Y_{D_i}-Y_i)^2\}^{1/2} \qquad (3.4.1)$$

where

- X_{D_i} and Y_{D_i} are the desired coordinates at the i^{th} position in the X-Y plane.
- X_i and Y_i are the actual coordinates at the i^{th} position in the X-Y plane.
- N is the number of positions desired.

The angular deviation is given by

$$Y_2 = \sum_{i=1}^{N} |(\alpha_{D_i} - \alpha_i)| \qquad (3.4.2)$$

where

- α_{D_i} is the desired angle that the line makes with the Y-axis at the i^{th} position.
- α_i is the actual angle that the coupler link makes with the Y-axis at the i^{th} position.

3.5 Objective Function

The problem in this work is formulated as a multi-factor optimization. The structural error is due to coupler point coordinates and the angular deviation of the coupler link. The problem involves simultaneous optimization of two dependent design variables. The best way to tackle this type of problem is through the use of utility functions. The concept of utility functions is presented by Siddall [19].

For the present work the concept of inverse utility developed by Sutherland [20] is used. Instead of maximizing the utilities, we invert each utility and minimize the inverse utility or minimize the undesirability. If U represents the utility for a particular dependent design variable, then U^{-1} is the inverse utility. Then the function to be minimized becomes,

$$U^{-1} = \sum_{j=1}^{r} U_j^{-1} \tag{3.4.3}$$

where

- U_j^{-1} is the inverse utility of j^{th} dependent design variable.
- r is the number of dependent design variables.

There is no set rule for defining the utility functions. It is something which the designer himself has to decide from his experience. The inverse utility functions chosen for the errors Y_1 and Y_2 are parabolic. An inverse utility of zero has been assigned to the most ideal value of the error involved, viz., an error equal to zero. An inverse utility of positive infinity is assigned to the least desirable value of the dependent design variable.

Inverse utility curves for our problem are shown in Figures 3.5.1 and 3.5.2 and the mathematical relationship is given by the following expressions.

$$U_1 = \frac{1}{N} \sum_{i=1}^{N} \left(\frac{\varepsilon_{1_i}^2}{\text{ERMAX1}^2}\right) \tag{3.4.4}$$

$$U_2 = \frac{1}{N} \sum_{i=1}^{N} \left(\frac{\varepsilon_{2_i}^2}{\text{ERMAX2}^2}\right) \tag{3.4.5}$$

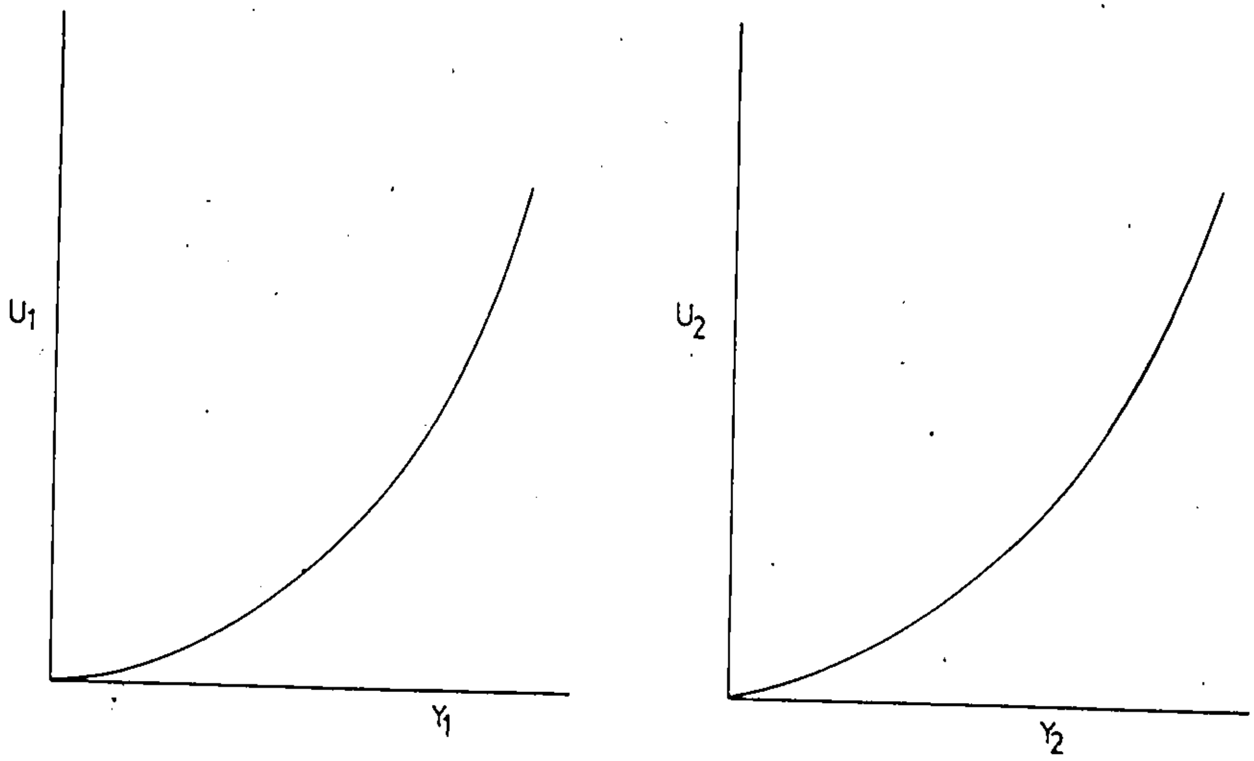


Figure 3.5.1

Figure 3.5.2

Inverse utilities for the errors.

- $\varepsilon_{1_i}^2$ and $\varepsilon_{2_i}^2$ are the square of the errors at the i^{th} position.
- N is the number of positions.
- ERMAX1 is the maximum error specified in tracing the point
- ERMAX2 is the maximum angular deviation specified.

The values of ERMAX1 and ERMAX2 are specified by the designer according to the requirements of the problem. Assuming that at all the positions specified the error involved in tracing the point is equal to ERMAX1 specified, the value of U_1 becomes one. Similarly the value of U_2 becomes one for angular deviation at all the specified positions equal to ERMAX2.

The reason for choosing parabolic functions for inverse utilities is that at errors close to zero the curve has a small slope and the rate of increase of the inverse utility is small whereas for larger errors inverse utility increases very rapidly, which is desired. Here both the dependent design variables are given equal importance.

Thus the objective function is the sum of the contributing utilities.

$$U = \sum_{j=1}^{r} U_j = U_1 + U_2 \text{ (minimum)} \qquad (3.4.6)$$

3.6 Constraints

We can control the design of the mechanism according to the requirement by imposing proper constraints. We shall

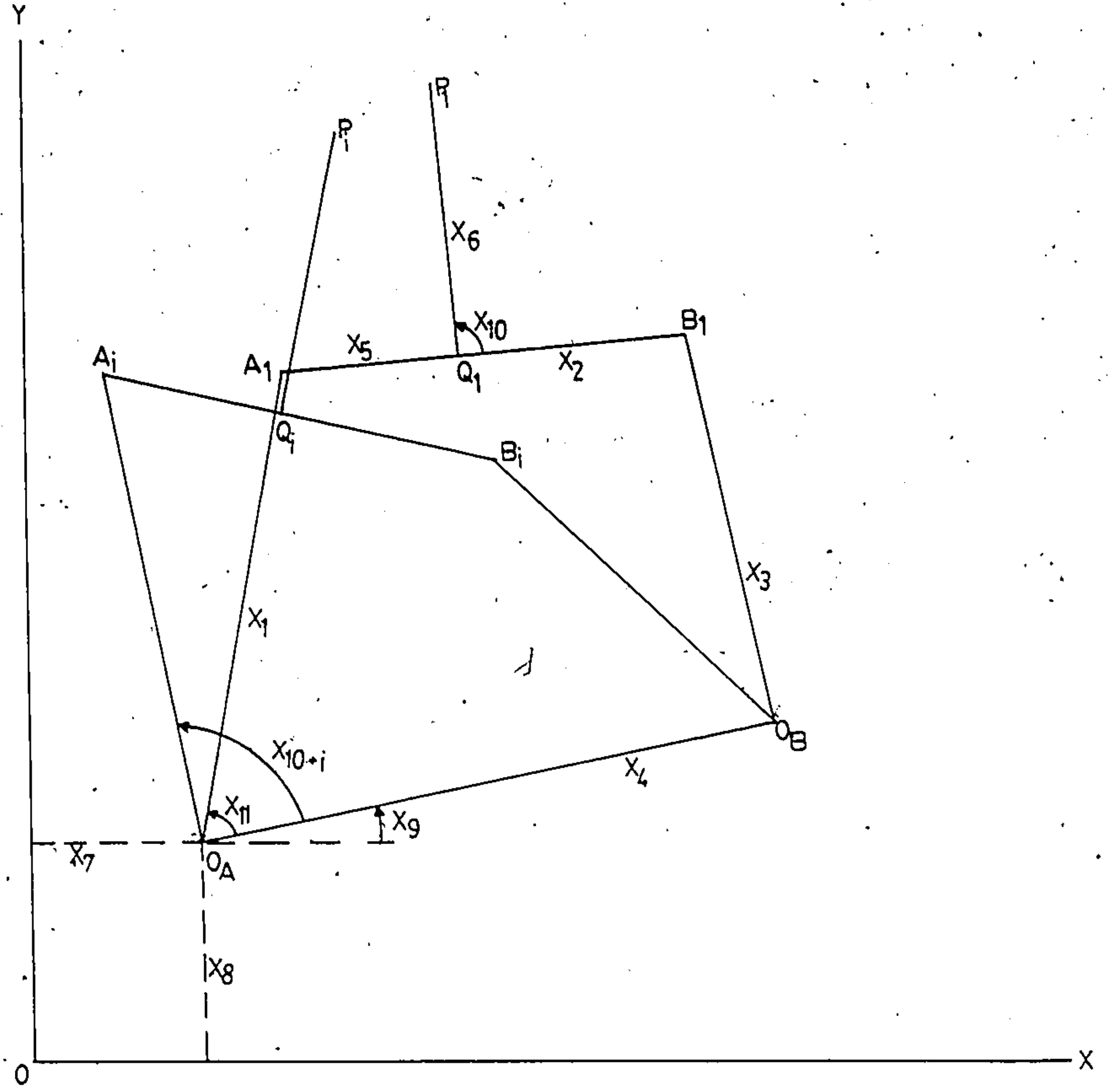


Figure 3.6.1 Design variables (crank input angles as independent design variables).

discuss the constraints for two cases:

I. specified crank input angles,

II. Crank input angles as independent design variables (Figure 3.6.1).

Case I.

a) Constraints on link lengths

Some control over link lengths is required in order to limit the link masses and moment of inertia. It is also known as a "rule of thumb" that linkages in which the ratio of the longest and the shortest link is high, do not make satisfactory linkages, so one would like to limit the maximum and minimum link length.

$$X_{\min,i} \leq X_i \leq X_{\max,i} \qquad i = 1,4 \qquad (3.6.1)$$

Similar constraints can be imposed on lengths of x_5 and x_6.

b) Constraints on the frame orientation

Constraint on the orientation of the frame with respect to the X-axis can be imposed

$$\theta_{\min} \leq x_9 \leq \theta_{\max} \qquad (3.6.2)$$

c) Constraint on pivot locations

In certain problems it may be desirable to limit the location of the pivots O_A and O_B because of space restrictions.

(i) Pivot O_A

$$X_{\min,7} \leq X_7 \leq X_{\max,7} \qquad (3.6.3)$$

$$X_{\min,8} \leq X_8 \leq X_{\max,8}$$

(ii) Pivot O_B

$$X_{min,OBX} \leq X_7 + X_4 \cos X_9 \leq X_{max,OBX}$$

3.6.4)

$$X_{min,OBY} \leq X_8 + X_4 \sin X_9 \leq X_{max,OBY}$$

(d) Constraint to ensure the closure of the mechanism

Constraint to ensure the closure of the mechanism for any value of ϕ is:

$$|(X_3^2 + E^2 - X_2^2) / 2X_3 E| \leq 1 \qquad (3.6.5)$$

where E is given by the expression

$$E = \sqrt{(x_1^2 + x_4^2 - 2x_1 x_4 \cos \phi)}$$

(e) Constraint to ensure single-valuedness of the angle X_{10}

$$|X_{10}| \leq 360 \qquad (3.6.6)$$

(f) Constraints to ensure that the linkages ensure proper Grashof relations

(i) Crank Rocker

$$\ell + s < p + q$$

The crank should be the shortest link. The inequality constraints to ensure the above conditions are:

$$\sum_{i=1}^{4} X_i > 2 (X_{max,i} + X_{min,i}) \quad i = 1,4 \qquad (3.6.7)$$

$$X_1 < X_2$$

$$X_1 < X_3$$

$$X_1 < X_4$$

ii) Double Crank

$$\ell + s < p + q$$

and the frame should be the smallest link.

$$\sum_{i=1}^{4} X_i > 2\,(X_{\max,i} + X_{\min,i}) \quad i = 1,4$$

$$X_4 < X_1 \qquad (3.6.8)$$

$$X_4 < X_2$$

$$X_4 < X_3$$

(iii) Double Rocker of Type 3

$$\ell + s < p + q$$

The coupler should be the smallest link.

$$\sum_{i=1}^{4} X_i > 2(X_{\max,i} + X_{\min,i}) \quad i = 1,4$$

$$(3.6.9)$$

$$X_2 < X_1$$

$$X_2 < X_3$$

$$X_2 < X_4$$

(iv) Double Rocker of Types 4 to 7

$$\ell + s > p + q$$

$$(3.6.10)$$

$$\sum_{i=1}^{4} X_i < 2\,(X_{\max,i} + X_{\min,i}) \quad i = 1,4$$

Constraints for the different types of double rocker mechanisms are:

Type 4:

$$X_1 > X_2$$
$$X_1 > X_3$$
$$X_1 > X_4$$

Type 5:

$$X_2 > X_1$$
$$X_2 > X_3$$
$$X_3 > X_4$$

Type 6:

$$X_3 > X_1$$
$$X_3 > X_2$$
$$X_3 > X_4$$

Type 7:

$$X_4 > X_1$$
$$X_4 > X_2$$
$$X_4 > X_3 \qquad (3.6.10)$$

Case II.

When the crank input angles are independent variables, some additional constraints are required to ensure that the coupler positions are occupied in the proper sequence. In other words, the i + 1th position is occupied after the i^{th} position of the coupler in the continuous motion of the crank. The remainder of the constraints are the same as defined above.

(a) Crank-Rocker

For clockwise rotation of the crank:

$$X\,Y\,X_i < X\,Y\,X_{i+1} \qquad i = 1,\ N-2$$

where (3.6.11)

$$X\,Y\,X_i = X_{11} - X_{11+i} \qquad i = 1,\ N-1$$

(Figure 3.6.2)

For counter-clockwise rotation of the crank

$$X\,Y\,X_{i+1} > X\,Y\,X_i \qquad i = 1,\ N-2$$

where (3.6.12)

$$X\,Y\,X_i = X_{11+i} - X_{11} \qquad i = 1,\ N-1$$

(Figure 3.6.3)

(b) Double Crank

Constraints for a double-crank mechanism are the same as those for a crank-rocker mechanism for both types of rotation.

(c) Double Rocker

As in the case of double-rocker mechanisms the crank can only oscillate between its limiting positions. The crank may rotate clockwise as well as counter-clockwise with a change in phase.

$$X\,Y\,X_{i+1} > X\,Y\,X_i \quad \text{for clockwise rotation}$$

(3.6.13)

$$X\,Y\,X_{i+1} < X\,Y\,X_i \quad \text{for counter-clockwise rotation}$$

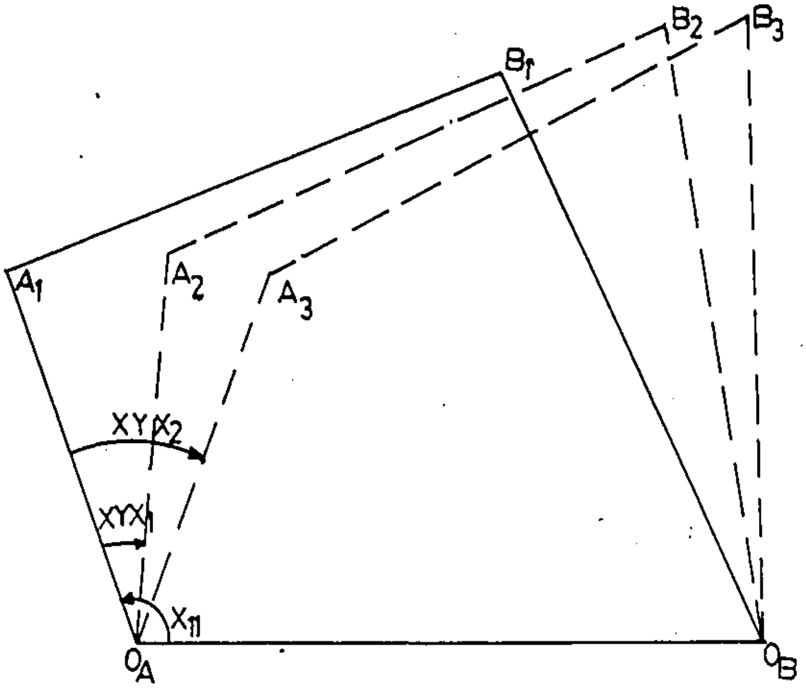


Figure 3.6.2

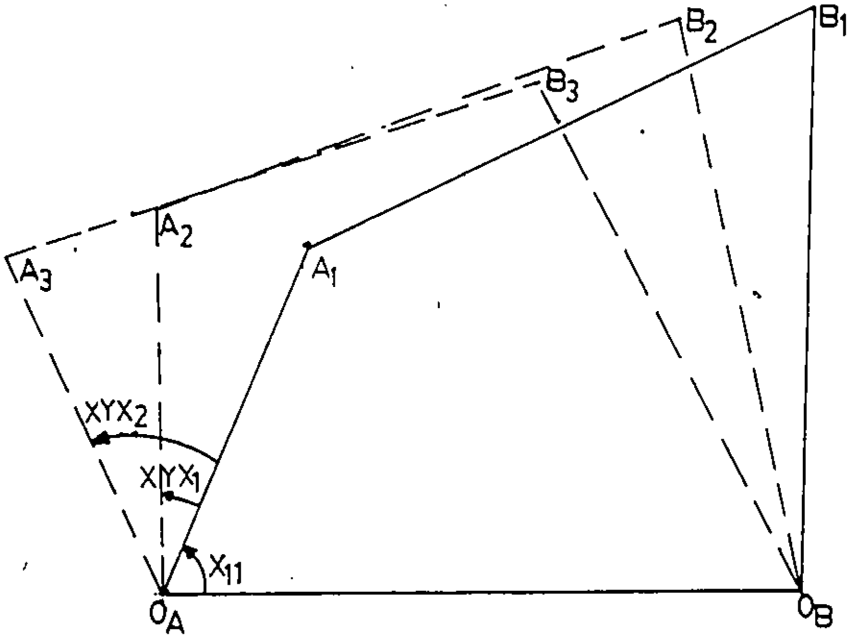


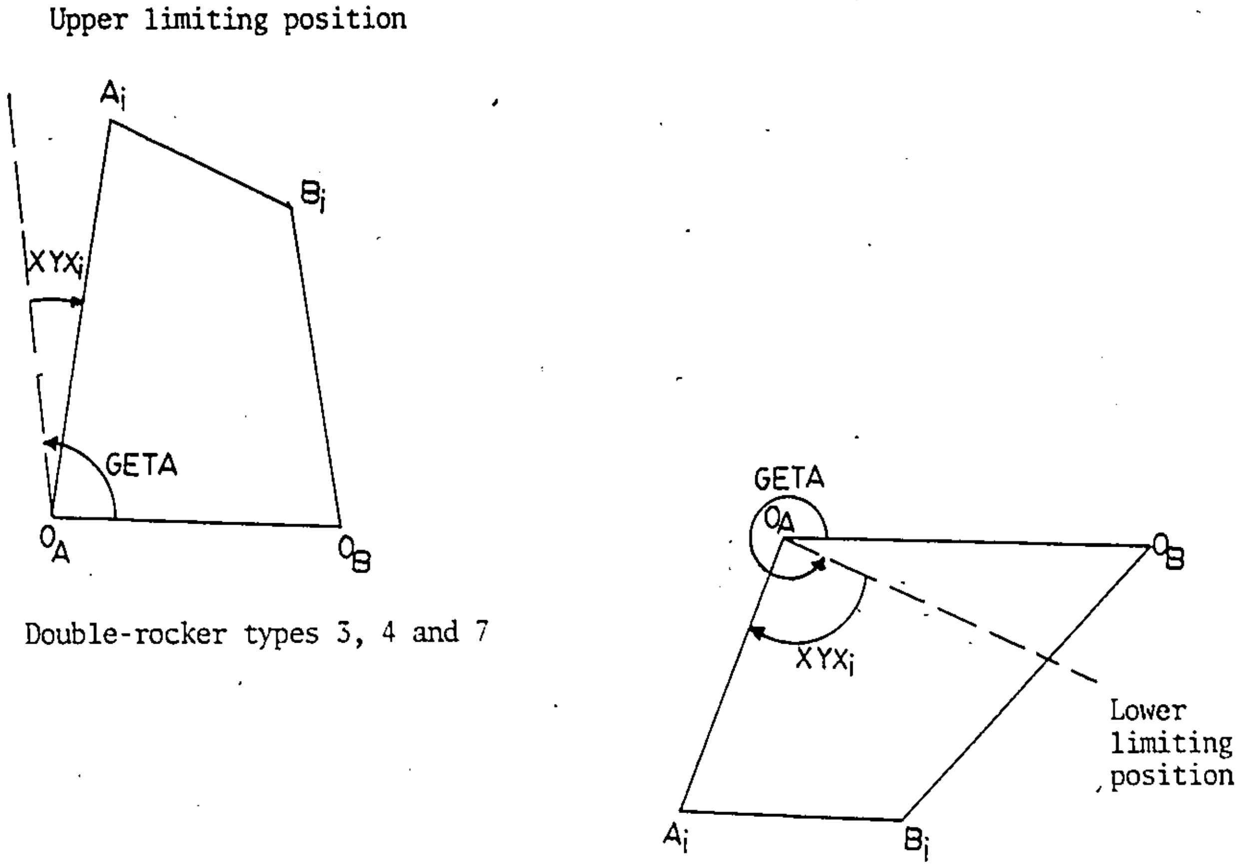
Figure 3.6.3

Configurations for clockwise and counter-clockwise rotation of crank.

where X Y X_i = GETA - X_{i+10} i = 1,N

GETA - upper limit of motion of input link for double rocker types 3, 4 and 7 (Figure 3.6.4).

GETA - lower limit of motion of input link for double rocker types 5 and 6 (Figure 3.6.4).



(a) Double-rocker types 3, 4 and 7

(b) Double-rocker types 5 and 6

Figure 3.6.4 Configurations for upper and lower limiting positions in double-rockers.

CHAPTER 4

OPTIMIZATION TECHNIQUE

4.1 Optimization Technique

The basic statement of nonlinear programming problem as stated earlier can be written as follows:

Minimize an objective function

$$U = U\ (X_1, X_2, \ldots X_n) \qquad (4.1.1)$$

Subject to p inequality constraints

$$\phi_i(X_1, X_2, \ldots, X_n) \geq 0 \text{ for } i = 1,2,\ldots,p \qquad (4.1.2)$$

and q equality constraints

$$\psi_j(X_1, X_2, \ldots, X_n) = 0 \text{ for } j = 1,2,\ldots,q \qquad (4.1.3)$$

All other constraints can be reduced to this form. For example:

$a(X) > b(X)$ is equivalent to $a(X) - b(X) > 0$

$a(X) <$ constant is equivalent to constant $-a(X) > 0$

Among the several optimization techniques available the iterative method is used for the present work. Iterative techniques fall mainly into two classes:

(a) Direct search methods are those which do not require the explicit evaluation of any partial derivatives of the function, but instead rely solely on the values of the objective function U, plus information gained from earlier iterations.

(b) Gradient methods on the other hand select the direction d_i using values of the partial derivatives of the objective function U with respect to the independent variables, as well as values of U, together with information gained from earlier iterations.

The direct search method as developed by Hooke, Jeeves and Wood [21] has been used for the present work. The algorithm is as follows for minimization:

1. Starting at some arbitrary point, the initial base point, an exploratory search is begun by changing one variable at a predetermined small positive step length If this improves the optimization function, it is used as the new reference value. If it does not, a negative step is taken. If both fail, no step is taken. The best value from the search of X_1 is used as the reference point for exploring X_2.

2. The final result of a successful exploratory search establishes a new base point.

3. A pattern move is now made by moving each independent variable from the latest base point an amount equal to the difference between the new and old base point values. The difference will commonly include a previous move.

4. If the move fails to improve the optimization function, it is cancelled and a new search made from the base point. If the move succeeds, it is followed by a new search.

5. The process is repeated until the univariate search cannot locate a better point. Then the step length is reduced

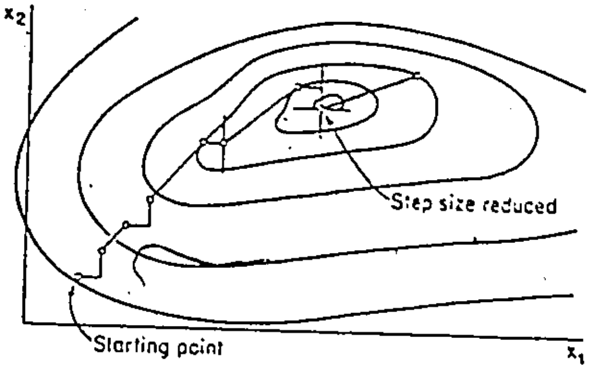


Figure 4.1.1 Direct search of Hooke and Jeeves. [21].

by some arbitrary fraction, and the exploratory search is continued. After each failure the step length is reduced until it reaches some predetermined minimum, when we assume the optimum has been reached. The method is illustrated for two dimensions in Figure 4.1.1.

4.2 Method of Handling Constraints

There are two optimization subroutines available in OPTISEP [17] which are based on Hooke and Jeeves' strategy, SEEK1 and SEEK3. In the author's view SEEK1 proved to be more efficient, hence it was used for all the problems. The method of handling constraints used in this algorithm is presented here.

A very simple and powerful method of handling constraints is through the use of penalty functions. Instead of minimizing the actual constrained function U, an artificial unconstrained function UART is minimized.

This artificial function has the form

$$\text{UART} = U(X_1, X_2, \ldots, X_n) + 10^{20} \sum_{j=1}^{q} |\psi_j| + 10^{20} \Sigma |\phi_k| \qquad (4.2.1)$$

where the last summation extends over only those of the p constraints which are violated at X. The penalty is therefore seen to be equal to the weighted sum of the absolute values of the amounts by which the constraints are violated and obviously the greater the violation the greater the penalty, whilst for feasible points the objective function is not modified

The method works reasonably well, although it creates steep valleys at the constraints. The sharp discontinuities in UART give trouble.

Many other optimization techniques available could have been used and the possibilites of obtaining better results are not ruled out. But the main objective of the present work was to synthesize coupler position problems rather than concentrating on the technique of optimization.

CHAPTER 5

MECHANISM SYNTHESIS

The software system which has been developed was tested on problems involving all types of four-bar linkages with the number of specified positions of the coupler plane varying from three to nine.

5.1 Sample Problems

1. Three arbitrary positions of the coupler plane with crank angles as independent design variables. Figure 5.1.1.
2. A crank-rocker mechanism whose coupler plane has to pass through five specified positions at specified crank angles. Figure 5.1.2.
3. A single-phase double-rocker mechanism whose coupler plane has to occupy six specified positions at specified crank angles. Figure 5.1.3.
4. A double-phase double-rocker mechanism with eight prescribed positions of the coupler plane allowing crank angles as independent design variables. Figure 5.1.4
5. A double-crank mechanism whose coupler plane occupies nine specified positions with crank angles as independent design variables. Figure 5.1.5.
6. Three arbitrary positions of the coupler plane specified by an outside agency. Figure 5.1.6.

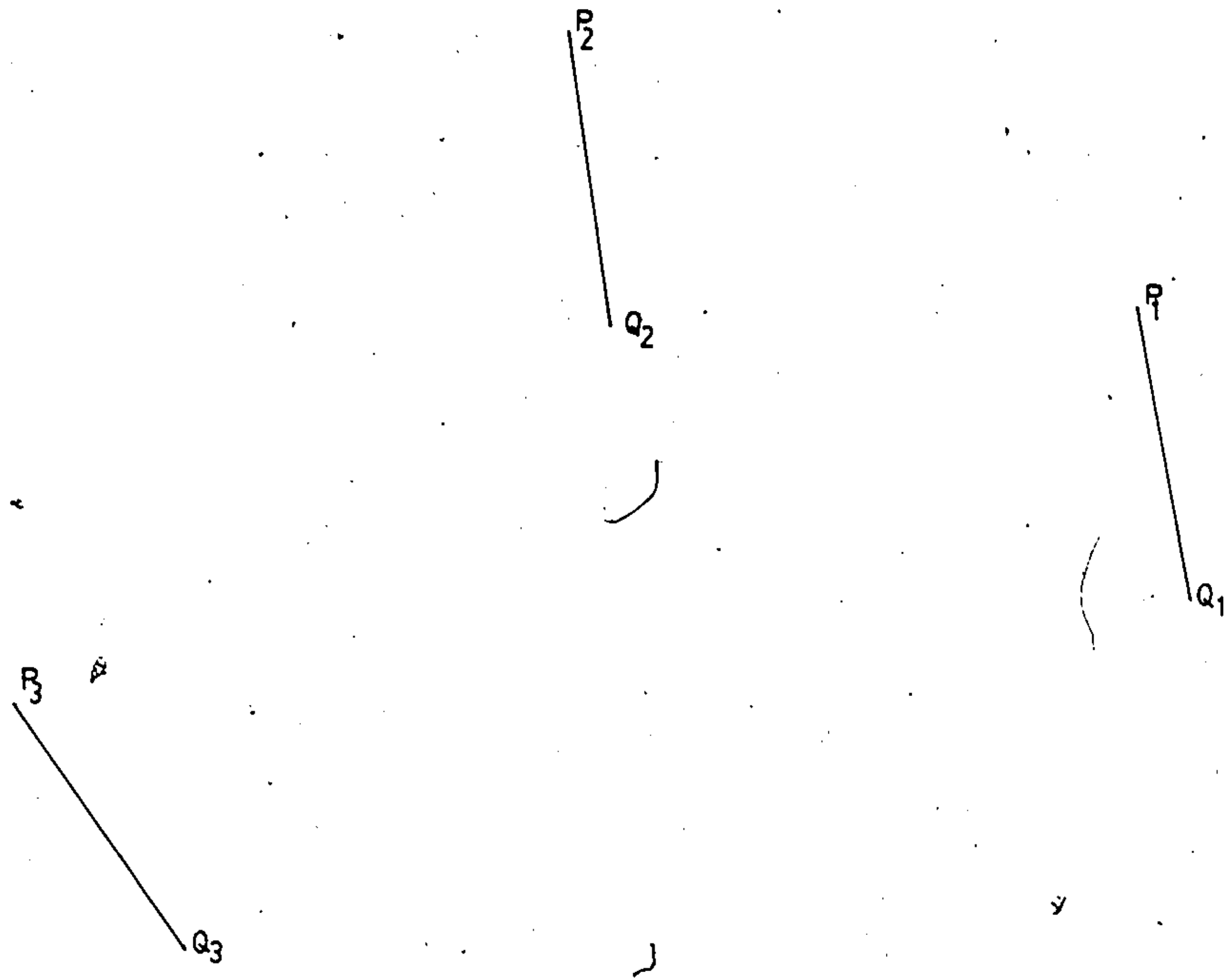


Figure 5.1.1 Problem 1

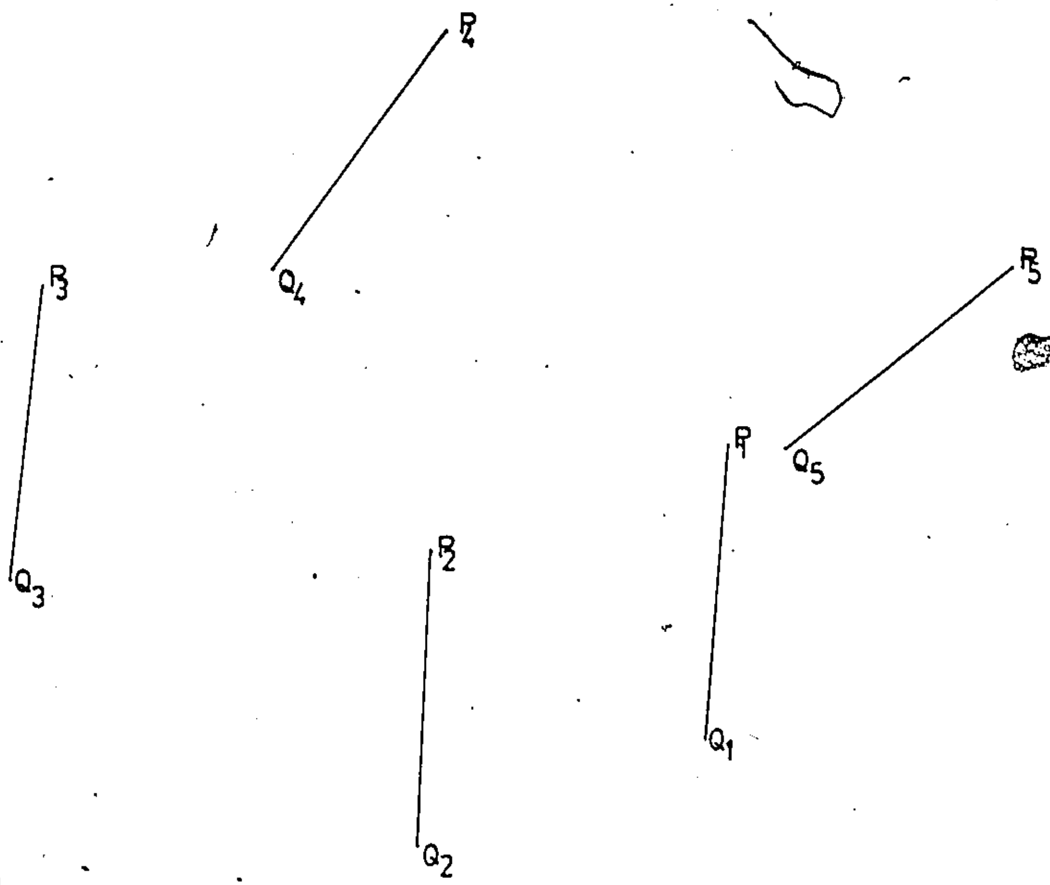


Figure 5.1.2 Problem 2

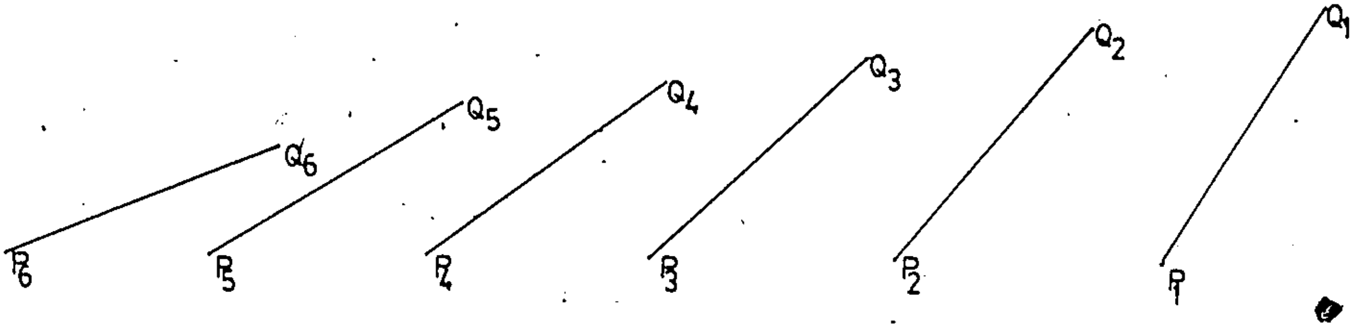


Figure 5.1.3 Problem 3

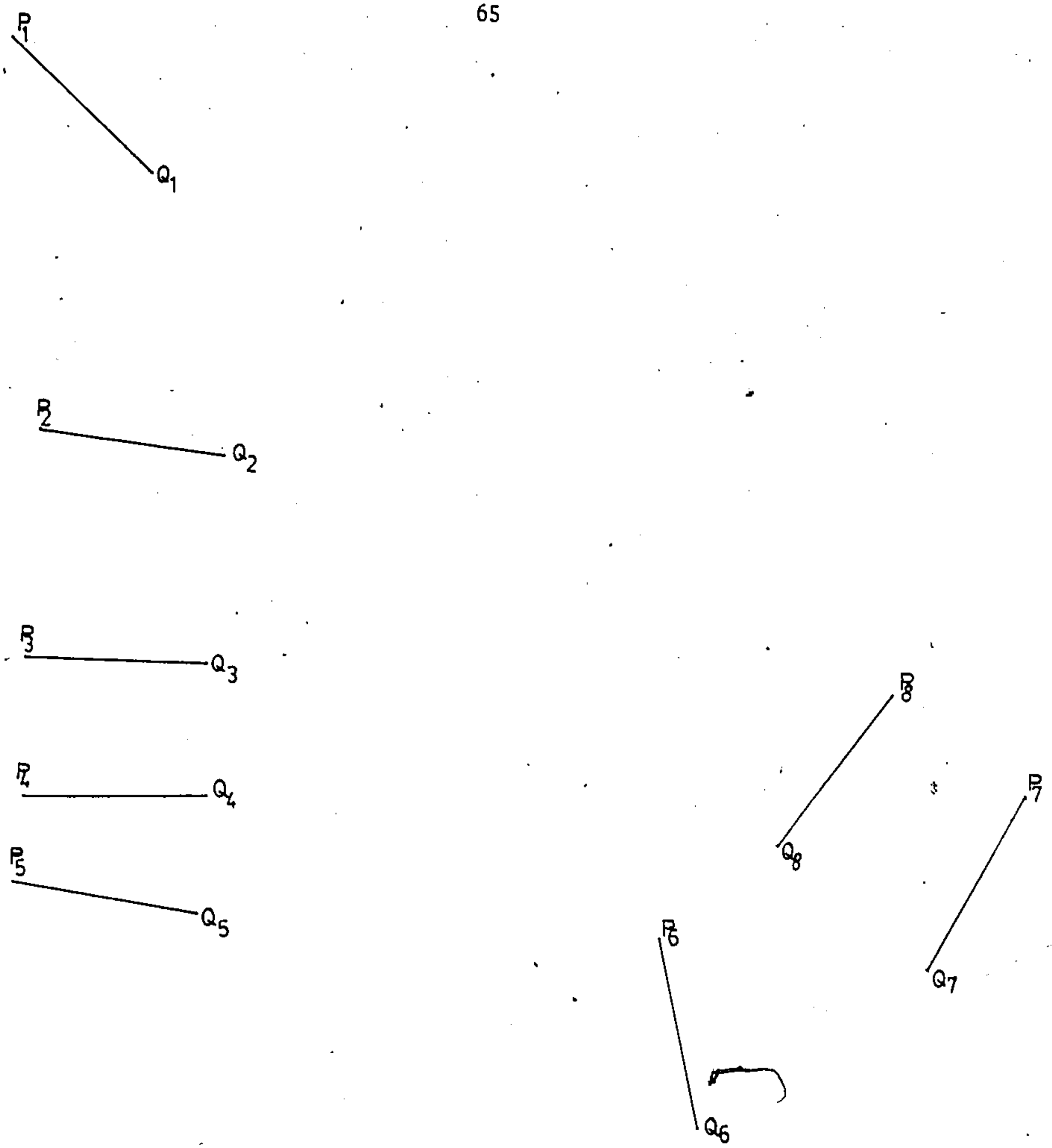


Figure 5.1.4 Problem 4

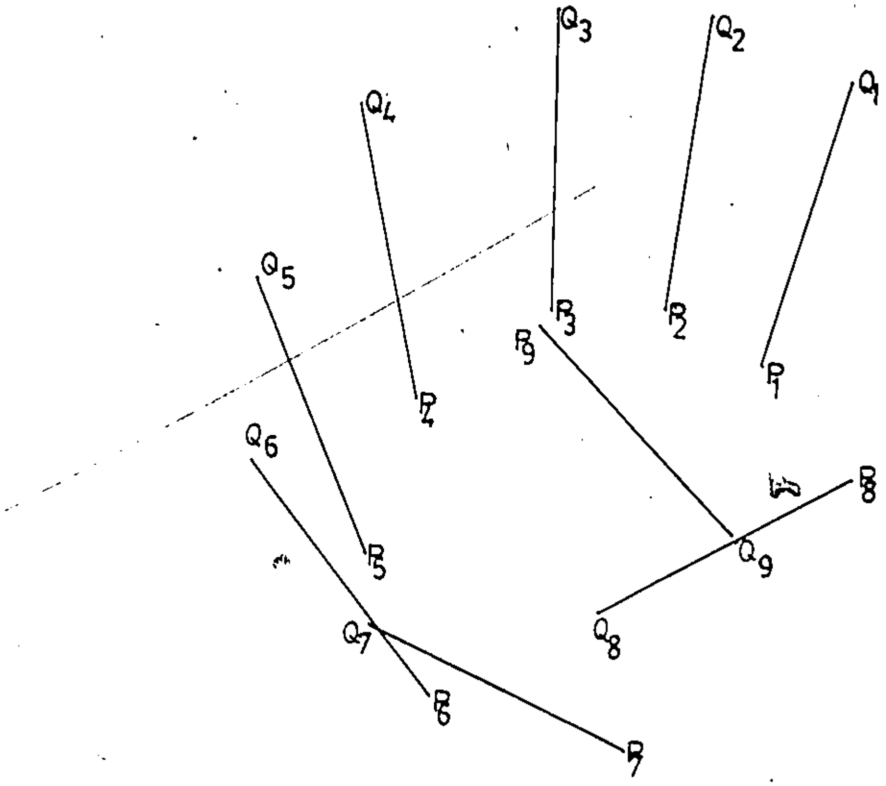


Figure 5.1.5   Problem 5

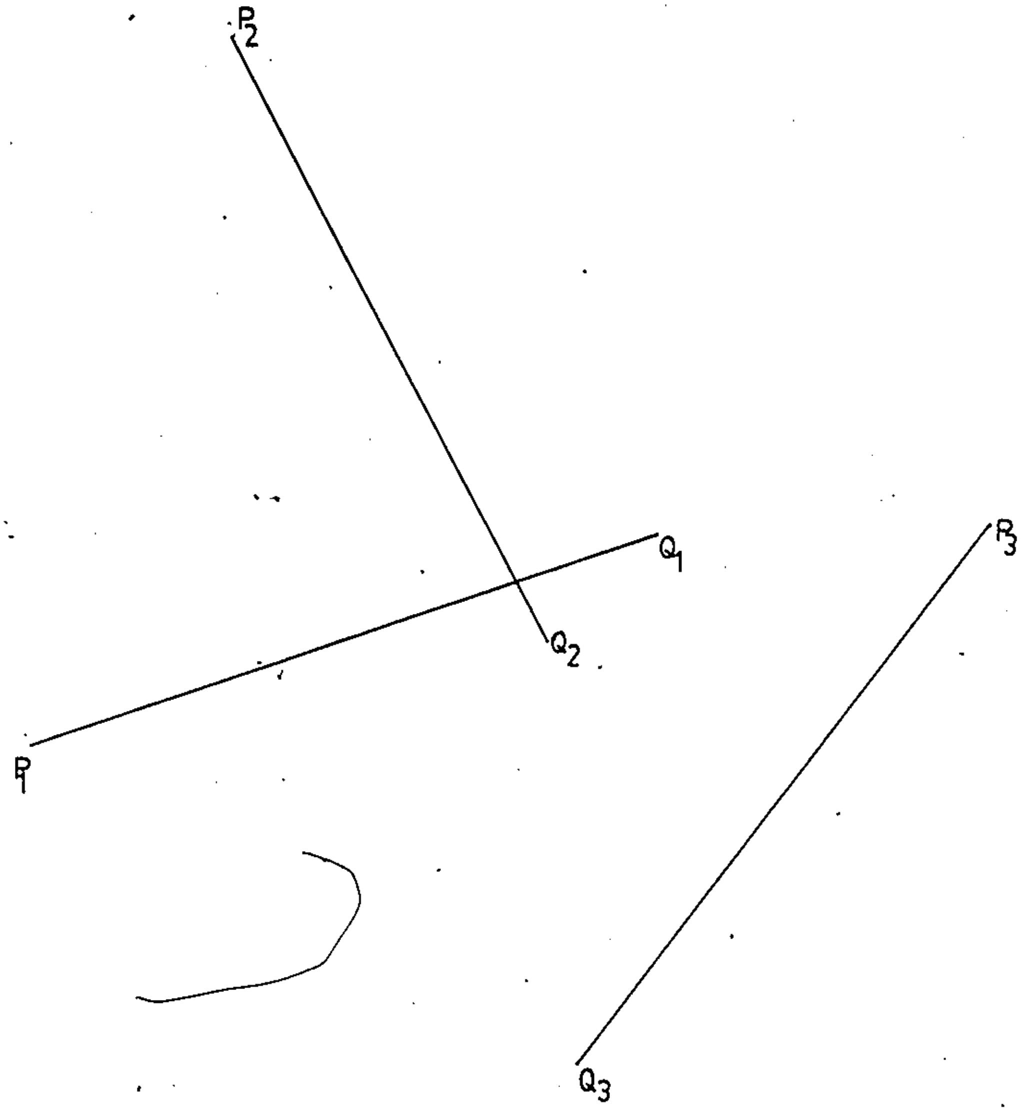


Figure 5.1.6 Problem 6

For the first problem three arbitrary positions were chosen and a crank-rocker mechanism was synthesized using graphical methods. These values were used as starting point values and obtained refined values for the design variables. Solutions were also obtained using arbitrary starting values.

For the second problem the five positions of the coupler plane were established by making a cardboard model. The idea in selecting this problem is to show that the software system can handle mechanisms with cross-closure, i.e., the value of ICASE = -1. Crank angles at every position were measured. Starting values of the variables required for the optimization routines were obtained by the perturbation of the model values.

For the third problem, keeping in mind the mechanism of a Jib-crane, six positions were chosen so that the coupler point is traversed horizontally. Knowing that this kind of motion is obtained by a double-rocker mechanism, starting values for the optimization routine were guessed. Here additional equality constraints are imposed on the design variables X_5 and X_{10} so that the coupler link is an extension of the crank and follower pins.

For the fourth problem a cardboard model was used to establish eight successive positions of the coupler plane. The first five positions were chosen in Phase 1 and the remaining three positions in Phase 2 of the double-rocker mechanism. The model values of the variables were perturbed to obtain starting values.

For the fifth problem a reference double-crank mechanism was chosen and the number of positions established were nine. The main idea in increasing the number of positions is to show that the system can handle any number of positions. The desired coordinates of the coupler point were specified with an accuracy of .001 inches and the desired inclination of the coupler plane with an accuracy of .01 degrees to observe the effect on the accuracy of the solution, and the computer time required. The starting values were obtained by perturbing model values.

Problem six was not chosen by the author but was given to him by an outside objective second party, thereby eliminating any personal prejudice the author might have had in selecting the earlier problems. The choice of the type of mechanism is open. Under these circumstances one would attempt all types of mechanisms.

5.2 Results

The solutions of all the problems are tabulated in Tables 5.2.1(a) to 5.2.12(b)

The graphical output program is controlled by the designer through the use of a light pen and the dynamic display screen. The designer has the option of displaying the desired and synthesized positions along with the mechanism or without the mechanism in different positions. The desired positions are seen as constantly blinking dot-dashed lines identified by a digit displayed adjacent to them indicating the precision position number. The frame of the mechanism is seen as a long-dashed line with the moving links as solid lines. The messages pertaining to the particular type of mechanism which has been designed and the number of positions being synthesized are seen at the upper right hand part of the screen. Messages indicating the maximum and minimum errors and the maximum and minimum angular deviations are seen at the bottom of the screen.

The designer has also the option of rotating the mechanism around dynamically with the coupler driving through various positions and the coupler point tracing the coupler path. The designer has the option of rotating the crank either clockwise or counter-clockwise in the case of the crank-rocker and double-crank mechanisms and the option of a particular phase in double-rocker mechanisms. As the mechanism is being animated, the crank angle, the follower angle and the transmission angle are also displayed. The case study photographs shown in Figures 5.2.1 to 5.2.30 give a better appreciation of the features of the graphics part of the software system.

TABLE 5.2.1(a)

PROBLEM 1 - SOLUTION 1

CRANK-ROCKER: 3 positions

Crank angles: independent design variables

Variable	Starting Value	Optimum Value
X_1	4.1	.40247773 E+01
X_2	6.0	.59088188 E+01
X_3	6.0	.59109482 E+01
X_4	5.8	.59147720 E+01
X_5	2.0	.20341660 E+01
X_6	2.0	.19180303 E+01
X_7	3.7	.37546943 E+01
X_8	4.6	.45621016 E+01
X_9	-15.0	-.14469668 E+02
X_{10}	90.0	.90360000 E+02
X_{11}	60.0	.59650898 E+02
X_{12}	120.0	.11918332 E+03
X_{13}	210.0	.20940586 E+03

TABLE 5.2.1(b)

Position	Crank Angle	Desired			Synthesized		
		X Inches	Y Inches	ALPHA Degrees	X Inches	Y Inches	ALPHA Degrees
1	59.65	8.343	9.585	7.94	8.343	9.585	7.94
2	119.18	4.593	10.53	4.99	4.593	10.53	4.99
3	209.40	.524	6.233	33.21	.524	6.233	33.21

U = .11256313 E-06

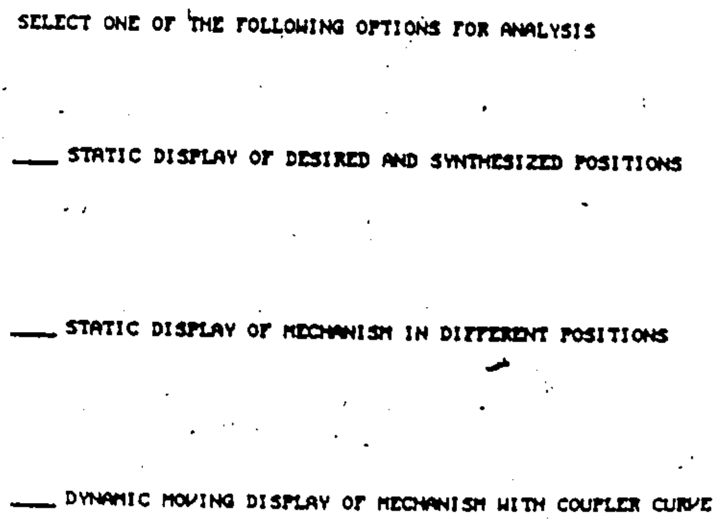
Min. Error = 0.000

Max. Error = 0.000

Min. Angular Dev. = 0.00

Max. Angular Dev. = 0.00

Execution Time = 16 secs.



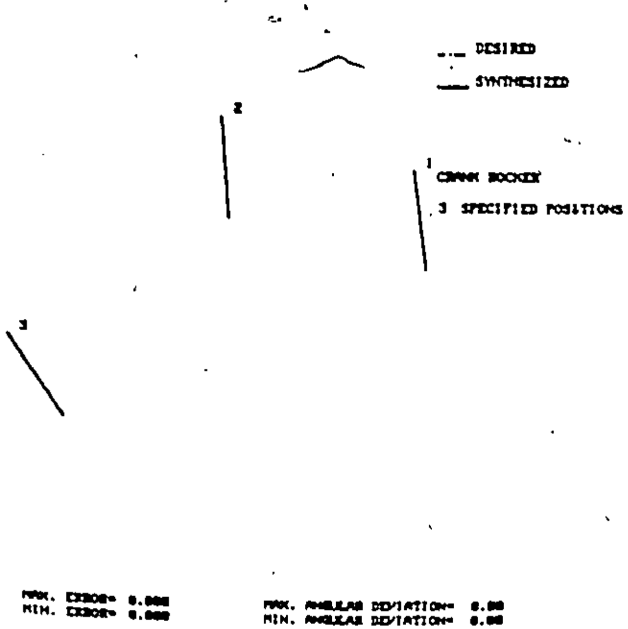
```
SELECT ONE OF THE FOLLOWING OPTIONS FOR ANALYSIS

____ STATIC DISPLAY OF DESIRED AND SYNTHESIZED POSITIONS

____ STATIC DISPLAY OF MECHANISM IN DIFFERENT POSITIONS

____ DYNAMIC MOVING DISPLAY OF MECHANISM WITH COUPLER CURVE
```

Figure 5.2.1 Computer requesting the designer to select an option for analysis.



```
MAX. ERROR= 0.000          MAX. ANGULAR DEVIATION=  0.00
MIN. ERROR= 0.000          MIN. ANGULAR DEVIATION=  0.00
```

Figure 5.2.2 Display of the desired and synthesized positions (Problem 1 - Solution 1).

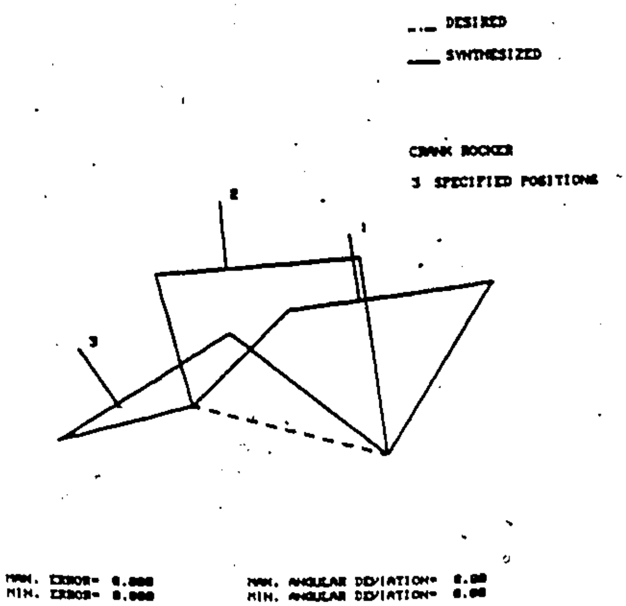
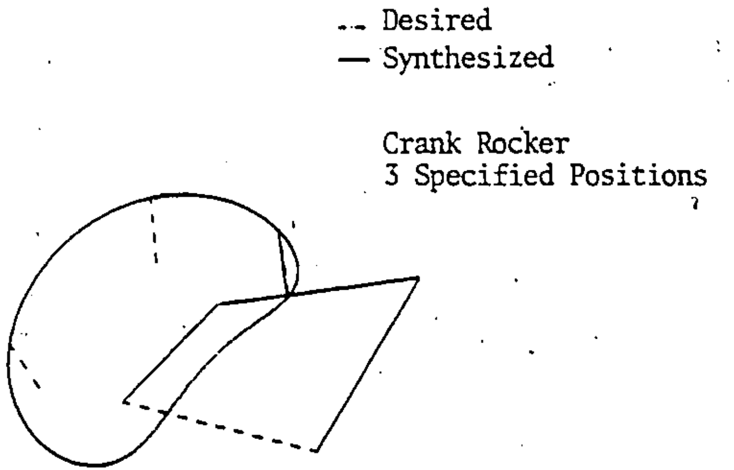


Figure 5.2.3 Display of the mechanism in the three design positions (Problem 1 - Solution 1).



Crank Angle = 60.6
Follower Angle = 74.8
Transmission Angle = 53.0

Max. Error = 0.000 Max. Angular Deviation = 0.00
Min. Error = 0.000 Min. Angular Deviation = 0.00

Figure 5.2.4 Display of the mechanism after the crank has made one revolution (Problem 1 - Solution 1).

TABLE 5.2.2(a)

PROBLEM 1 - SOLUTION 2

CRANK ROCKER: 3 positions

Crank angles - independent design variables

Variable	Starting Value	Optimum Value
X_1	5	.40312606 E+01
X_2	10	.74990349 E+01
X_3	10	.89255977 E+01
X_4	10	.59655498 E+01
X_5	5	.16761304 E+01
X_6	5	.13113481 E+01
X_7	10	.42770254 E+01
X_8	10	.45274086 E+01
X_9	0	-.13967988 E+02
X_{10}	80	.66410000 E+02
X_{11}	40	.59609180 E+02
X_{12}	80	.11894367 E+03
X_{13}	100	.20532918 E+03

TABLE 5.2.2(b)

Position	Crank Angle	Desired			Synthesized		
		X Inches	Y Inches	ALPHA Degrees	X Inches	Y Inches	ALPHA Degrees
1	59.6	8.343	9.585	7.94	8.343	9.585	7.94
2	118.94	4.593	10.53	4.99	4.593	10.53	4.99
3	205.32	.524	6.233	33.21	.524	6.233	33.21

U = .23883871 E-06

Min.Error = 0.000

Max. Error = 0.000

Min.Angular Dev. = 0.00

Max. Angular Dev. = 0.00

Execution Time = 35 secs.

TABLE 5.2.3(a)

Problem 1 - Solution 3
CRANK ROCKER: 3 positions

Crank angles: independent design variables

Variable	Starting Value	Optimum Value
X_1	3	.36125000 E+01
X_2	5	.62250000 E+01
X_3	5	.56125000 E+01
X_4	5	.43109000 E+01
X_5	5	.43273997 E+01
X_6	5	.41241563 E+00
X_7	5	.30339658 E+01
X_8	5	.33908662 E+01
X_9	100	.37167578 E+02
X_{10}	0	.44975234 E+02
X_{11}	40	.30205938 E+01
X_{12}	80	.71989648 E+02
X_{13}	120	.17161794 E+03

TABLE 5.2.3(b)

Position	Crank Angle	Desired			Synthesized		
		X Inches	Y Inches	ALPHA Degrees	X Inches	Y Inches	ALPHA Degrees
1	3.02	8.343	9.585	7.94	8.343	9.585	7.94
2	71.99	4.593	10.53	4.99	4.593	10.53	4.99
3	171.62	0.524	6.233	33.21	0.524	6.233	33.21

U = .15170228 E-05

Min. Error = 0.000

Max. Error = 0.000

Min. Angular Dev. = 0.00

Max. Angular Dev. = 0.00

Execution Time = 59 secs.

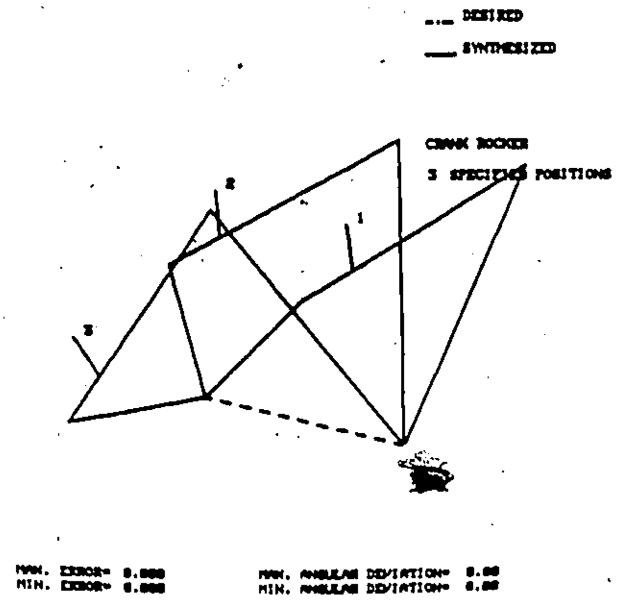


Figure 5.2.5 Display of the mechanism in the three design positions (Problem 1 - Solution 2).

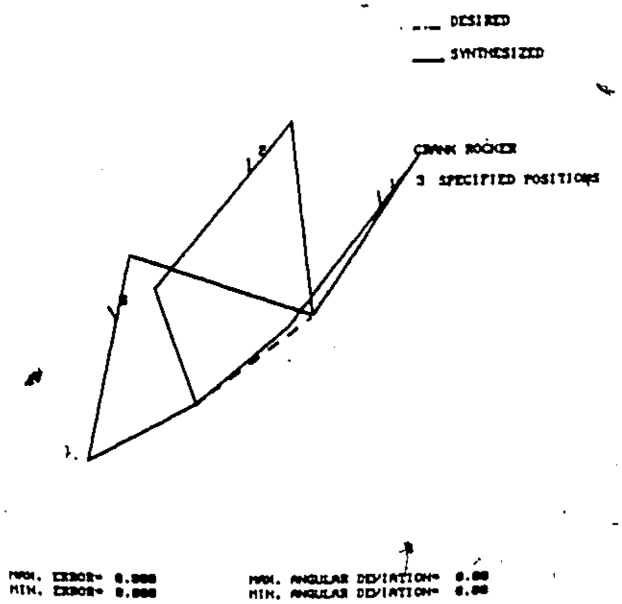


Figure 5.2.6 Display of the mechanism in the three design positions (Problem 1 - Solution 3).

TABLE 5.2.4(a)

PROBLEM 2

CRANK ROCKER: 5 positions

Crank angles - specified

Variable	Starting Value	Optimum Value
X_1	4.00	.30003629 E+01
X_2	8.00	.70954697 E+01
X_3	5.00	.34101469 E+01
X_4	8.00	.70408027 E+01
X_5	3.00	.25356885 E+01
X_6	6.00	.40440220 E+01
X_7	7.00	.49494824 E+01
X_8	7.00	.49328945 E+01
X_9	5.00	.36476562 E-01
X_{10}	100.00	.89074375 E+02

TABLE 5.2.4(b)

Position	Crank Angle	Desired			Synthesized		
		X Inches	Y Inches	ALPHA Degrees	X Inches	Y Inches	ALPHA Degrees
1	310.0	9.74	6.50	355.0	9.749	6.492	355.17
2	270.0	7.80	5.83	356.0	7.779	5.821	355.80
3	200.0	5.20	7.56	352.0	5.216	7.592	351.90
4	120.0	8.00	9.18	321.0	7.978	9.138	321.37
5	50.0	11.65	7.62	307.0	11.667	7.645	306.75

U = .39057605 E-01

Min. Error = .012

Max. Error = .046

Min. Angular Dev. = .09

Max. Angular Dev. = .37

Execution Time = 52 secs.

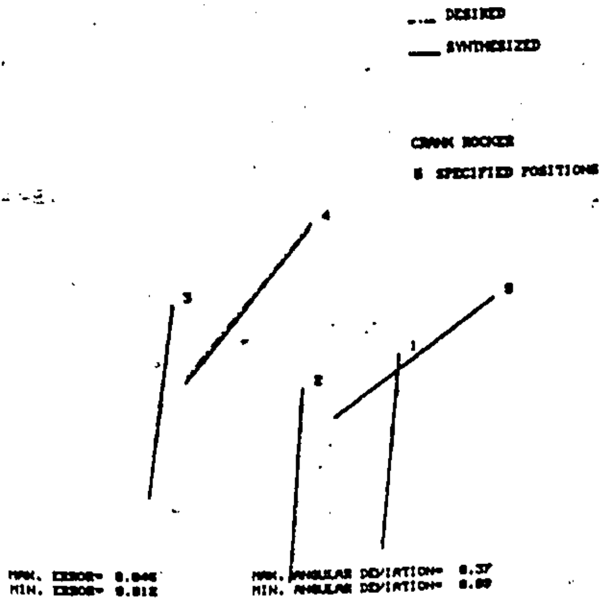


Figure 5.2.7 Display of the desired and synthesized positions (Problem 2).

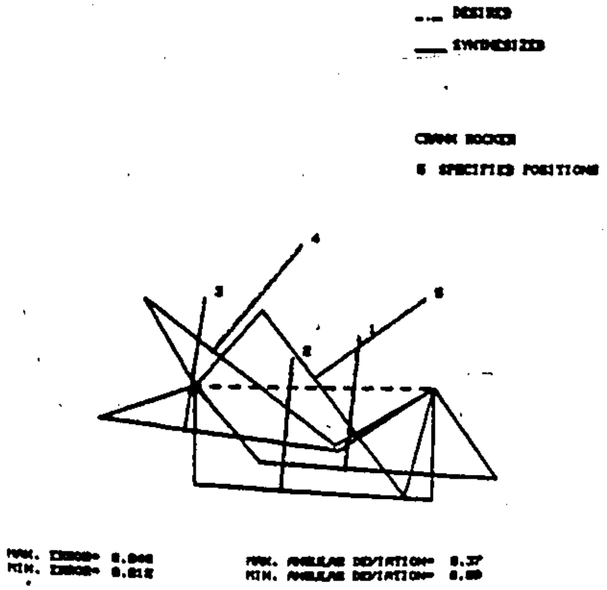


Figure 5.2.8 Display of the mechanism in the five design positions (Problem 2).

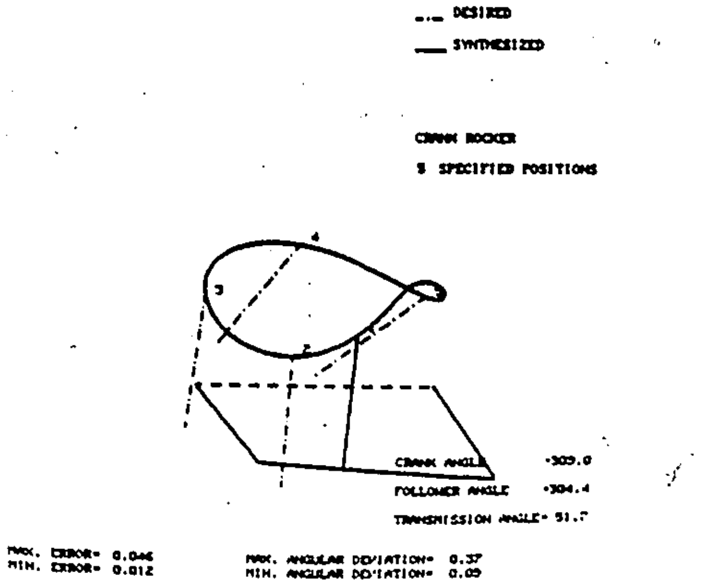


Figure 5.2.9 Display of the mechanism after the crank has made one revolution (Problem 2).

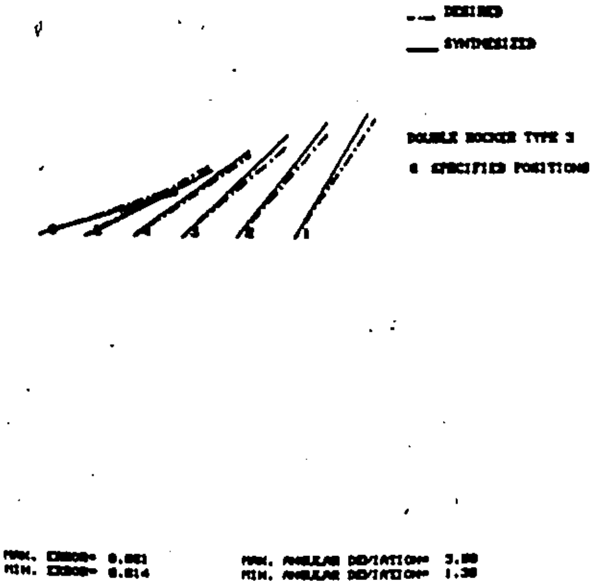


Figure 5.2.10 Display of the desired and synthesized positions (Problem 3).

TABLE 5.2.5(a)

PROBLEM 3

Double Rocker Type 3: 6 positions

Crank angles - specified

Variable	Starting Value	Optimum Value
X_1	20.0	.14723187 E+02
X_2	3.0	.32903750 E+01
X_3	16.0	.11858937 E+02
X_4	10.0	.85102500 E+01
X_5	0.0	0.0
X_6	5.0	.44471875 E+01
X_7	20.0	.21298563 E+02
X_8	6.0	.72968438 E+01
X_9	50.0	.55062496 E+02
X_{10}	180.0	.18000000 E+03

TABLE 5.2.5(b)

Crank Angle	Desired			Synthesized		
	X Inches	Y Inches	ALPHA Degrees	X Inches	Y Inches	ALPHA Degrees
45	16.500	18.000	146.0	16.471	17.960	149.5
50	14.700	18.000	139.00	14.705	18.032	141.5
55	13.000	18.000	131.50	13.048	18.037	133.9
60	11.500	18.000	125.00	11.479	17.998	126.3
65	10.000	18.000	120.00	9.992	17.958	117.9
70	8.600	18.000	110.00	8.598	18.014	107.5

U = .22415816 E+00

Min. Error = .014

Max. Error = .061

Min. Angular Dev. = 1.3

Max. Angular Dev. = 3.5

Execution Time = 258 secs.

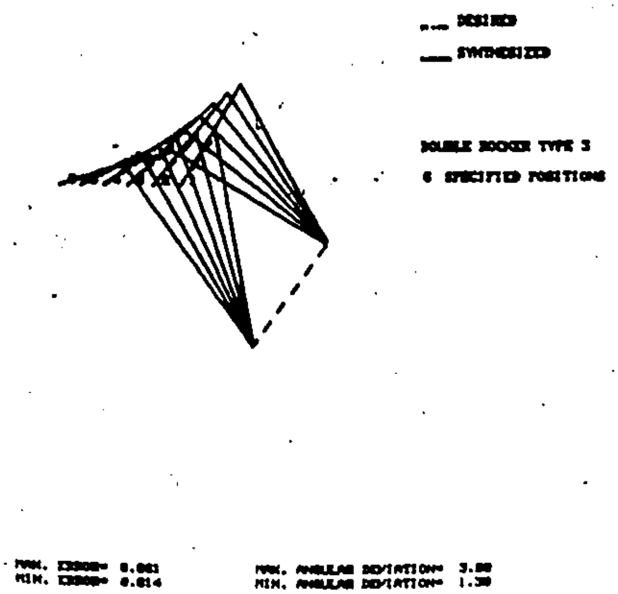


Figure 5.2.11 Display of the mechanism in the six design positions (Problem 3).

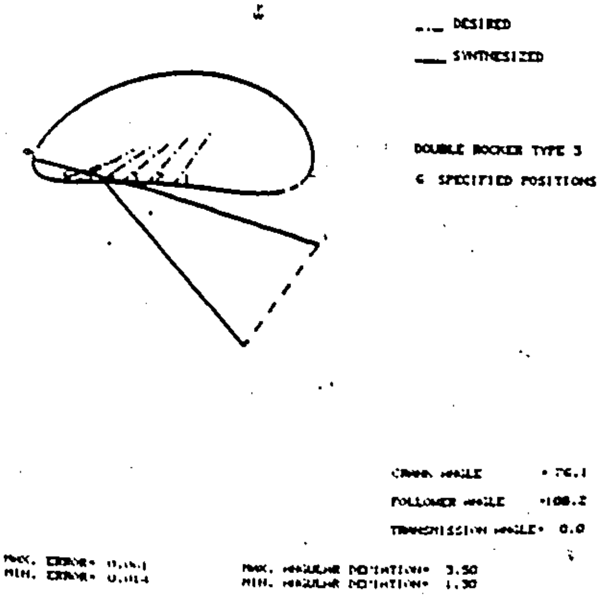


Figure 5.2.12 Display of the mechanism after the crank has made one cycle (Problem 3).

TABLE 5.2.6(a)

PROBLEM 4

Double Rocker Type 7 - 8 positions

Crank angles - independent design variables

Variable	Starting Value	Optimum Value
X_1	3.25	.29752910 E+01
X_2	5.20	.49287578 E+01
X_3	5.90	.60072754 E+01
X_4	10.50	.99832910 E+01
X_5	3.00	.30424746 E+01
X_6	3.00	.30071973 E+01
X_7	1.00	.10616602 E+01
X_8	1.00	.10464023 E+01
X_9	22.00	.26193203 E+02
X_{10}	80.00	.90440781 E+02
X_{11}	60.00	.64626562 E+02
X_{12}	0.00	.23165625 E+00
X_{13}	-20.00	-.23570625 E+02
X_{14}	-35.00	-.42054219 E+02
X_{15}	-60.00	-.62884688 E+02
X_{16}	-80.00	-.74086719 E+02
X_{17}	-4.00	-.16593750 E+01
X_{18}	30.00	.28574531 E+02

TABLE 5.2.6(b)

Position	Crank Angle	Desired			Synthesized		
		X Inches	Y Inches	ALPHA Degrees	X Inches	Y Inches	ALPHA Degrees
1	64.63	.91	8.29	47.	.913	8.281	46.98
2	.23	1.08	5.71	83.5	1.086	5.715	83.84
3	-23.57	1.03	4.21	90.0	1.036	4.211	90.27
4	-42.05	1.00	3.30	90.00	.976	3.311	89.33
5	-62.88	.90	2.70	82.00	.906	2.689	82.17
6	-74.08	5.40	2.40	12.00	5.403	2.396	12.142
7	- 1.65	7.90	3.35	330.00	7.894	3.348	330.05
8	28.57	7.00	4.00	323.00	7.006	4.008	322.73

U = .39058225 E-01

Min. Error = 0.005

Max. Error = 0.026

Min. Angular Dev. = 0.02

Max. Angular Dev. = 0.67

Execution Time = 96 secs.

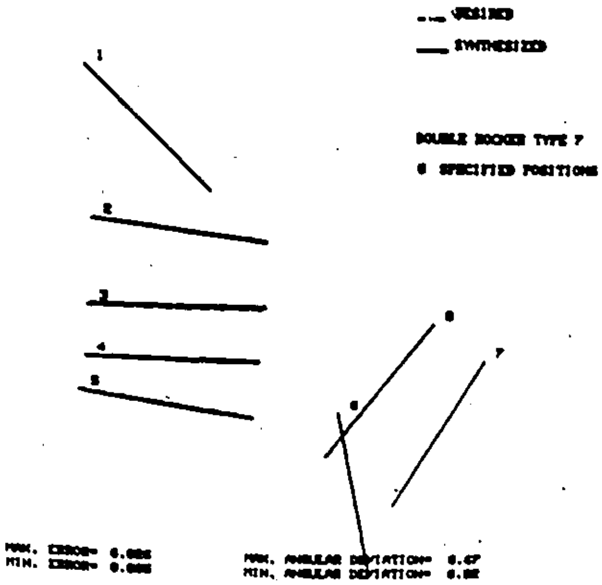


Figure 5.2.13 Display of the desired and synthesized positions (Problem 4).

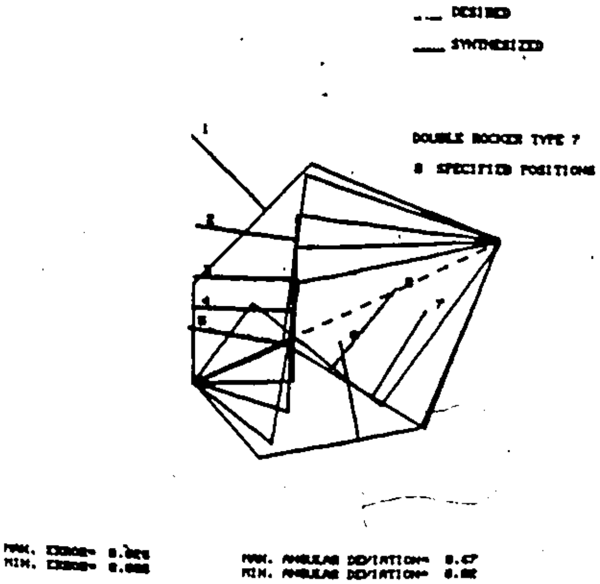


Figure 5.2.14 Display of the mechanism in the eight design positions (Problem 4).

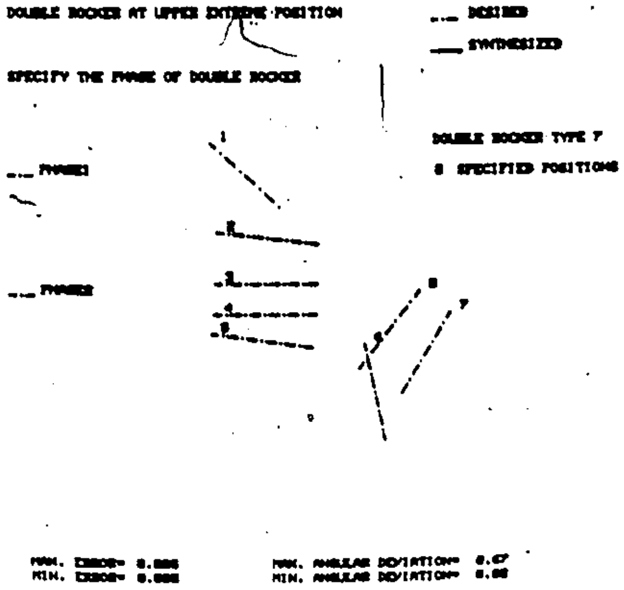


Figure 5.2.15 Computer requesting the designer to specify the phase of the double rocker at the upper extreme position (Problem 4).

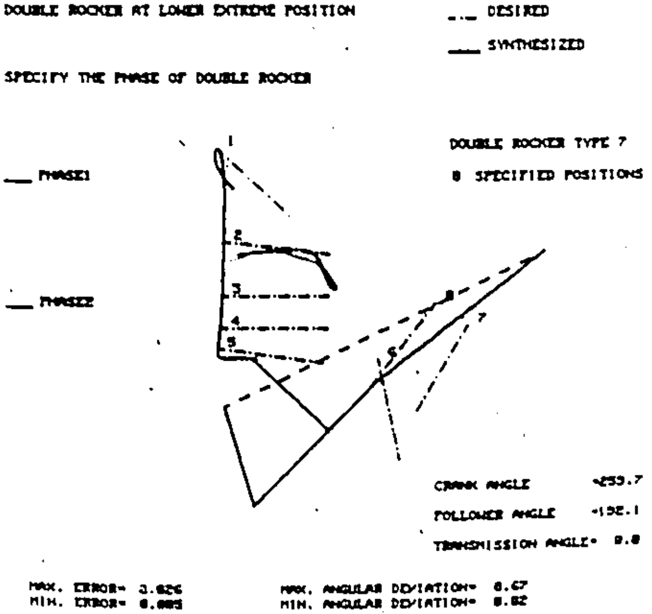


Figure 5.2.16 Computer requesting the designer to specify the phase of the double rocker at the lower extreme position (Problem 4).

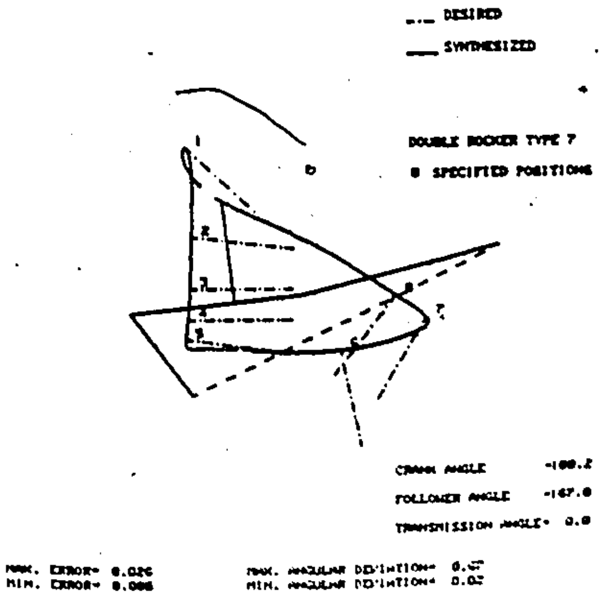


Figure 5.2.17 Display of the mechanism after the crank has made one cycle (Problem 4).

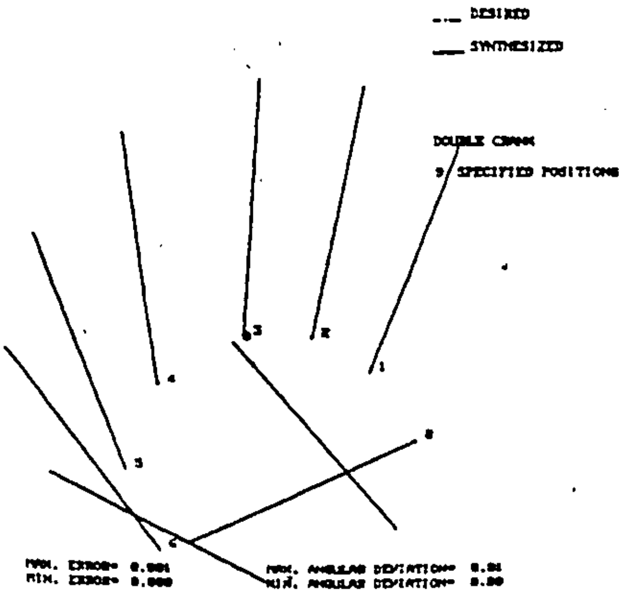


Figure 5.2.18 Display of the desired and synthesized positions (Problem 5).

TABLE 5.2.7(a)

PROBLEM 5

Double Crank; 9 positions

Crank angles - independent design variables

Variable	Starting Value	Optimum Value
X_1	8.00	.62609966 E+01
X_2	8.00	.74966705 E+01
X_3	9.00	.74928191 E+01
X_4	3.00	.45005700 E+01
X_5	3.00	.39978483 E+01
X_6	7.00	.57512682 E+01
X_7	5.00	.39996429 E+01
X_8	5.00	.40058352 E+01
X_9	5.00	.19859920 E+02
X_{10}	230.00	.24221820 E+03
X_{11}	40.00	.50159375 E+02
X_{12}	70.00	.70156914 E+02
X_{13}	100.00	.90150430 E+02
X_{14}	130.00	.12012320 E+03
X_{15}	170.00	.15008863 E+03
X_{16}	190.00	.18006828 E+03
X_{17}	210.00	.22001918 E+03
X_{18}	260.00	.27996930 E+03
X_{19}	310.00	.34998602 E+03

TABLE 5.2.7(b)

Position	Crank Angle	Desired X Inches	Desired Y Inches	Desired ALPHA Degrees	Synthesized X Inches	Synthesized Y Inches	Synthesized ALPHA Degrees
1	50.16	8.051	4.994	159.04	8.051	4.994	159.04
2	70.15	6.724	5.773	168.95	6.723	5.773	168.94
3	90.15	5.176	5.813	176.86	5.176	5.813	176.86
4	120.12	3.252	4.679	188.07	3.252	4.678	188.06
5	150.08	2.515	2.707	200.64	2.515	2.706	200.63
6	180.07	3.264	.825	216.22	3.264	0.825	216.21
7	220.02	5.929	-.027	242.96	5.928	-.026	242.96
8	279.97	9.142	3.424	295.00	9.142	3.423	295.00
9	349.99	4.947	5.675	41.16	4.946	5.675	41.16

U = .39600060 E-04

Min. Error = 0.000

Max. Error = 0.001

Min. Angular Dev. = 0.00

Max. Angular Dev. = 0.01

Execution Time = 510 secs.

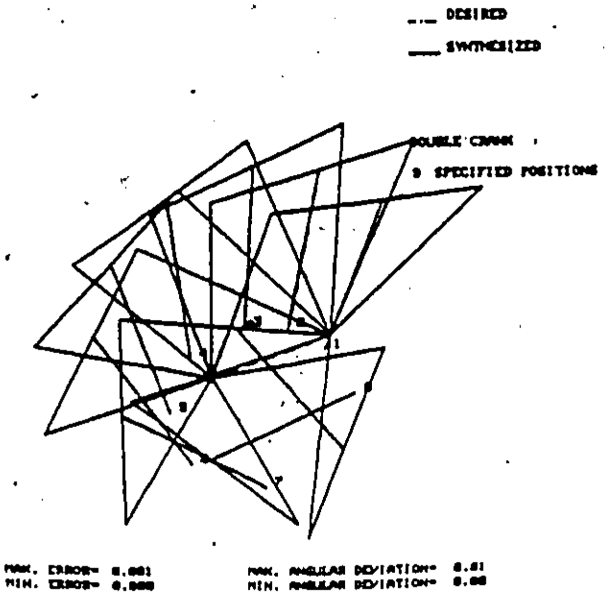


Figure 5.2.19 Display of the mechanism in the nine design positions (Problem 5).

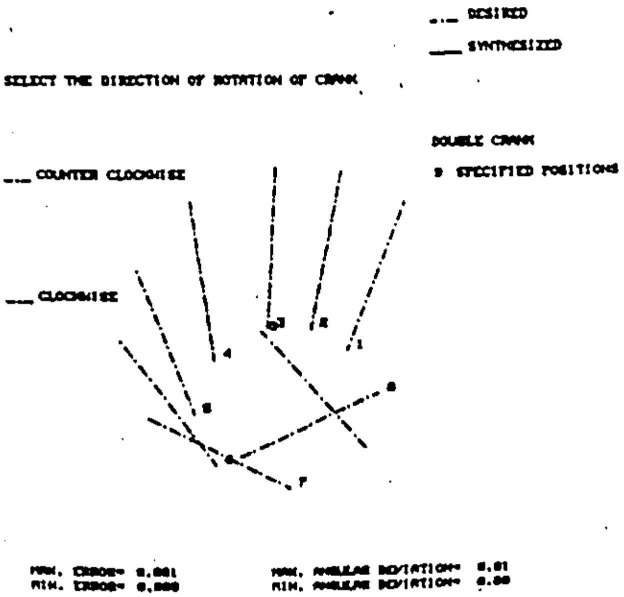


Figure 5.2.20 Computer requesting the designer to select the direction of rotation of crank (Problem 5).

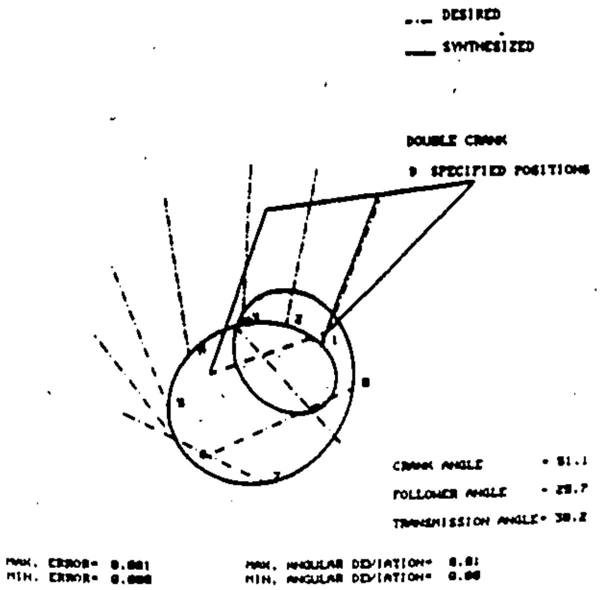


Figure 5.2.21 Display of the mechanism after the crank has made one revolution (Problem 5).

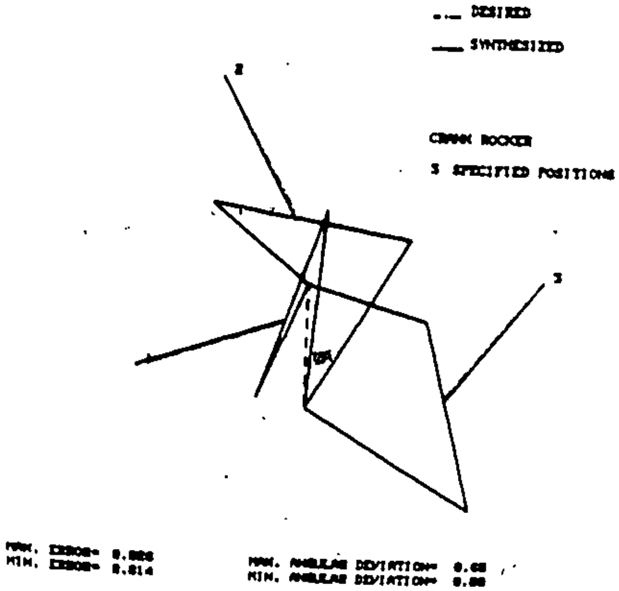


Figure 5.2.22 Display of the mechanism in the three design positions (Problem 6 - Solution 1).

TABLE 5.2.8(a)

PROBLEM 6 - SOLUTION 1

Crank Rocker: 3 positions

Crank angles: independent design variables

Variable	Starting Value	Optimum Value
X_1	5	.80791856 E+01
X_2	7	.12923900 E+02
X_3	9	.12924100 E+02
X_4	12	.80794000 E+01
X_5	3	.53292238 E+01
X_6	4	.99539908 E+01
X_7	6	.10880872 E+02
X_8	7	.13659586 E+02
X_9	0	-.89999716 E+02
X_{10}	180	.12806815 E+03
X_{11}	300	.33673067 E+03
X_{12}	150	.23119398 E+03
X_{13}	30	.74044639 E+02

TABLE 5.2.8(b)

Position	Crank Angle	Desired			Synthesized		
		X Inches	Y Inches	ALPHA Degrees	X Inches	Y Inches	ALPHA Degrees
1	336.73	0.000	8.000	109.19	0.012	8.008	109.19
2	231.19	5.000	26.588	30.00	4.974	26.591	29.35
3	74.04	26.000	14.248	322.33	26.013	14.237	322.98

U = .32369469 E+00

Min. Error = 0.014

Max. Error = 0.026

Min. Angular Dev. = 0.00

Max. Angular Dev. = 0.65

Execution Time = 70 secs.

TABLE 5.2.9(a)

PROBLEM 6 - SOLUTION 2

Double Crank - 3 positions

Crank angles - independent design variables

Variable	Starting Value	Optimum Value
X_1	4	.73137720 E+01
X_2	5	.69812506 E+01
X_3	6	.75017678 E+01
X_4	1	.63461993 E+01
X_5	2	.37696227 E+01
X_6	4	.11440830 E+02
X_7	6	.13526367 E+02
X_8	6	.14225479 E+02
X_9	0	-.51461680 E+02
X_{10}	100	.13581048 E+03
X_{11}	300	.28437176 E+03
X_{12}	150	.20303824 E+03
X_{13}	50	.51671484 E+01

TABLE 5.2.9(b)

Position	Crank Angle	Desired			Synthesized		
		X Inches	Y Inches	ALPHA Degrees	X Inches	Y Inches	ALPHA Degrees
1	284.37	0.000	8.000	109.19	0.000	8.000	109.19
2	203.04	5.000	26.588	30.00	5.000	26.588	30.00
3	5.167	26.000	14.248	322.33	26.000	14.248	322.33

U = .56919886 E-04

Min. Error = 0.000

Max. Error = 0.000

Min. Angular Dev. = 0.00

Max. Angular Dev. = 0.00

Execution Time = 63 secs.

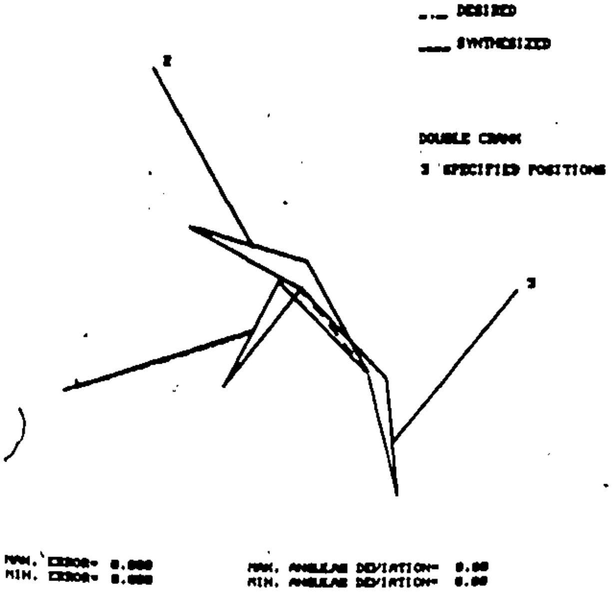


Figure 5.2.23 Display of the mechanism in the three design positions (Problem 6 - Solution 2).

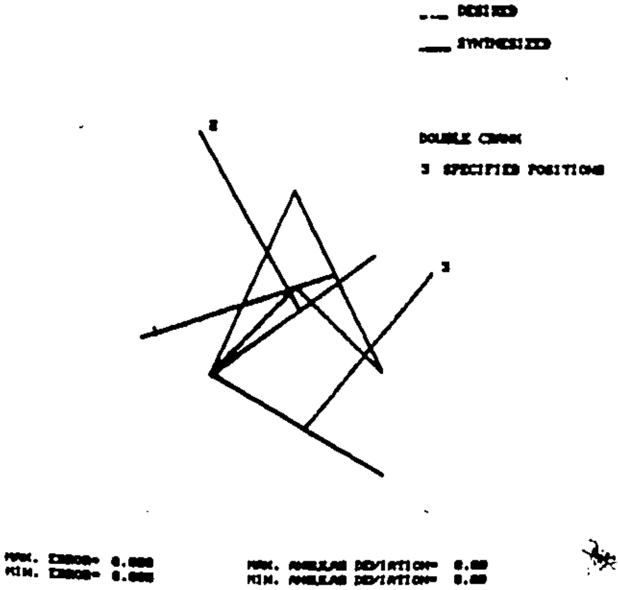


Figure 5.2.24 Display of the mechanism in the three design positions (Problem 6 - Solution 3).

TABLE 5.2.10(a)

PROBLEM 6 - SOLUTION 3

Double Crank: 3 positions

Crank angles - independent design variables

Variable	Starting Value	Optimum Value
X_1	5	.183491479 E+02
X_2	6	.18402180 E+02
X_3	8	.11160268 E+02
X_4	3	.11091410 E+02
X_5	3	.84543628 E+01
X_6	5	.18357527 E+02
X_7	5	.62644434 E+01
X_8	10	.47524624 E+01
X_9	150	.47334844 E+02
X_{10}	180	.26258445 E+03
X_{11}	330	.37926410 E+03
X_{12}	170	.34979195 E+03
X_{13}	40	.28222969 E+03

TABLE 5.2.10(b)

Position	Crank Angle	Desired			Synthesized		
		X Inches	Y Inches	ALPHA Degrees	X Inches	Y Inches	ALPHA Degrees
1	379.26	0.000	8.000	109.19	0.000	8.000	109.19
2	349.79	5.000	26.588	30.00	5.000	26.588	30.00
3	282.23	26.000	14.248	322.33	26.000	14.248	322.33

U = .10306328 E-04

Min. Error = 0.000

Max. Error = 0.000

Min. Angular Dev. = 0.00

Max. Angular Dev. = 0.00

Execution Time = 120 secs.

TABLE 5.2.11(a)

PROBLEM 6 - SOLUTION 4

Double Crank: 3 positions

Crank angles: independent design variables

Variable	Starting Value	Optimum Value
X_1	5.25	.86944297 E+01
X_2	5.00	.26867955 E+01
X_3	6.00	.89362142 E+01
X_4	3.00	.24339390 E+01
X_5	3.00	.31032144 E+01
X_6	2.00	.67694699 E+01
X_7	4.00	.11764635 E+02
X_8	6.00	.14089380 E+02
X_9	15.00	.27126773 E+01
X_{10}	90.00	.10615237 E+03
X_{11}	260.00	.23049641 E+03
X_{12}	120.00	.13461559 E+03
X_{13}	5.00	-.20764570 E+02

TABLE 5.2.11(b)

Position	Crank Angle	Desired			Synthesized		
		X Inches	Y Inches	ALPHA Degrees	X Inches	Y Inches	ALPHA Degrees
1	230.49	0.000	8.000	109.19	0.000	8.000	109.19
2	134.61	5.000	26.588	30.00	5.000	26.588	30.00
3	- 20.76	26.000	14.248	322.33	26.000	14.248	322.33

U = .16616893 E-04

Min. Error = 0.000

Max. Error = 0.000

Min. Angular Dev. = 0.00

Max. Angular Dev. = 0.00

Execution Time = 76 secs.

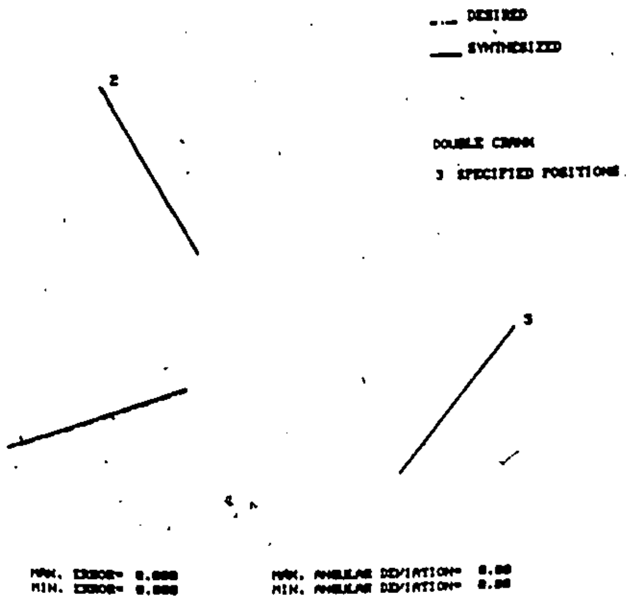


Figure 5.2.25 Display of the desired and synthesized positions (Problem 6 - Solution 4).

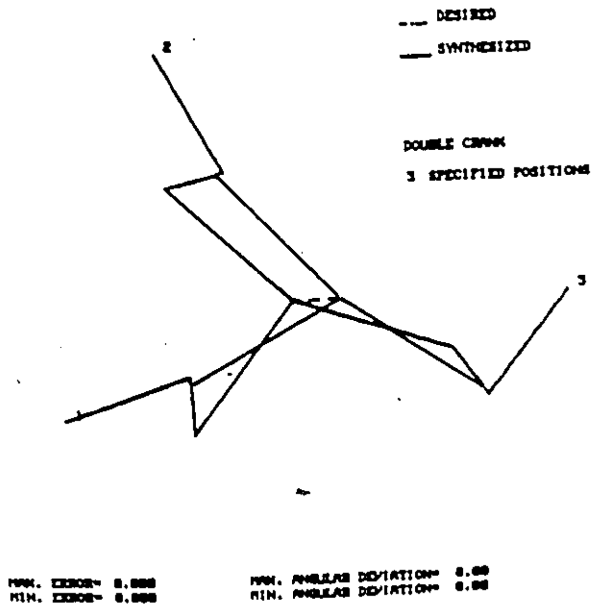


Figure 5.2.26 Display of the mechanism in the three design positions (Problem 6 - Solution 4).

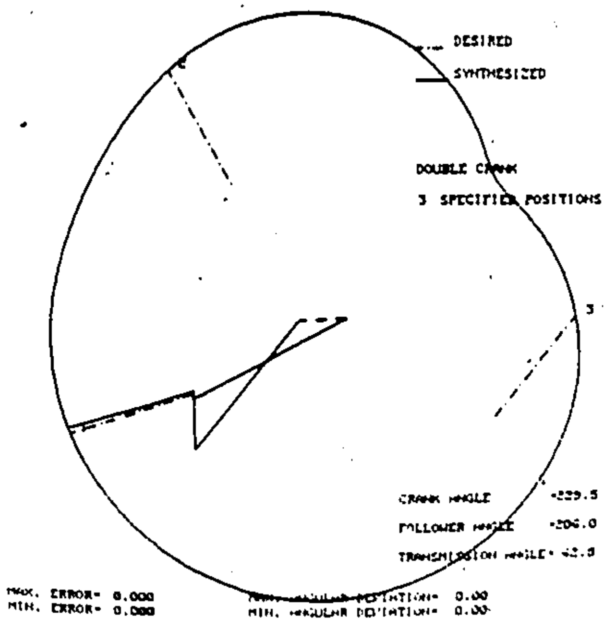


Figure 5.2.27 Display of the mechanism after the crank has made one revolution (Problem 6 - Solution 4).

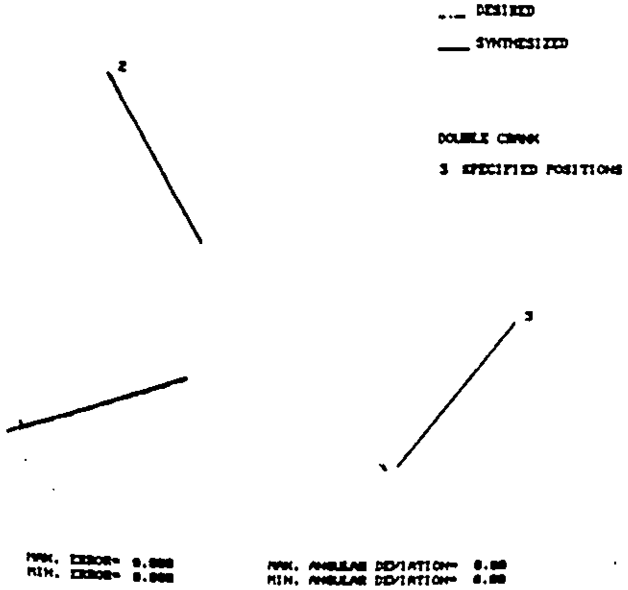


Figure 5.2.28 Display of the desired and synthesized positions (Problem 6 - Solution 5).

TABLE 5.2.12(a)

PROBLEM 6 - SOLUTION 5

Double Crank: 3 positions

Crank angles - independent design variables

Variable	Starting Value	Optimum Value
X_1	4.3	.78780703 E+01
X_2	4.0	.86895220 E+01
X_3	5.8	.89121025 E+01
X_4	2.45	.64267324 E+01
X_5	2.0	.34108940 E+01
X_6	3.0	.96442837 E+01
X_7	5.4	.12767678 E+02 ✓
X_8	6.9	.14150004 E+02
X_9	-16.0	-.64990156 E+02
X_{10}	90.0	.13104016 E+03
X_{11}	258.0	.29626164 E+03
X_{12}	156.0	.20800977 E+03
X_{13}	2.0	.32850937 E+02

TABLE 5.2.12(b)

Position	Crank Angle	Desired			Synthesized		
		X Inches	Y Inches	ALPHA Degrees	X Inches	Y Inches	ALPHA Degrees
1	296.26	0.000	8.000	109.19	0.000	8.000	109.19
2	208.00	5.000	26.588	30.00	5.000	26.588	30.00
3	32.85	26.000	14.248	322.33	26.00	14.248	322.33

U = .83241967 E-07

Min. Error = 0.000

Max. Error = 0.000

Min. Angular Dev. = 0.00

Max. Angular Dev. = 0.00

Execution Time = 63 secs.

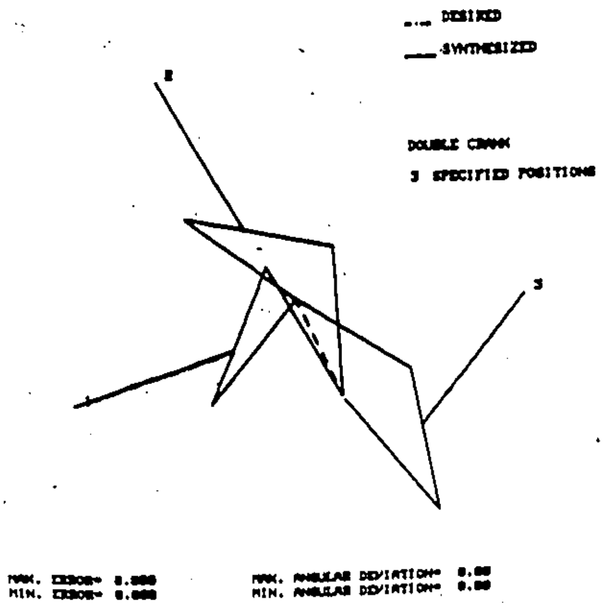


Figure 5.2.29 Display of the mechanism in the three design positions (Problem 6 - Solution 5).

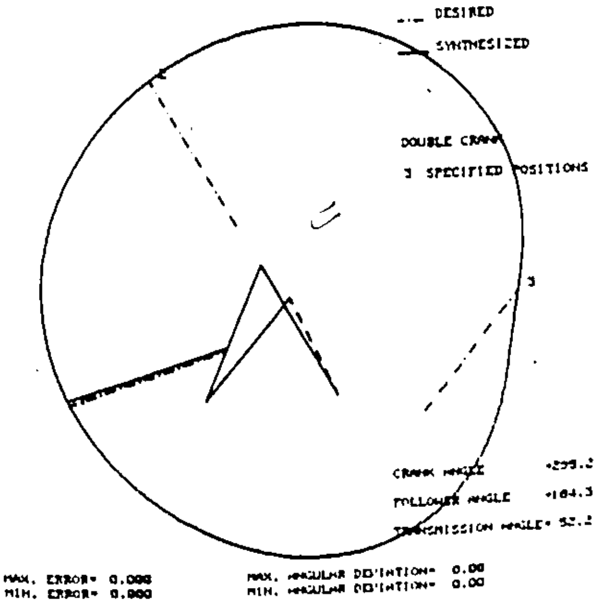


Figure 5.2.30 Display of the mechanism after the crank has made one revolution (Problem 6 - Solution 5).

CHAPTER 6

DISCUSSION AND RECOMMENDATIONS

6.1 Discussion of Results

Several problems were tried with several different objectives to determine how the software system works; though the main objective was to obtain mechanisms which would occupy the specified coupler positions as close as possible. A detailed discussion of the study will now be presented.

For the first problem three different solutions were obtained using different starting values. The starting values for the first solution were very close (obtained from a graphical technique) and hence the computer time required was as small as 16 seconds and the value of the objective function is smaller compared to the other two solutions. The computer times for the second and third solutions were comparatively higher (35 and 59 seconds), since the starting values were arbitrary. Though the objective function values are different for the three solutions, the coordinates of the coupler point and the orientation of the coupler link are accurate to .001 inch and .01 degrees respectively. For this type of problem the optimization surface would consist of a series of local minima. As there are infinite solutions for three position synthesis problems many more solutions could have been obtained using different starting values.

For the second problem the number of positions synthesized were five, the theoretical maximum for a four-bar mechanism. Starting values were close and the computer time required was 52 seconds.

In the third problem, the mechanism of a Jib-crane, the formulation for optimization could have been simplified. The main idea of using this kind of mechanism in cargo cranes is due to the fact that if the coupler point traces a horizontal path the load which is attached to the coupler point travels horizontally during luffing motion of the crane. This design minimizes the power required for luffing motion. The objective function could have been set up as the sum of the deviations of the coupler point from a horizontal line. Having solved this as a four-bar coupler position synthesis problem less importance is given for the orientation of coupler link by specifying 10 degrees as the maximum allowable deviation on the inclination of the coupler link and .1 inches as the maximum allowable deviation in tracing the coupler point. The angular deviation is as high as 3.5 degrees. The starting values were rough and the computer time was 258 seconds.

The starting values for the fourth problem were close and the computer time required was 96 seconds. For the fifth problem the solution was obtained with an accuracy of .001 inches for coupler point coordinates and .01 degrees for the inclination of the coupler link, for all the nine positions. Though the starting values were perturbed values of the model values, in the author's opinion they are sufficiently far removed from the model values and the computer time required was 510 seconds. This clearly shows that we can synthesize mechanisms for any number of positions provided the solution exists. But the computer time required will considerably increase if the starting values are far from the optimum values.

In the sixth problem a crank-rocker mechanism has been attempted and a solution found with an accuracy of .02 inches for coupler point coordinates and 0.7 degrees for the inclination of the coupler link. But if we notice the sum of the longest and smallest link lengths (i.e. $\ell + s$) and the sum of the other two link lengths (i.e. $p + q$) have a difference of .00001 inches. This results in a linkage with $\ell + s = p + q$ which is not good from the point of needing guidance and from the force transmission characteristics. Then a double-crank mechanism was tried and four different solutions were found with an accuracy of .001 inches for the coupler point coordinates and .01 degrees for the orientation of the coupler link. Solution three also results in a linkage with $\ell + s = p + q$. The double-rocker mechanisms were also attempted but a satisfactory solution could not be obtained. Hence it is important to know which type of mechanism suits the problem although in solving any particular problem one could try all possible types.

The study clearly shows that starting values have a direct effect on the computer time required for the convergence of the problem. This was observed in almost all the problems. For problems 2 and 4 the starting values were very close to the model values so the computer times required for the convergence were small compared to the rest of the problems. From the author's view, for three position synthesis problems one can obtain solutions with arbitrary starting values. A three position design will usually satisfy most problems found in practice. It is some times desirable to specify additional approximate positions which only need to be generated roughly so that the link will clear other machine parts or make a return stroke within a specified space.

In a situation where a mechanism needs to be designed for more prescribed positions, one could design a mechanism for three of the important precision positions and analyze the mechanism motion characteristics, then redesign for all the positions until a satisfactory linkage is obtained. Another logical way is to analyze the coupler curve. This would lead to certain valuable information about the particular type of mechanism required. The Hrones and Nelson motion catalogue [22] can be of much help in obtaining link length proportions which would approximate the desired coupler curve. This catalogue contains roughly 7300 coupler curves drawn to large scale and constitutes a very practical tool for the designer, who by paging through may find a shape and configuration suitable for a given application.

An important factor which gave rise to complications is that in the region where a problem is particularly suited for a crank-rocker solution, and the link proportions in the original design are such that the mechanism is not a crank-rocker, the optimization technique will not necessarily bring the design variables back to the feasible region from the unfeasible.

Another factor to be noticed is the values of maximum errors for coupler point co-ordinates and coupler link orientation. As given in Equations (3.4.4 and 3.4.5)

$$U_1 = \frac{1}{N} \sum_{i=1}^{N} \left(\frac{{\varepsilon_1}_i^{2}}{\text{ERMAX1}^{2}} \right)$$

$$U_2 = \frac{1}{N} \sum_{i=1}^{N} \left(\frac{{\varepsilon_2}_1^{2}}{\text{ERMAX}_2^{\,2}} \right)$$

The parameters ERMAX1 and ERMAX2 establish scales for obtaining the inverse utility. If to a designer, an error of .1 inch in point tracing is equally undesirable as 5 degrees of angular deviation then the parameters ERMAX1 and ERMAX2 will have values of 0.1 and 5.0 respectively. Specifying some values of the above parameters does not necessarily mean that the maximum error involved will be less than the specified value, as there is no such constraint imposed on the problem, but it sets the relative weighting scale for both the errors.

Table 6.1.1

Problem No.	Position	Original Values			New Values[a]		
		X Inches	Y Inches	ALPHA Degrees	X Inches	Y Inches	ALPHA Degrees
Problem 1	1	8.343	9.585	7.94	8.347	9.580	7.96
Solution 1	2	4.593	10.530	4.99	4.594	10.529	5.00
	3	0.524	6.233	33.21	0.524	6.234	33.21
		U = .11256313E-06			U = .14992548E-02		
Problem 6	1	0.000	8.000	109.19	0.001	7.999	109.19
Solution 5	2	5.000	26.588	30.00	5.010	26.593	29.94
	3	26.000	14.248	322.33	26.003	14.233	322.26
		U = .83241967E-07			U = .15931968E-01		

An additional feature is that the optimum design variables as obtained by the computer have values up to 8 decimal places. Because of the practical limitations in the fabrication of the mechanisms, it was felt necessary to investigate the effect of small changes in the values of the design variables on the objective function and the desired coupler link position coordinates and coupler link orientation. The values of the design variables were rounded off at the third place of decimal assuming that a linkage can be machined to an accuracy of one-thousandth of an inch and the angular dimensions were rounded off at the first place of decimal assuming an angle can be measured to the accuracy of one-tenth of a degree. The analysis was done for the first and the sixth problems. Table 6.1.1 shows the values of the coupler point coordinates and inclination of the coupler link for the original and rounded values of the design variables as well as the objective function values. It is clear from the table that the effect on the dimensions of the coupler link positions is marginal. It is also clear from the objective function values that we need not look for convergence to the order of 1E-07 in objective function.

6.2 Recommendations

As the synthesis and analysis parts of the software system are being executed separately, the system lacks the full utility of the graphics output to the designer immediately.

Hence it has to be made a single system through a satellite graphics approach as mentioned earlier. The designer could sketch the design positions and initial design of the mechanism on the screen using a light pen.

There are some obvious areas of interest which could be investigated. Briefly they are:

1. An obvious extension of this work is for multi-loop planar mechanisms and also to spatial four-bars.

2. Within the area of planar four-bars:

(a) Greater accuracy at some positions: To a designer some positions of the coupler plane may be more important than others from the point of view of accuracy. One could specify a suitable weighting factor, and the inverse utilities when computed for these positions are multiplied by the weighting factor. This would result in greater minimization of the errors at those positions.

(b) Transmission Angle: It may be very important for some mechanisms to have a good transmission angle at certain prescribed positions of the coupler link. This could be done by imposing constraints on the transmission angle. Another approach is by introducing the transmission angle as another dependent design variable. A suitable inverse utility curve can be assumed for the deviation of the actual transmission angle from 90° and the objective function will be the sum of the structural error and the transmission angle error. Similar work has been done by Srivastava [23] for the synthesis of coupler curves.

(c) An interesting study could involve constraints on velocity and/or acceleration of the links or the coupler point. In many cases the velocity of the coupler point might be an important consideration.

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APPENDIX A

MECHANISM SYNTHESIS EQUATIONS

A.1 Follower Angle as a Function of the Crank Angle

We shall define the following parameters as shown in Fig. A.1.

a = Input link (crank) length

b = Coupler link length

c = Follower link length

d = Frame length

ϕ = Crank angle

ψ = Follower angle

Using plane trigonometry the following relations were derived:

$$\sin \theta_1 = \frac{a}{e} \sin \phi$$

$$\cos \theta_2 = \frac{e^2 + c^2 - b^2}{2ec}$$

where $e = \sqrt{a^2 + d^2 - 2ad \cos \phi}$

$$\theta_1 = \sin^{-1} \left(\frac{a \sin \phi}{e}\right)$$

$$\theta_2 = \cos^{-1} \left(\frac{e^2 + c^2 - b^2}{2ec}\right)$$

The following relation for follower angle is derived depending upon the range of the crank angle.

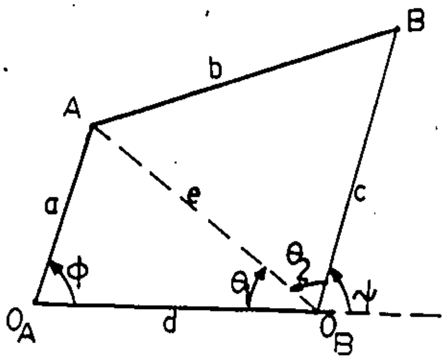
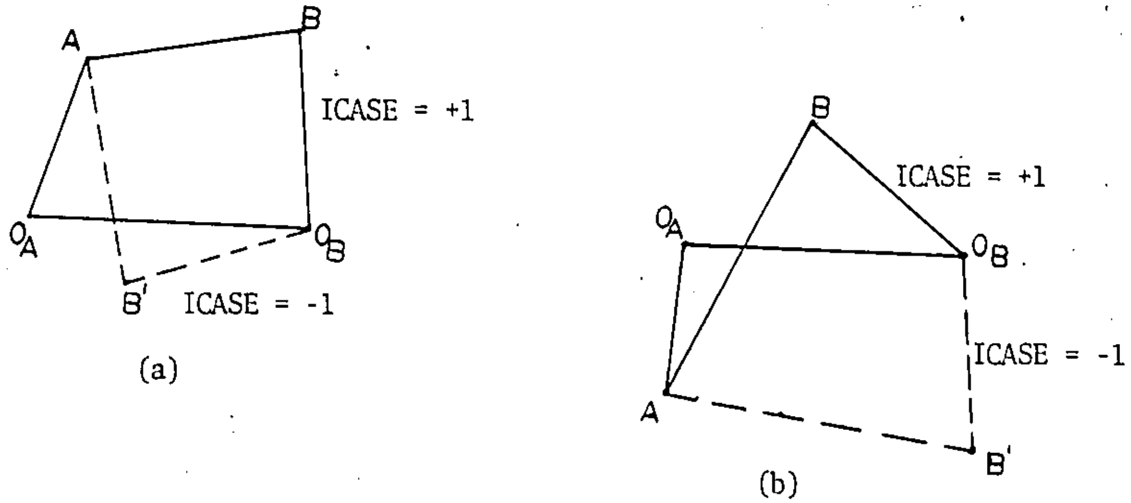


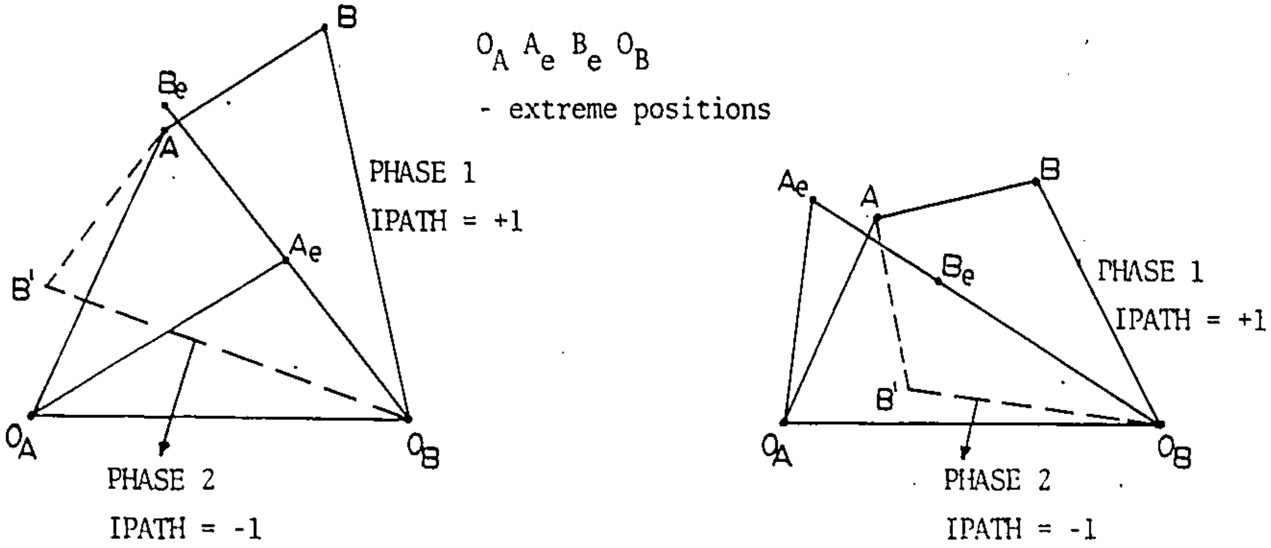
Figure A.1 Four-bar linkage parameters.



(a)

(b)

Figures A.2 Configurations for closure of mechanism.



(a) Double-rocker types 5 and 6.

(b) Double-rocker types 3, 4 and 7

Figure A.3 Configurations for the phases of double-rockers.

$$\psi = 180 - (\theta_1 + ICASE*IPATH*\theta_2)$$

$$\text{for } 180 > \phi > 0$$

$$\psi = 180 + (\theta_1 - ICASE*IPATH*\theta_2)$$

$$\text{for } 360 > \phi > 180 \qquad (A.1)$$

The values of ICASE are shown in Figure A.2. The values of IPATH are shown in Figure A.3.

For Crank-Rocker and Double-Crank Mechanisms:

ICASE = $\pm$ 1 depending upon the closure of the mechanism

IPATH = + 1

For Double-Rocker Mechanisms:

ICASE = +1

IPATH = $\pm$ 1 depending upon the phase of the mechanism.

A.2 Coupler Point Co-ordinates

We shall define the following parameters as shown in Figure A.4.

f = perpendicular distance from coupler point P to coupler link AB.

g = distance along the coupler link from the crank pin to intersection with PQ.

θ = Angle made by the frame with x-axis measured c.c.w.

ℓ, m = Co-ordinates of the pivot O_A on the reference plane XOY

ε, p = Coordinates of point Q

X, Y = Coupler point co-ordinates

The following relations were derived using plane geometry.

$$\begin{aligned} M &= A'B' \\ &= O_A'O_B' - O_A'A' + O_B'B' \\ &= d \cos \theta - a \cos (\phi+\theta) + c \cos (\psi+\theta) \end{aligned}$$

$$\begin{aligned} N &= A''B'' \\ &= O_A''O_B'' + O_B''B'' - O_A''A'' \\ &= d \sin \theta + c \sin (\psi+\theta) - a \sin (\phi+\theta) \end{aligned}$$

$$\begin{aligned} \varepsilon &= \ell + O_A'A' + \frac{m}{b} . g \\ &= \ell + a \cos (\phi+\theta) + \frac{M}{b} . g \end{aligned}$$

$$\begin{aligned} p &= m + O_A''A'' + \frac{N}{b} . g \\ &= m + a \sin (\phi+\theta) + \frac{N}{b} . g \end{aligned}$$

Using similar triangles (see Figure A.5):

$$\begin{aligned} X &= \varepsilon - \frac{N}{b} . f \\ &= \varepsilon - f \, . \sin \alpha \end{aligned} \tag{A.2}$$

$$\begin{aligned} Y &= p + \frac{M}{b} . f \\ &= p + f \, . \cos \alpha \end{aligned} \tag{A.3}$$

A.3 Angle that on the Coupler Plane Makes with Y-Axis

A.3.1 Line PQ Perpendicular to the Coupler Link

α = angle which a line PQ on the coupler plane

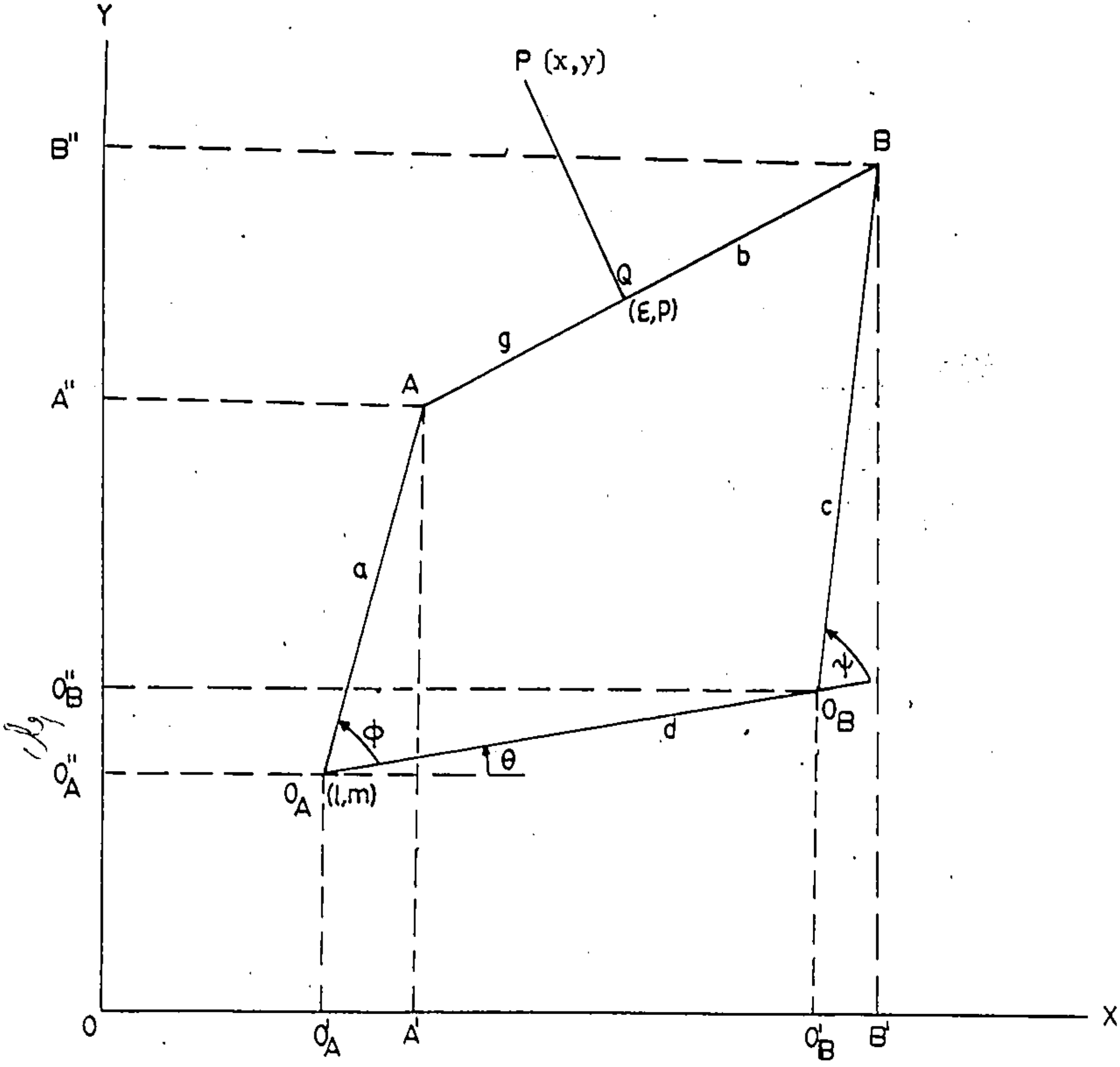


Figure A.4 Parameters for the four-bar coupler point.

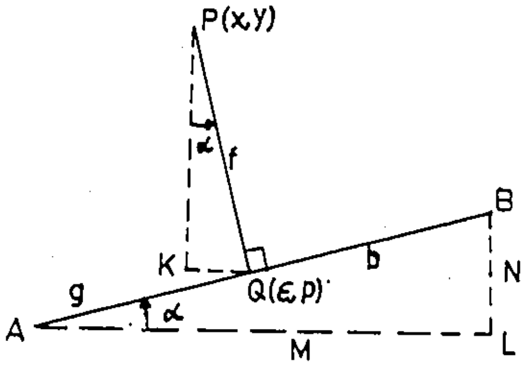


Figure A.5 Parameters for the coupler link orientation (Line PQ perpendicular to coupler link AB).

makes with Y axis measured c.c.w.

$$\angle KPQ = \angle LAB \quad \text{(see Figure A.5)}$$

$$\tan \alpha' = \frac{N}{M}$$

$$\alpha' = \tan^{-1} \left(\frac{N}{M}\right)$$

$$\alpha'' = |\alpha'|$$

ATAN returns angles between -90° to + 90° whereas α lies between 0° to 360°. Hence to obtain the correct angle we introduce two vectors (Figure A.6).

M	N	$\angle\alpha$
+ve	-ve	$=\alpha''$
-ve	+ve	$=180-\alpha''$
+ve	-ve	$=360-\alpha''$
-ve	-ve	$=180+\alpha''$

Figure A.6 shows all the four possible cases.

A.3.2 Line PQ Makes an Angle γ with the Coupler Link

We shall define the following parameters as shown in Figure A.7.

γ = Angle that the line PQ makes with the coupler link measured c.c.w.

β = Angle that the line PQ makes with the Y-axis measured c.c.w.

α = Angle that the coupler link AB makes with the X-axis measured c.c.w.

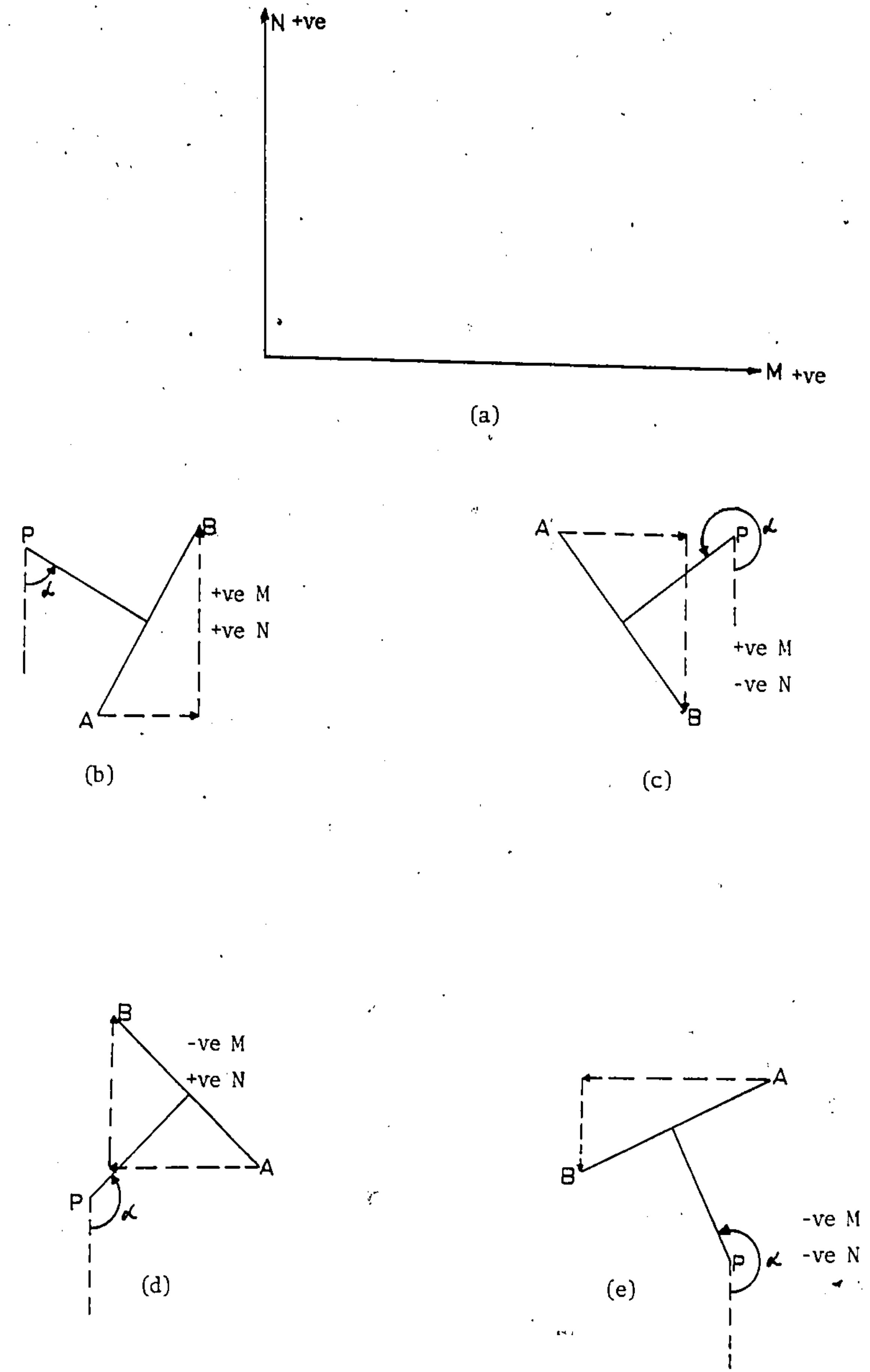


Figure A.6 Configurations for the coupler link orientation.

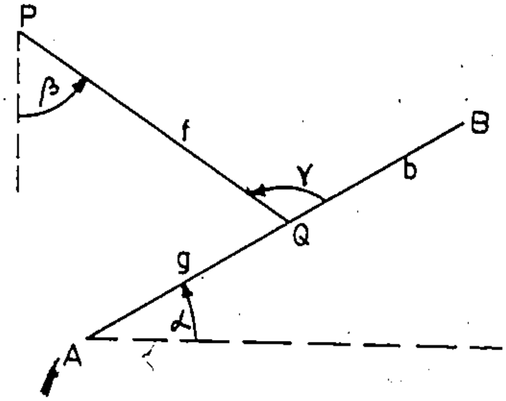


Figure A.7 Parameters for the coupler link orientation (Line PQ makes an angle γ with coupler link AB).

The following equations were derived using plane geometry.

$$\beta = \alpha - 90^{\circ} + \gamma$$

$$X = \varepsilon - f \cdot \sin\beta \qquad (A.4)$$

$$Y = p + f \cdot \cos\beta$$

A.4 Limits of Input Motion (Double-Rockers)

The limits of input motion are given by the following equations and were derived using plane trigonometry (Figure A.8).

$$\xi = \cos^{-1}\left[\left(a^2 + d^2 - p^2\right) | 2ad\right] \qquad (A.5)$$

For Types 4 and 7: $p = b+c$ GETA1 = ξ

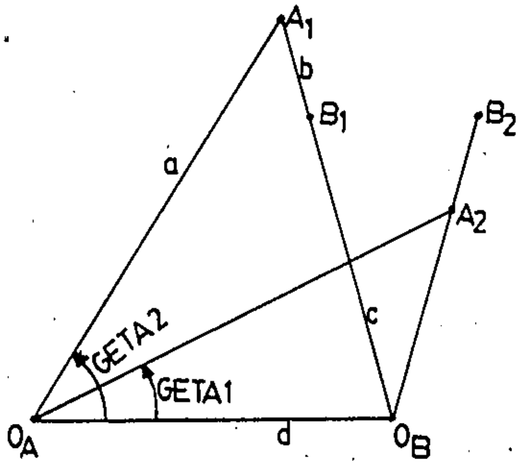
and GETA2 = - GETA1

For Types 5 and 6: $p = b-c$ GETA1 = ξ

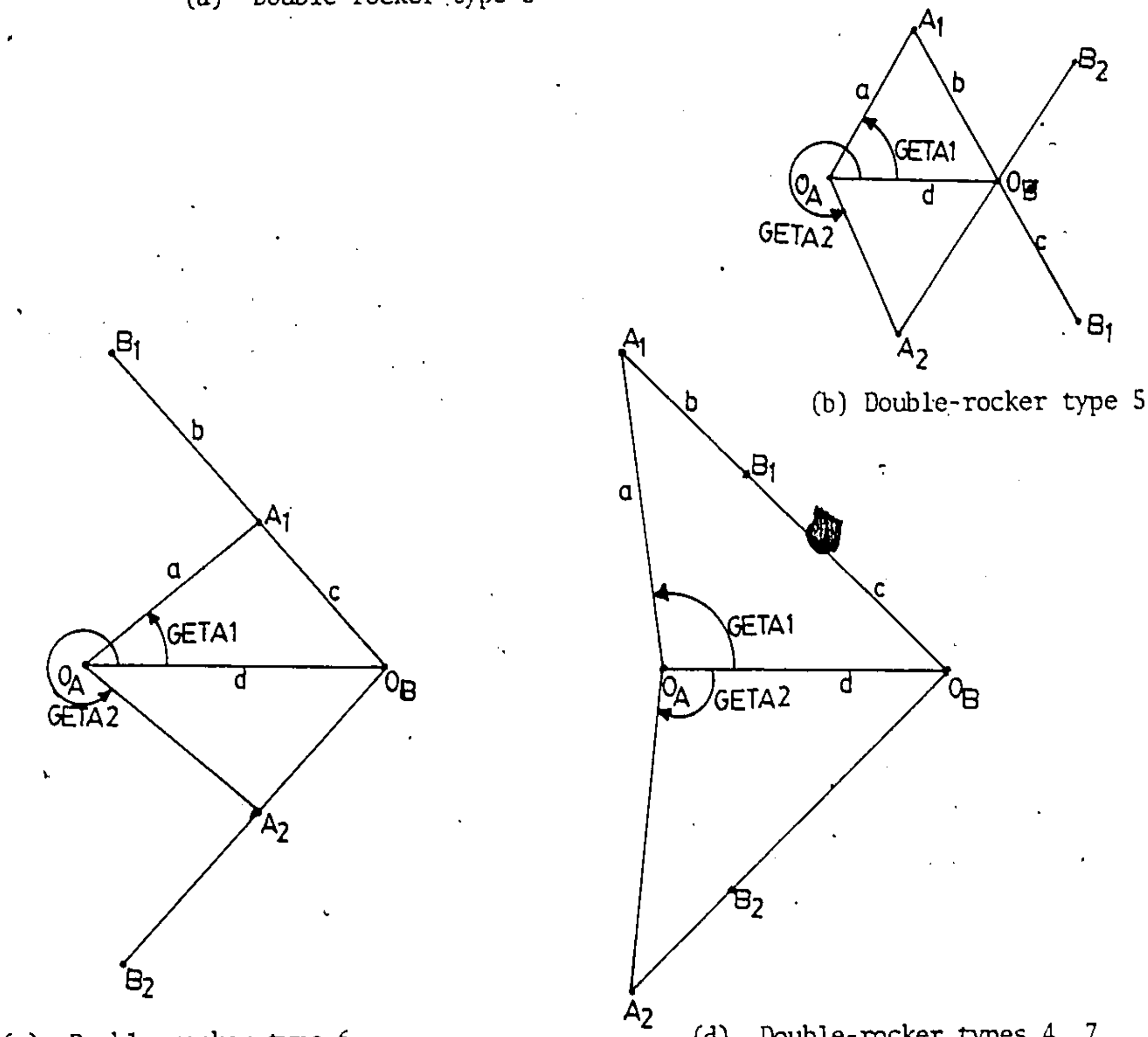
and GETA2 = 360 - GETA1

For Type 3: $p = b+c$ for GETA1 = ξ.

$p = b-c$ for GETA2 = ξ



(a) Double-rocker type 3



(b) Double-rocker type 5

(c) Double-rocker type 6

(d) Double-rocker types 4, 7

Figure A.8 Configurations of extreme positions for double-rocker mechanisms.

APPENDIX B

SOFTWARE SYSTEM (FBAR) USERS' INFORMATION

B.1 How to Use

There are two different parts of the software system. The synthesis part can be run on a remote terminal connected to a CDC6400. The graphical analysis part can be run on a PDP11/34 mini-computer. For synthesis, two separate programs were written for two different types of formulations. The file names used for the first and second types of formulation are FBAR1 and FBAR2 respectively.

1. Specified crank input angles (FBAR1)
2. Crank input angles as independent design variables (FBAR2)

Both the programs are general and can handle any type of mechanism (i.e., crank-rocker, double-crank and double-rockers single phase and double phase).

The programs are conveniently developed so that designers who have little knowledge about computers can make use of this system (FBAR) effectively for the design of four-bar mechanisms. All the programs are executed interactively thereby enabling the user to respond to the computer in a language which is more familiar. All the input data is read in free format.

To run the synthesis programs the user has to log-in the terminal and has to enter a few control statements.

To better understand the use of the system refer to the following example No. 1. (Problem 6 - Solution 4) which makes use of FBAR2 and all other features are described later.

Example 1 (Problem 6 - Solution 4)

```
 79/10/18. 20.40.14.
MCMASTER - SYSTEM R
STUDENT OR USER NUMBER: 7726431
PASSWORD
[redacted]
TERMINAL:     10, TTY
  COURSE OR CHARGE NUMBER:  ? HVN
EXIT.STARTUP
/GRAB(OPTISEP)
 GRAB COMPLETE.
/FETCH,FBAR2
/FTN,I=FBAR2,L=0
/T   4.399 CP SECONDS COMPILATION TIME
/XEQ
? LDSET(LIB=OPTISEP)
? LGO(PL=9000)
?

THIS  PROGRAM  CAN BE USED TO SYNTHESIZE
FOUR-BAR MECHANISMS FOR COUPLER LINK POSITIONS
WITH CRANK ANGLES AS INDEPENDENT DESIGN VARIABLES

SPECIFY THE TYPE OF MECHANISM REQUIRED


              CRANK ROCKER---ENTER 1

              DOUBLE CRANK---ENTER 2

              DOUBLE ROCKER---ENTER 3
? 2

ENTER THE NUMBER OF POSITIONS TO BE SYNTHESIZED
 MAXIMUM NUMBER OF POSITIONS=20
? 3
```

```
ENTER THE DESIRED COUPLER POINT COORDINATES AND
 THE ANGLE MADE BY COUPLER LINK WITH Y-AXIS
? 0.  8.  109.19
? 5.  26.588  30.
? 26.  14.248  322.33

ENTER THE VALUE OF ICASE INDICATING THE MECHANISM CLOSURE
? 1

ENTER THE VALUES OF MAXIMUM PERMIMISSIBLE ERRORS IN
COUPLER POINT CO-ORDINATES AND THE COUPLER LINK INCLINATION
? .1  1.

ENTER THE MAXIMUM AND MINIMUM PERMISSIBLE VALUES ON LINK LENGTHS
? 20.    .5

ENTER THE ESTIMATED UPPER BOUNDS ON THE  13 DESIGN VARIABLES
? 15.
? 15.
? 15.
? 15.
? 15.
? 10.
? 15.
? 15.
? 90.
? 360.
? 360.
? 360.
? 360.

ENTER THE ESTIMATED LOWER BOUNDS ON THE  13 DESIGN VARIABLES
? .5
? .5
? .5
? .5
```

```
? .5
? .5
? .5
? .5
? -90.
? 0.
? 0.
? 0.
? 0.

ENTER THE STARTING VALUES OF  13 DESIGN VARIABLES
? 5.25
? 5.
? 6.
? 3.
? 3.
? 2.
? 4.
? 6.
? 15.
? 90.
? 250.
? 120.
? 5.

VALUES OF OPTIMIZATION ROUTINE PARAMETERS-SEEK1
                             F= .10000000E-01
                             G= .10000000E-01
                          MAXM=1000
                        IPRINT= 40
                         IDATA= 1

                          NSHOT=  2

                         NTEST= 100

WOULD YOU LIKE TO CHANGE THE VALUES OF THESE PARAMETERS
              IF YES ENTER 1
              OTHERWISE ENTER 0
? 0
```

```
          DIRECT SEARCH OPTIMIZATION USING SEEK1

INTERMEDIATE OUTPUT EVERY IPRINT(TH) CYCLE. . . .  IPRINT  =     40

INPUT DATA IS PRINTED OUT FOR IDATA=1 ONLY. . . .   IDATA  =      1

NUMBER OF INDEPENDENT VARIABLES . . . . . . . . .       N  =     13

NUMBER OF INEQUALITY (.GE.) CONSTRAINTS . . . . .   NCONS  =     19

FRACTION OF RANGE USED AS STEP SIZE . . . . . . .       F  =       .10000000E-01

MAXIMUM NUMBER OF MOVES PERMITTED . . . . . . . .    MAXM  =   1000

STEP SIZE FRACTION USED AS CONVERGENCE CRITERION.       G  =       .10000000E-01

NUMBER OF EQUALITY CONSTRAINTS. . . . . . . . . .   NEQUS  =      0

NUMBER OF SHOTGUN SEARCHES PERMITTED. . . . . . .   NSHOT  =      2

NUMBER OF TEST POINTS IN SHOTGUN SEARCH . . . . .   NTEST  =    100

ESTIMATED UPPER BOUND ON RANGE OF X(I). . . . . . RMAX(I)  =

   .15000000E+02    .15000000E+02    .15000000E+02    .15000000E+02    .15000000E+02
   .10000000E+02    .15000000E+02    .15000000E+02    .90000000E+02    .36000000E+03
   .36000000E+03    .36000000E+03    .36000000E+03

ESTIMATED LOWER BOUND ON RANGE OF X(I). . . . . . RMIN(I)  =

   .50000000E+00    .50000000E+00    .50000000E+00    .50000000E+00    .50000000E+00
   .50000000E+00    .50000000E+00    .50000000E+00   -.90000000E+02   0.
  0.               0.               0.
```

```
STARTING VALUES OF X(I) . . . . . . . . . . . . . . .XSTRT(I)  =

 .52500000E+01   .50000000E+01   .60000000E+01   .30000000E+01   .30000000E+01
 .20000000E+01   .40000000E+01   .60000000E+01   .15000000E+02   .90000000E+02
 .25000000E+03   .12000000E+03   .50000000E+01



STEP            U                     INDEPENDENT VARIABLES

 40     .15910281E+02   .82134375E+01   .31875000E+01   .89725000E+01   .24200000E+01
                        .55556250E+01   .47550000E+01   .98271875E+01   .13032500E+02
                        .23550000E+02   .77850000E+02   .22840000E+03   .11550000E+03
                       -.19525000E+02


 80     .13375874E+02   .82134375E+01   .31829688E+01   .89725000E+01   .24200000E+01
                        .51387500E+01   .50459375E+01   .10080938E+02   .13095938E+02
                        .22312500E+02   .80550000E+02   .22660000E+03   .11493750E+03
                       -.20312500E+02

120     .12555856E+02   .82111719E+01   .31829688E+01   .89725000E+01   .24200000E+01
                        .48532813E+01   .52374219E+01   .10257656E+02   .13186563E+02
                        .20146875E+02   .82293750E+02   .22671250E+03   .11656875E+03
                       -.20143750E+02

160     .11845206E+02   .82111719E+01   .31829688E+01   .89725000E+01   .24200000E+01
                        .46380469E+01   .53917969E+01   .10402656E+02   .13283984E+02
                        .18150000E+02   .83587500E+02   .22727500E+03   .11848125E+03
                       -.19862500E+02

200     .11205675E+02   .82111719E+01   .31829688E+01   .89725000E+01   .24200000E+01
                        .44658594E+01   .55253906E+01   .10540859E+02   .13361016E+02
                        .16265625E+02   .84993750E+02   .22772500E+03   .12028125E+03
                       -.19581250E+02
```

```
240       .68788996E+01   .83017969E+01   .30923438E+01   .89725000E+01   .24200000E+01
                          .39515625E+01   .59098437E+01   .10919219E+02   .13594375E+02
                          .10865625E+02   .89943750E+02   .22918750E+03   .12568125E+03
                         -.19018750E+02

                OPTIMUM SOLUTION FOUND

               MINIMUM  U =    .11997596E-02

                  X( 1) =    .86937500E+01
                  X( 2) =    .26879297E+01
                  X( 3) =    .89362500E+01
                  X( 4) =    .24335938E+01
                  X( 5) =    .31008203E+01
                  X( 6) =    .67678125E+01
                  X( 7) =    .11765430E+02
                  X( 8) =    .14087148E+02
                  X( 9) =    .27734375E+01
                  X(10) =    .10617188E+03
                  X(11) =    .23045312E+03
                  X(12) =    .13454062E+03
                  X(13) =   -.20762500E+02
```

```
INEQUALITY CONSTRAINTS
                      PHI( 1) =   .81937500E+01
                      PHI( 2) =   .21879297E+01
                      PHI( 3) =   .84362500E+01
                      PHI( 4) =   .19335938E+01
                      PHI( 5) =   .11306250E+02
                      PHI( 6) =   .17312070E+02
                      PHI( 7) =   .11063750E+02
                      PHI( 8) =   .17566406E+02
                      PHI( 9) =   .67678125E+01
                      PHI(10) =   .35727656E+03
                      PHI(11) =   .10123791E-01
                      PHI(12) =   .25382812E+03
                      PHI(13) =   .11835938E-01
                      PHI(14) =   .62601562E+01
                      PHI(15) =   .25433594E+00
                      PHI(16) =   .65026562E+01
                      PHI(17) =   .15530312E+03
                      PHI(18) =  0.
                      PHI(19) =  0.

DO YOU WANT TO RUN THE  PROGRAM WITH DIFFERENT STARTING VALUES

              IF YES ENTER 1

              OTHERWISE ENTER 0
? 1

DO YOU WANT TO CHANGE THE VALUES OF UPPER BOUNDS-RMAX

              IF YES ENTER 1

              OTHERWISE ENTER 0
? 0
```

```
DO YOU WANT TO CHANGE THE VALUES OF LOWER BOUNDS-RMIN

              IF YES ENTER 1

              OTHERWISE ENTER 0
? 0

ENTER THE STARTING VALUES OF  13 DESIGN VARIABLES
? 8.69375
? 2.6879
? 8.9362
? 2.4335
? 3.1
? 6.7678
? 11.7654
? 14.0871
? 2.7234
? 106.171
? 230.45
? 134.54
? -20.76

VALUES OF OPTIMIZATION ROUTINE PARAMETERS-SEEK1
                             F= .10000000E-01
                             G= .10000000E-01
                          MAXM=1000
                        IPRINT= 40
                         IDATA= 1

                          NSHOT=  2

                         NTEST= 100

WOULD YOU LIKE TO CHANGE THE VALUES OF THESE PARAMETERS
              IF YES ENTER 1
              OTHERWISE ENTER 0
? 1
```

```
ENTER THE VALUES OF THE OPTIMIZATION PARAMETERS
? .001
? .001
? 600
? 5
? 0
? 2
? 100


          DIRECT SEARCH OPTIMIZATION USING SEEK1


STEP            U                 INDEPENDENT VARIABLES

  5     .80982122E-03    .86937500E+01    .26879000E+01    .89362000E+01    .24335000E+01
                         .31000000E+01    .67683938E+01    .11766306E+02    .14086647E+02
                         .27234000E+01    .10615975E+03    .23045000E+03    .13455125E+03
                        -.20760000E+02

 10     .35190849E-03    .86937500E+01    .26876734E+01    .89362000E+01    .24339531E+01
                         .31009063E+01    .67689875E+01    .11765627E+02    .14086194E+02
                         .27205875E+01    .10614288E+03    .23046688E+03    .13457375E+03
                        -.20760000E+02

 15     .23842588E-03    .86937500E+01    .26876734E+01    .89362000E+01    .24338398E+01
                         .31015859E+01    .67686906E+01    .11765287E+02    .14087213E+02
                         .27205875E+01    .10614288E+03    .23047250E+03    .13457938E+03
                        -.20760000E+02

 20     .16585436E-03    .86938633E+01    .26874469E+01    .89362000E+01    .24338398E+01
                         .31018125E+01    .67685422E+01    .11764947E+02    .14087440E+02
                         .27205875E+01    .10614006E+03    .23047813E+03    .13458500E+03
                        -.20760000E+02
```

```
25     .45275991E-04    .86944297E+01   .26868805E+01   .89362000E+01   .24338398E+01
                        .31032852E+01   .67692844E+01   .11764380E+02   .14088573E+02
                        .27149625E+01   .10615131E+03   .23049219E+03   .13460750E+03
                       -.20760000E+02

30     .29257039E-04    .86945430E+01   .26868238E+01   .89362000E+01   .24338398E+01
                        .31034551E+01   .67692844E+01   .11764380E+02   .14089139E+02
                        .27135562E+01   .10615413E+03   .23049500E+03   .13461313E+03
                       -.20760000E+02

35     .27866940E-04    .86945430E+01   .26868238E+01   .89362000E+01   .24338398E+01
                        .31033984E+01   .67692658E+01   .11764380E+02   .14089252E+02
                        .27128531E+01   .10615413E+03   .23049570E+03   .13461383E+03
                       -.20760000E+02

40     .26360351E-04    .86945288E+01   .26868230E+01   .89362000E+01   .24338540E+01
                        .31033560E+01   .67692565E+01   .11764409E+02   .14089238E+02
                        .27126773E+01   .10615413E+03   .23049570E+03   .13461383E+03
                       -.20760703E+02

45     .21032679E-04    .86944863E+01   .26860238E+01   .89362142E+01   .24339106E+01
                        .31032852E+01   .67693400E+01   .11764508E+02   .14089309E+02
                        .27126773E+01   .10615342E+03   .23049605E+03   .13461453E+03
                       -.20762813E+02

50     .16978629E-04    .86944297E+01   .26867955E+01   .89362142E+01   .24339390E+01
                        .31032427E+01   .67694143E+01   .11764593E+02   .14089394E+02
                        .27128531E+01   .10615237E+03   .23049641E+03   .13461523E+03
                       -.20764570E+02
```

```
          OPTIMUM SOLUTION FOUND

        MINIMUM  U =    .16616893E-04


             X( 1) =    .86944297E+01
             X( 2) =    .26867955E+01
             X( 3) =    .89362142E+01
             X( 4) =    .24339390E+01
             X( 5) =    .31032144E+01
             X( 6) =    .67694699E+01
             X( 7) =    .11764635E+02
             X( 8) =    .14089380E+02
             X( 9) =    .27126773E+01
             X(10) =    .10615237E+03
             X(11) =    .23049641E+03
             X(12) =    .13461559E+03
             X(13) =   -.20764570E+02

INEQUALITY CONSTRAINTS
           PHI( 1) =    .81944297E+01
           PHI( 2) =    .21867955E+01
           PHI( 3) =    .84362142E+01
           PHI( 4) =    .19339390E+01
           PHI( 5) =    .11305570E+02
           PHI( 6) =    .17313204E+02
           PHI( 7) =    .11063786E+02
           PHI( 8) =    .17566061E+02
           PHI( 9) =    .67694699E+01
           PHI(10) =    .35728732E+03
           PHI(11) =    .10089553E-01
           PHI(12) =    .25384763E+03
           PHI(13) =    .11072070E-01
           PHI(14) =    .62604907E+01
           PHI(15) =    .25285654E+00
           PHI(16) =    .65022752E+01
           PHI(17) =    .15538016E+03
           PHI(18) =   0.
           PHI(19) =   0.
```

```
DO YOU WANT TO RUN THE  PROGRAM WITH DIFFERENT STARTING VALUES
              IF YES ENTER 1
              OTHERWISE ENTER 0
? 0


                    FOUR-BAR COUPLER POSITION SYNTHESIS
                    ---- --- ------- -------- ---------
        DOUBLE CRANK:
         3 SPECIFIED POSITIONS
   MAXIMUM ERROR SPECIFIED FOR COUPLER POINT CO-ORDINATES.=   .1000 INCHES
   MAXIMUM ERROR SPECIFIED FOR ORIENTATION OF COUPLER LINK=  1.0000 DEGREES
   MAXIMUM PERMISSIBLE VALUE ON LINK LENGTHS............ .= 20.0000 INCHES
   MINIMUM PERMISSIBLE VALUE ON LINK LENGTHS.............=   .5000 INCHES
   INITIAL CLOSURE OF THE MECHANISM.................ICASE= 1

   DETAILS OF THE REQUIRED COUPLER PLANE POSITIONS
   ------- -- --- -------- ------- ----- ---------
   XD,YD---CO-ORDINATES OF COUPLER POINT IN INCHES
   ANGLE---ANGLE MADE BY COUPLER LINK WITH Y-AXIS IN DEGREES
   POSITION      XD             YD             ANGLE
    1              0.0000        8.0000       109.1900
    2              5.0000       26.5880        30.0000
    3             26.0000       14.2480       322.3300
```

```
OPTIMUM DIMENSIONS OF THE MECHANISM
------- ---------- -- --- ---------

    INPUT LINK(CRANK) LENGTH=  8.6944 INCHES

    COUPLER LINK LENGTH.....=  2.6868 INCHES

    FOLLOWER LINK LENGTH....=  8.9362 INCHES

    FRAME LENGTH............=  2.4339 INCHES

    COUPLER LINK DETAILS
    ------- ---- -------

               X5=  3.1032 INCHES

               X6=  6.7695 INCHES

              X10=106.1524 DEGREES

    DETAILS OF PIVOT LOCATIONS
    ------- -- ----- ---------

              X7= 11.7646 INCHES

              X8= 14.0894 INCHES

              X9=  2.7127 DEGREES

    DETAILS OF SYNTHESIZED POSITIONS
    ------- -- ----------- ---------

         PHY---CRANK ANGLE IN DEGREES

         PSY---FOLLOWER ANGLE IN DEGREES

         X,Y---CO-ORDINATES OF COUPLER POINT IN INCHES

         ALPHA---ANGLE MADE BY COUPLER LINK WITH Y-AXIS IN DEGREES
```

```
POSITION     PHY            PSY            X             Y            ALPHA
 1         230.4964       206.7468       -.0002        8.0000       109.1929
 2         134.6156       131.3539       5.0003       26.5877        30.0006
 3         -20.7646       323.4327      26.0000       14.2483       322.3268

     DETAILS OF DEVIATIONS OF SYNTHESIZED POSITIONS FROM DESIRED POSITIONS
     ------- -- ---------- -- ----------- --------- ---- ------- ---------

          ERROR1---ERROR DUE TO MISMATCH OF COUPLER POINT IN INCHES

          ERROR2---ERROR IN THE ORIENTATION OF COUPLER LINK IN  DEGREES

          Y1,Y2---INDIVIDUAL VALUES OF OBJECTIVE FUNCTION

POSITION     ERROR1              ERROR2

 1            .23744044E-03     .29199034E-02

 2            .41526597E-03     .61518722E-03

 3            .27467754E-03     .32433367E-02

     Y1= .10142385E-04     Y2= .64745080E-05

DO YOU WANT TO SOLVE ANOTHER PROBLEM

          IF YES ENTER 1

          OTHERWISE ENTER 0
? 0
  101.717 CP SECONDS EXECUTION TIME
/BYE
JOBCOST. APPROXIMATE COST= $   8.68  ***
/
7726431   LOG OFF    21.05.07.
7726431   SRU     69.468 SRUS.
```

In the case of FBAR1, i.e., where the crank input angles are specified by the user, the design variables are 10 and the user has to enter the values of the crank input angles. In the case of double-rockers the user has to enter the values corresponding to the phase of the mechanism in each position either +1 or -1.

To run the graphical analysis program the user has to start the mini-computer system and then type the following command.

```
.RU DX1:FBAR
```

Then the computer requests the data from the user and the user has to enter the data, then afterwards the graphical analysis is being controlled through the use of the light pen. The user has to point the light pen to the line adjacent to the desired option. The examples 2 and 3 given below will give a clear understanding regarding the use of the graphics part of the system.

Once a single system is made the user need not enter the data for the analysis program. The data will automatically be transferred to the mini-computer from the CDC6400. As it is, the designer has to enter the data in a format requested by the computer. It was found to be difficult to program for the screen scaling coordinates and hence an option of choosing the screen scaling coordinates is provided.

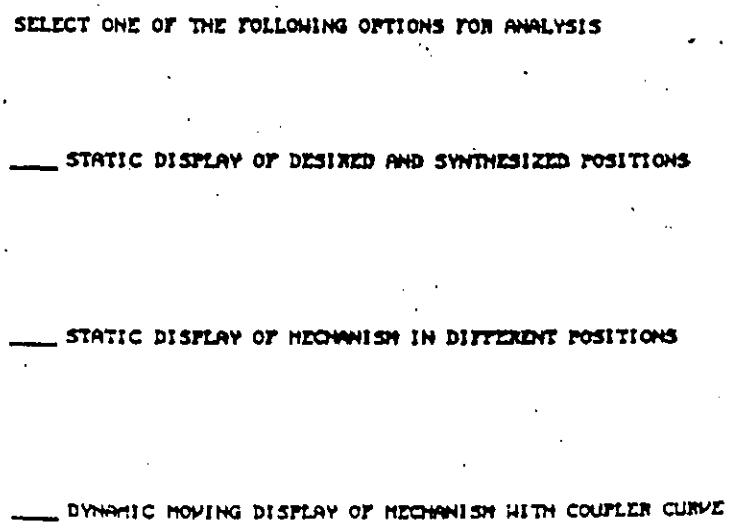
In example 2 (Problem 5) a double-crank mechanism is considered for nine positions. After the data is entered the computer requests the designer to select an option for analysis as shown in Figure B.1.1. Depending on the users choice the computer displays the configurations shown in Figures B.1.2 to B.1.5. In Figure B.1.4 the computer is requesting the designer to select the direction of rotation of the crank. Figure B.1.5 shows the mechanism after the crank has made one complete revolution. At the end the designer can go to the beginning of the analysis.

In example 3 a double-rocker mechanism is considered for eight positions (Problem 4). Figures B.1.6 to B.1.10 show the configurations in the case of the double-rockers. In Figures B.1.8 and B.1.9 the computer is requesting the designer to specify the phase of the mechanism.

Example 2 (Problem 5)

```
.RU DX1!FBAR



ENTER THE DIMENSIONS OF THE MECHANISM-E14.8
 .62609966E+01
 .74966705E+01
 .74928191E+01
 .45005700E+01
 .39978483E+01
 .57512682E+01
 .39996429E+01
 .40058352E+01
 .19859920E+02
 .24221820E+03

ENTER THE NUMBER OF POSITIONS-I2
9

ENTER THE CRANK INPUT ANGLES-E14.8
 .50159375E+02
 .70156914E+02
 .90150430E+02
 .12012320E+03
 .15008863E+03
 .22001918E+03
 .27996930E+03
 .34998602E+03

.18006828E+03


ENTER THE VALUE OF ICASE INDICATING MECHANISM CLOSURE
1
```

```
ENTER THE DESIRED COUPLER POINT CO-ORDINATES AND THE
 INCLINATION OF COUPLER LINK WITH Y-AXIS--3F8.3
8.051,4.994,159.04
6.724,5.773,168.95

5.176,5.813,176.86
3.252,4.679,188.07
2.515,2.707,200.64
3.264,.825,216.22
5.929,-.027,242.96
9.142,3.424,295.00
4.947,5.675,41.16

ENTER THE MAXIMUM AND MINIMUM ERRORS-2F5.3

.001  0.000

ENTER THE MAXIMUM AND MINIMUM ANGULAR DEVIATIONS-2F5.3

0.01  0.00

 SCREEN SCALING CO-ORDINATES
XMI= -7.51XMA= 19.21YMI= -7.51YMA= 19.21
WOULD YOU LIKE TO CHANGE THESE VALUES
 IF YES ENTER 1 OTHERWISE ENTER 0


0


 STOP --

 PAUSE --
 TYPE <CR> TO EXIT
```



SELECT ONE OF THE FOLLOWING OPTIONS FOR ANALYSIS

____ STATIC DISPLAY OF DESIRED AND SYNTHESIZED POSITIONS

____ STATIC DISPLAY OF MECHANISM IN DIFFERENT POSITIONS

____ DYNAMIC MOVING DISPLAY OF MECHANISM WITH COUPLER CURVE

Figure B.1.1 Computer requesting the designer to select an option for analysis.

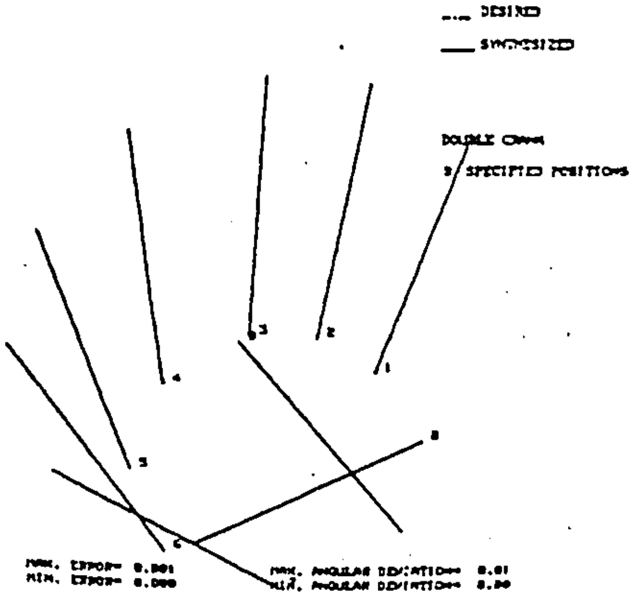


Figure B.1.2 Display of the desired and synthesized positions (Example 2).

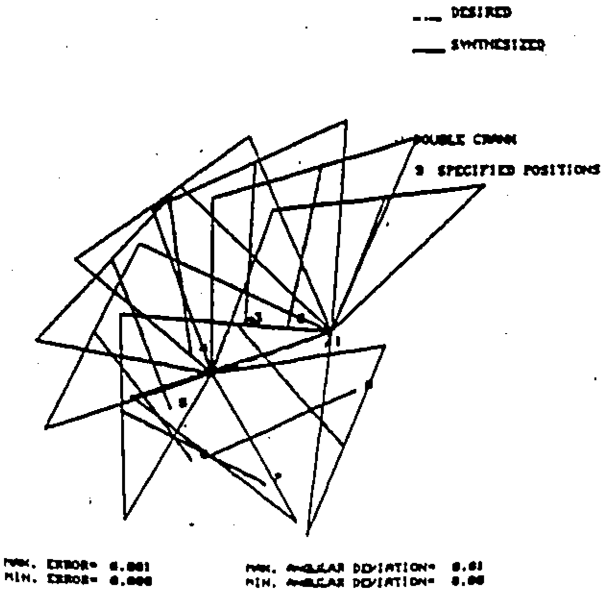


Figure B.1.3 Display of the mechanism in the design positions (Example 2).

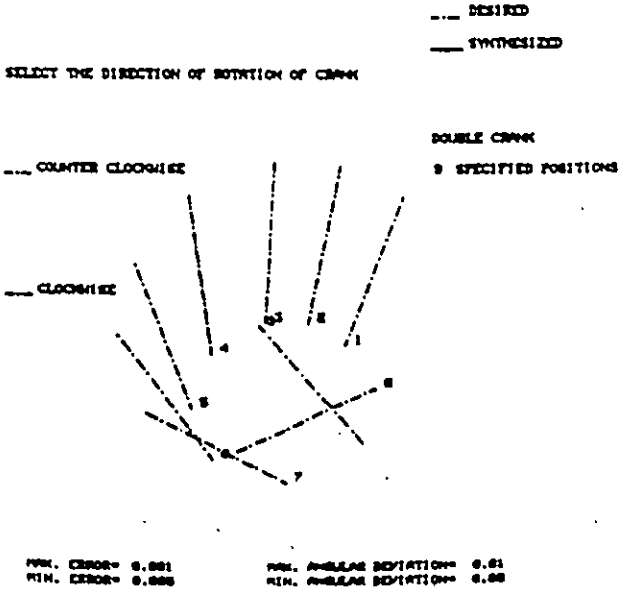


Figure B.1.4 Computer requesting the designer to select the direction of rotation of the crank.

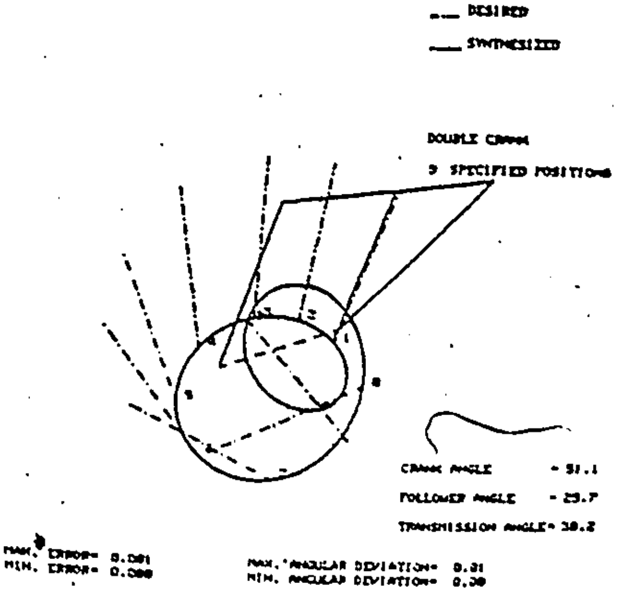


Figure B.1.5 Display of the mechanism after the crank has made one revolution (Example 2).

Example 3 (Problem 4)

```
RU DX1:FBAR

ENTER THE DIMENSIONS OF THE MECHANISM-E14.8
 .29752910E+01
 .49287578E+01

 .60072754E+01
 .99832910E+01
 .30424746E+01
 .30071973E+01
 .10616602E+01
 .10464023E+01
 .26193203E+02
 .90440781E+02

ENTER THE NUMBER OF POSITIONS-I2
8

ENTER THE CRANK INPUT ANGLES-E14.8
 .64626562E+02
 .23165625E+00
-.23570625E+02
-.42054219E+02
-.62884688E+02
-.74086719E+02
-.16593750E+01
 .28574531E+02

ENTER THE VALUES OF NPATH INDICATING THE PHASE OF THE DOUBLE-ROCKER
1
1
1
1
1
-1
-1
-1
```

```
ENTER THE DESIRED COUPLER POINT CO-ORDINATES AND THE
 INCLINATION OF COUPLER LINK WITH Y-AXIS--3F8.3
.91,8.29,47.
1.08,5.71,83.5
1.03,4.21,90.
1.00,3.30,90.0
.90,2.70,82.00
5.40,2.40,12.00
7.90,3.35,330.
7.00,4.00,323.00

ENTER THE MAXIMUM AND MINIMUM ERRORS-2F5.3
0.026  0.005

ENTER THE MAXIMUM AND MINIMUM ANGULAR DEVIATIONS-2F5.3

0.67   0.02



SCREEN SCALING CO-ORDINATES
XMI= -3.57XMA= 19.19YMI= -3.57YMA= 19.19
WOULD YOU LIKE TO CHANGE THESE VALUES
 IF YES ENTER 1 OTHERWISE ENTER 0

0


STOP --

PAUSE --
TYPE <CR> TO EXIT
```

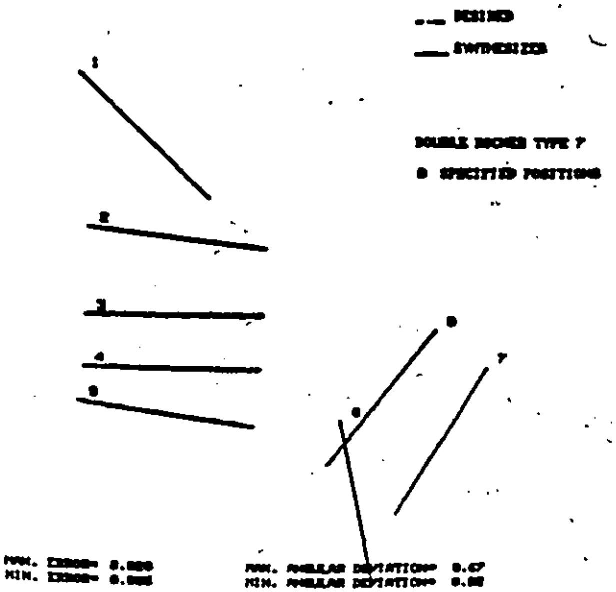


Figure B.1.6 Display of the desired and the synthesized positions (Example 3).

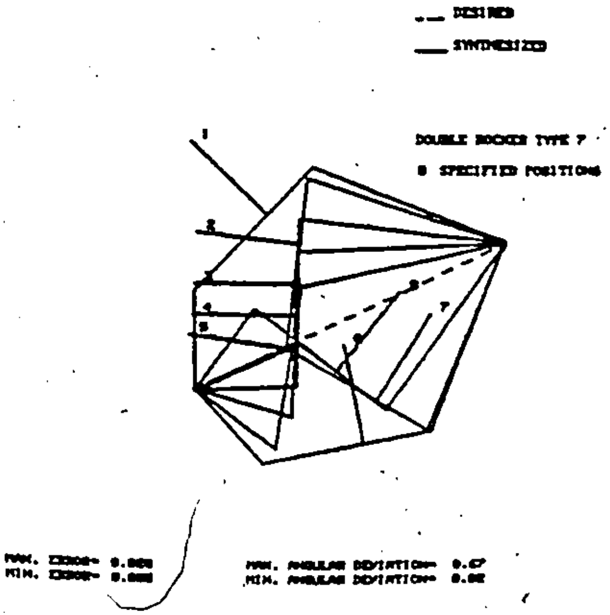
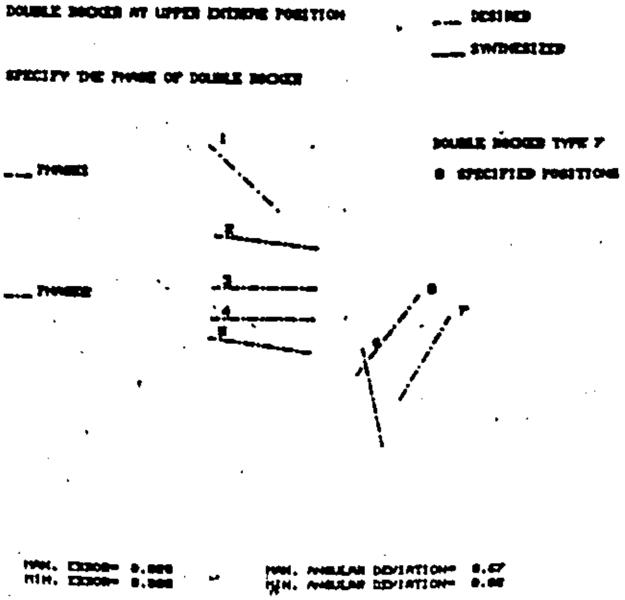
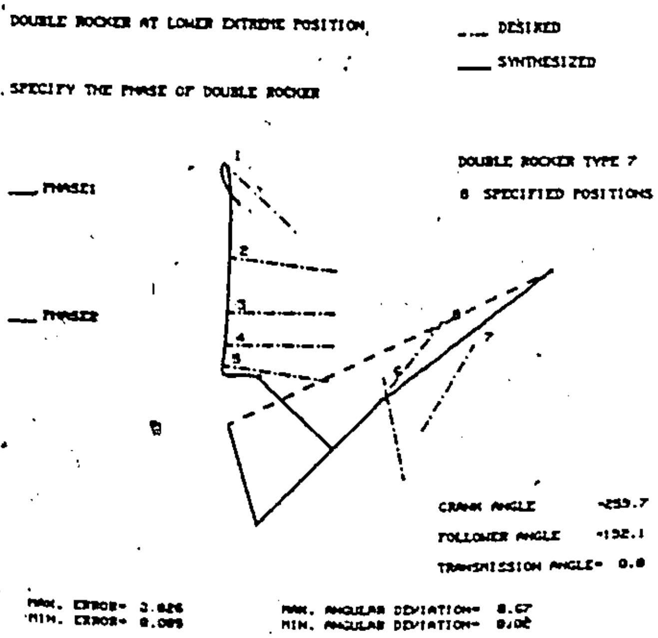


Figure B.1.7 Display of the mechanism in the design positions (Example 3).



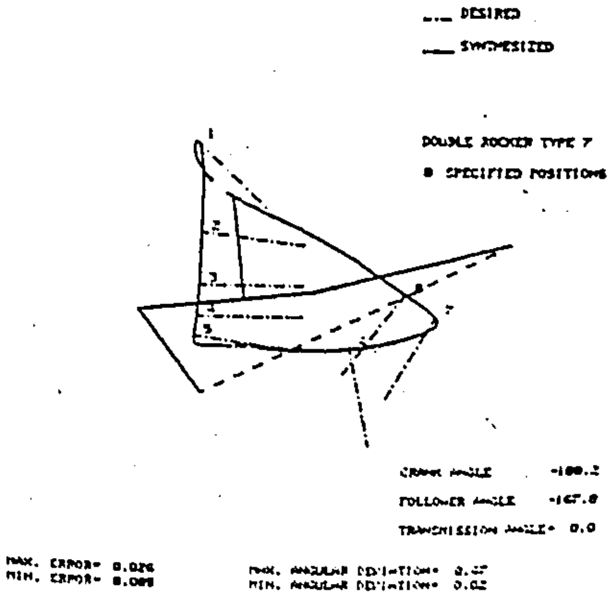
```
DOUBLE ROCKER AT UPPER EXTREME POSITION        ___ DESIRED
                                               ___ SYNTHESIZED
SPECIFY THE PHASE OF DOUBLE ROCKER

                                               DOUBLE ROCKER TYPE 7
___ PHASE1                                     8 SPECIFIED POSITIONS

___ PHASE2

MAX. ERROR= [illegible]        MAX. ANGULAR DEVIATION= 0.67
MIN. ERROR= [illegible]        MIN. ANGULAR DEVIATION= 0.0[illegible]
```

Figure B.1.8 Computer requesting the designer to specify the phase at upper extreme position (Example 3).



```
DOUBLE ROCKER AT LOWER EXTREME POSITION        ___ DESIRED
                                               ___ SYNTHESIZED
SPECIFY THE PHASE OF DOUBLE ROCKER

                                               DOUBLE ROCKER TYPE 7
___ PHASE1                                     8 SPECIFIED POSITIONS

___ PHASE2

                                               CRANK ANGLE        =253.7
                                               FOLLOWER ANGLE     =192.1
                                               TRANSMISSION ANGLE=  0.0
MAX. ERROR= 3.026              MAX. ANGULAR DEVIATION= 0.67
MIN. ERROR= 0.005              MIN. ANGULAR DEVIATION= 0.02
```

Figure B.1.9 Computer requesting the designer to specify the phase at lower extreme position (Example 3).



```
CRANK ANGLE         -180.2
FOLLOWER ANGLE      -167.0
TRANSMISSION ANGLE=  0.0

MAX. ERROR= 0.026          MAX. ANGULAR DEVIATION= 0.47
MIN. ERROR= 0.008          MIN. ANGULAR DEVIATION= 0.02
```

Figure B.1.10 Display of the mechanism after the crank has made one cycle of operation (Example 3).

B.2 Input and Output Variables

Although the user need not know about the variables used, a description of the important variables is given below.

MTYPE - defines the type of mechanism desired. Set it equal to 1, 2, 3 for crank-rocker, double-crank and double-rockers respectively.

NP - number of accuracy positions. Dimension statements are provided for a maximum of 20 positions.

XD(I), YD(I), ANG(I) - desired coordinates of the coupler point and the desired inclination of the coupler link with y-axis.

ICASE - defines the type of closure of the mechanism. + 1 or -1 depending on the type of closure. See Appendix A for the configurations.

NPATH - defines the particular phase in the case of the double-rockers. + 1 or - 1 depending upon which phase the position corresponds to. See Appendix A for the configurations of phase.

ERMX1, ERMX2 - Maximum permissible values on errors in tracing the coupler point and the orientation of the coupler link.

XXMAX, XXMIN - upper and lower bounds on the link lengths.

RMAX(I), RMIN(I) - upper and lower bounds on the design variables.

XSTRT(I) - starting values for the design variables. It is recommended that the starting values result in a mechanism that is being attempted. For a description of the design variables see Figures 3.3.1 and 3.6.1.

The optimization subroutine used is SEEK1 which is available in the "OPTISEP" library package. The method of direct search as developed by Hooke and Jeeves is incorporated in this subroutine SEEK1 and the constraints are handled through the penalty functions.

Recommended values for the optimization routine parameters are:

fraction of range used as initial step size F = .01

fraction of initial step size used as minimum step length G = .01

maximum number of search cycles, MAXM = 50

maximum number of complete cycles through search and shotgun search, NSHOT = 2

number of random points to be generated in shotgun search, NTEST = 100

The variables IDATA and IPRINT are used to get a printout of the input data to the optimization routines, and to printout the results of the optimization routine after every IPRINT cycle. If IDATA is set to 0 the input data is not printed. If IDATA is set to 1 the input data is printed out.

Output Variables

X(I) - values of the design variables at the optimum

U - values of the optimization function, evaluated in UREAL

PHI(I)- inequality constraint functions evaluated in CONST.

All other output data is printed and explained in the computer listing itself.

B.3 Routine Descriptions

Synthesis Main Program

All the conversation with the user is done by this program and all input data is read in free format and is transferred to optimization subroutines and the results from the optimization routines are transferrred back to this main program.

Subroutine SUB1:

This routine calculates the follower angle for a four-bar mechanism with the data of link lengths, crank angle and the closure or phase of the mechanism.

Subroutine SUB2:

This routine calculates the coupler point coordinates and the coupler link inclination with the y-axis from the design variables of the mechanism.

Subroutine UREAL:

This routine calculates the errors involved in tracing the coupler point coordinates and the orientation of the coupler link. Then by using the inverse utility functions the objective function value is calculated.

Subroutine CONST:

This routine calculates the values of the inequality constraints imposed on the problem.

Subroutine RESULT:

This routine prints the output information in a better appreciable form to the user.

Graphics Main Program:

All the output data as obtained from the synthesis program is read as input data to the graphics main program and all the configurations of graphical display are controlled by this program which issues calls to various subprograms.

Subroutine LINKPL:

This routine displays the four-bar mechanism as per the dimensions.

Subroutine GSUB:

This routine calculates the coordinates of all the nodal points in the mechanism from the dimensions of the mechanism.

Subroutine TYPE:

This routine finds the type of mechanism from the dimensions of the mechanism using the Grashof criterion.

Subroutine ALIM:

This routine calculates the limiting angles for the crank in the case of double-rocker mechanisms.

Subroutines SFAC and SFAC1:

These routines scale the screen coordinates depending upon the dimensions of the mechanism and depending upon the coordinates of the desired and synthesized positions.

Subroutines CHECK1 and CHECK2:

These routines request the designer to select options available in the graphical analysis and return the tag of the light pen hit to the main program.

Subroutines TEXT1, TEXT2 and TEXT3:

These routines display the messages regarding the type of mechanism, details of the errors and the crank angle, follower angle and the transmission angle.

APPENDIX C

PROGRAM LISTING

SYNTHESIS MAIN PROGRAM (FILE-FBAR2)

```
      PROGRAM TST (INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
      DIMENSION X(30),FMAX(30),FMIN(30),XSTRT(30),WORK1(30),
     *WORK2(30),WORK3(30),WORK4(30),PHI(40),PSI(1)
C    **********************************************************************
C     THIS IS AN INTERACTIVE PROGRAM THAT CAN BE USED FOR THE SYNTHESIS OF
C     FOUR-BAR MECHANISMS WHOSE COUPLER LINK IS REQUIRED TO PASS THROUGH
C     A  NUMBER OF SPECIFIED POSITIONS
C
C     THE THEORY IS BASED ON A MULTI-FACTOR OPTIMIZATION OF TWO DEPENDENT
C     DESIGN VARIABLES(ERROR DUE TO MISMATCH OF COUPLER POINT AND ERROR
C     DUE TO THE MISMATCH OF COUPLER LINK ORIENTATION).MAKES USE OF THE
C     DIRECT SEARCH METHOD OF HOOKE AND JEEVES WHICH IS AVAILABLE IN THE
C     LIBRARY PROGRAM  OPTISEP ( OPTIMIZATION SUBROUTINE SEEK1)
C
C     THIS IS THE PART OF THE SOFTWARE SYSTEM (FBAR) DEVELOPED FOR
C     M.ENG. THESIS.  PROGRAMMED BY P. R. GUDAVALLI.   OCT-79.

C      DESIGN VARIABLES
C      ------ ---------
C       X(1)-INPUT LINK LENGTH
C       X(2)-COUPLER LINK LENGTH
C       X(3)-FOLLOWER LINK LENGTH
C       X(4)-FRAME LENGTH
C       X(5)-DISTANCE ALONG LINE AB FROM CRANK PIN TO INTERSECTION OF PQ
C       X(6)-DISTANCE PQ
C       X(7)-X-CO-ORDINATE OF PIVOT OA
C       X(8)-Y-CO-ORDINATE OF PIVOT OA
C       X(9)-FRAME ORIENTATION
C       X(10)-INCLINATION OF LINE PQ WITH LINE AB.
C       X(11) TO X(10+N)-CRANK INPUT ANGLES

C    THE FILE NAME USED FOR THIS PROGRAM IS FBAR2

C    DESCRIPTION OF PARAMETERS
C    ----------- -- ----------
C       MTYPE-TYPE OF MECHANISM.SET IT TO 1,2OR 3 FOR CRANK-ROCKER
C            DOUBLE-CRANK AND DOUBLE-ROCKERS RESPECTIVELY.

C       XO(I),YO(I),ANG(I)-DESIREC COUPLER POINT CO-ORDINATES AND THE
C                         INCLINATIONSOF COUPLER LINK WITH Y-AXIS.
C       ICASE-VARIABLE INDICATING THE CLOSURE OF THE MECHANIOM.SET IT
C            +1 OR -1 DEPENDING ON THE CLOSURE OF THE MECHANISM.
C       NPATH-VARIABLE INDICATING THE PHASE IN THE CASE OF DOUBLE-ROCKERS
C            SET IT +1 OR -1 DEPENDING ON THE PHASE OF THE MECHANISM.
C       ERMX1,ERMX2--MAXIMUM PERMISSIBLE ERRORS ON THE COUPLER POINT
C                   CO-ORDINATES AND THE ORIENTATION OF THE COUPLER LINK.
C       XXMAX,XXMIN--UPPER AND LOWER BOUNDS ON THE LINK LENGTHS.
C       PHY--CRANK INPUT ANGLES.
C
```

```
      COMMON /TYPE/ MTYPE,KTYPE,NP,ICASE,NPATH(20)
      COMMON /ERR/ ERMX1,ERMX2
      COMMON /CLINK/ XXMIN,XXMAX
      COMMON /REQD/ XD(20),YD(20),ANG(20),PHY(20),PSY(20)
      COMMON /SYNS/ XX(20),YY(20),ALPH(20)
      COMMON /CLOSURE/ CLOSEN
      COMMON /ERROR/ ER1(20),ER2(20),Y1,Y2
C
      DATA IPRINT,IDATA,NEQUS/40,1,0/
      DATA F,G,MAXM,NSHOT,NTEST/.01,.01,1000,2,100/
C
1      CONTINUE
      WRITE(6,100)
      WRITE(6,101)
C
      READ(5,*) MTYPE


      WRITE(6,102)
      READ(5,*) NP
      WRITE(6,103)
      DO 500 I=1,NP
      READ(5,*) XD(I),YD(I),ANG(I)
500   CONTINUE
C
      N=10+NP
      NCONS=16+NP
C
      IF(MTYPE.LE.2) WRITE(6,104)
      IF(MTYPE.LE.2) READ(5,*) ICASE
      IF(MTYPE.EQ.3) ICASE=1
      IF(MTYPE.EQ.3) WRITE(6,116)
      DO 550 I=1,NP
      IF(MTYPE.LE.2) NPATH(I)=1
550   IF(MTYPE.EQ.3) READ(5,*) NPATH(I)
C
      WRITE(6,105)
      READ(5,*) ERMX1,ERMX2
      WRITE(6,106)
      READ(5,*) XXMAX,XXMIN
C
      WRITE(6,107) N
      DO 501 I=1,N
501   READ(5,*) RMAX(I)
      WRITE(6,108) N
      DO 502 I=1,N
502   READ(5,*) RMIN(I)
3     CONTINUE
```

```
C
      WRITE(6,109) N
      DO 503 I=1,N
  503 READ(5,*) XSTRT(I)
      WRITE(6,111) F,G,MAXM,IPRINT,IDATA
      WRITE(6,112) NSHOT,NTEST
      WRITE(6,114)
      READ(5,*) IOPT
      IF(IOPT.NE.1) GO TO 30
      WRITE(6,115)
      READ(5,*) F
      READ(5,*) G
      READ(5,*) MAXM
      READ(5,*) IPRINT
      READ(5,*) IDATA
      READ(5,*) NSHOT
      READ(5,*) NTEST
C
   30 CONTINUE
C
      CALL SEEK1(N,RMAX,RMIN,NCONS,NEQUS,F,G,XSTRT,NSHOT,NTEST,
     *MAXM,IPRINT,IDATA,X,U,PHI,PSI,WORK1,WORK2,WORK3,WORK4)
C
      CALL ANSWER(U,X,PHI,PSI,N,NCONS,NEQUS)
C
      WRITE(6,117)
      READ(5,*) ISTR
      IF(ISTR.NE.1) GO TO 36
       WRITE(6,118)
      READ(5,*) IMAX
      IF(IMAX.NE.1) GO TO 34
C
      DO 504 I=1,N
  504 READ(5,*) RMAX(I)
   34  WRITE(6,119)


      READ(5,*) IMIN
      IF(IMIN.NE.1) GO TO 3
      DO 505 I=1,N
  505  READ(5,*) RMIN(I)
      GO TO 3
C
   36 CALL RESULT(X)
C
      WRITE(6,120)
      READ(5,*) ISOL
      IF(ISOL.EQ.1) GO TO 1
C
```

```
      STOP
100   FORMAT(1H0,*THIS PROGRAM CAN BE USED TO SYNTHESIZE*/
     ** FOUR-BAR MECHANISMS FOR COUPLER LINK POSITIONS*/
     ** WITH CRANK ANGLES AS INDEPENDENT DESIGN VARIABLES*)
101   FORMAT(1H0,*SPECIFY THE TYPE OF MECHANISM REQUIRED*//
     *15X,*CRANK ROCKER---ENTER 1*//15X,*DOUBLE CRANK---ENTER 2*//
     *15X,*DOUBLE ROCKER---ENTER 3*)
102   FORMAT(1H0,*ENTER THE NUMBER OF POSITIONS TO BE SYNTHESIZED*/
     **   MAXIMUM NUMBER OF POSITIONS=20*)
103   FORMAT(1H0,*ENTER THE DESIRED COUPLER POINT COORDINATES AND*/
     **   THE ANGLE MADE BY COUPLER LINK WITH Y-AXIS*)
104   FORMAT(1H0,*ENTER THE VALUE OF ICASE INDICATING THE MECHANISM CLOS
     *URE*)
116   FORMAT(1H0,*ENTER THE VALUES OF NPATH INDICATING THE PHASE OF DOUB
     *LE ROCKER*)
105   FORMAT(1H0,*ENTER THE VALUES OF MAXIMUM PERMIMISSIBLE ERRORS IN*/
     ** COUPLER POINT CO-ORDINATES AND THE COUPLER LINK INCLINATION*)
106   FORMAT(1H0,*ENTER THE MAXIMUM AND MINIMUM PERMISSIBLE VALUES ON LI
     *NK LENGTHS*)
107   FORMAT(1H0,*ENTER THE ESTIMATED UPPER BOUNDS ON THE*,I4,1X,*DESIGN
     * VARIABLES*)
108   FORMAT(1H0,*ENTER THE ESTIMATED LOWER BOUNDS ON THE*,I4,1X,*DESIGN
     * VARIABLES*)
109   FORMAT(1H0,*ENTER THE STARTING VALUES OF*,I4,1X,*DESIGN VARIABLES*
     *)
111   FORMAT(1H0,*VALUES OF OPTIMIZATION ROUTINE PARAMETERS-SEEK1*
     */25X,*      F=*,E14.8,/25X,*      G=*,E14.8,/25X,*  MAXM=*,I4,/25X,
     ** IPRINT=*,I3,/25X,* IDATA=*,I2)
 112   FORMAT(1H0,25X,* NSHOT=*,I3,//25X,* NTEST=*,I4)
113   FORMAT(1H0,25X,*      R=*,E14.8,//25X,*REDUCE=*,E14.8)
114   FORMAT(1H0,*WOULD YOU LIKE TO CHANGE THE VALUES OF THESE PARAMETER
     *S*,/15X,*IF YES ENTER 1*/15X,*OTHERWISE ENTER 0*)
115   FORMAT(1H0,*ENTER THE VALUES OF THE OPTIMIZATION PARAMETERS *)
117   FORMAT(1H0,*DO YOU WANT TO RUN THE  PROGRAM WITH DIFFERENT STARTIN
     *G VALUES*,//15X,*IF YES ENTER 1*//15X,*OTHERWISE ENTER 0*)
118   FORMAT(1H0,*DO YOU WANT TO CHANGE THE VALUES OF UPPER BOUNDS-RMAX*
     *,//15X,*IF YES ENTER 1*//15X,*OTHERWISE ENTER 0*)
119   FORMAT(1H0,*DO YOU WANT TO CHANGE THE VALUES OF LOWER BOUNDS-RMIN*
     *,//15X,*IF YES ENTER 1*//15X,*OTHERWISE ENTER 0*)
120   FORMAT(1H0,*DO YOU WANT TO SOLVE ANOTHER PROBLEM*,//15X,
     **IF YES ENTER 1*//15X,*OTHERWISE ENTER 0*)
      END
```

```
C
C
      SUBROUTINE UREAL(X,U)
      DIMENSION X(1)
C ********************************************************************
C  THIS ROUTINE CALCULATES THE OBJECTIVE FUNCTION VALUE WHICH IS THE
C  THE SUM OF THE INVERSE UTILITIES OF BOTH THE ERRORS.
C   ERR1--ERROR DUE TO THE MISMATCH OF THE COUPLER POINT.
C   ERR2--ERROR IN THE ORIENTATION OF THE COUPLER LINK
C    U--OBJECTIVE FUNCTION VALUE
C
      COMMON /REQD/ XD(20),YD(20),ANG(20),PHY(20),PSY(20)
      COMMON /TYPE/ MTYPE,KTYPE,NP,ICASE,NPATH(20)
      COMMON /ERR/ ERMX1,ERMX2
      COMMON /SYNS/ XX(20),YY(20),ALPH(20)
      COMMON /CLOSURE/ CLOSEN
      COMMON /ERROR/ ER1(20),ER2(20),Y1,Y2
C
      PI=4.*ATAN(1.)
      ERR1=0.
      ERR2=0.
      CLOSEN=0.
      DO 3 I=1,NP
      IPATH=NPATH(I)
C
      CALL SUB1(X,ICASE,IPATH,I)
C
      CALL SUB2(X,I)
      ER1(I)=(XD(I)-XX(I))**2+(YD(I)-YY(I))**2
      IF(ABS(ANG(I)-ALPH(I)).GT.180.) GO TO 220
C
      ER2(I)=(ANG(I)-ALPH(I))**2
      GO TO 210
220   ER2(I)=(ABS(ANG(I)-ALPH(I))-360.)**2
210   ERR1=ERR1+ER1(I)
      ERR2=ER2(I)+ERR2
C
3     CONTINUE
       Y1=ERR1/((ERMX1**2)*NP)
      Y2=ERR2/((ERMX2**2)*NP)
      U=Y1+Y2
      RETURN
      END
```

```
C
C
      SUBROUTINE SUB1(X,ICASE,IPATH,I)
      DIMENSION X(1),XS(4)
C   ******************************************************************
C     THIS ROUTINE CALCULATES THE FOLLOWER ANGLE FROM THE DIMENSIONS
C     OF THE MECHANISM CORRESPONDING TO THE CRANK ANG LE.MAKES USE OF
C     THE TYPE OF CLOSURE AND THE PHASE IN DOUBLE-ROCKERS.
C
C     PHY,PHYR--CRANK INPUT ANGLES
C     PSY-FOLLOWER ANGLE.
C
      COMMON /REQD/ XD(20),YD(20),ANG(20),PHY(20),PSY(20)
      COMMON /CLOSURE/ CLOSEN
C
      PI=4.*ATAN(1.)
      PHYR=X(I+10)*PI/180.
      PHR=AMOD(PHYR,2.*PI)
      IF(PHR.GT.PI.AND.PHR.LT.(2.*PI)) PHR=2.*PI-PHR
      IF(PHYR.LT.0..AND.PHYR.GT.(-PI)) PHR=-PHR
C
      DO 1 K=1,4
 1    XS(K)=X(K)*X(K)
      EE=XS(1)+XS(4)-2.*X(1)*X(4)*COS(PHR)
      E=SQRT(EE)
      ST1=X(1)*SIN(PHR)/E
      THE1=ASIN(ABS(ST1))
      IF(XS(1).GT.(XS(4)+EE)) THE1=PI-THE1
C
      CT2=(EE+XS(3)-XS(2))/(2.*X(3)*E)
      CLOSE=ABS(CT2)
      IF(ABS(CT2).GT.1.) CT2=1.
      THE2=ACOS(ABS(CT2))
      IF(XS(2).GT.(EE+XS(3))) THE2=PI-THE2.
C
      IF(PHYR.GT.PI.AND.PHYR.LT.2.*PI) GO TO 2
      IF(PHYR.LT.0..AND.PHYR.GT.(-PI)) GO TO 2
      PSYR=PI-(THE1+ICASE*IPATH*THE2)
      GO TO 3
 2    PSYR=PI+(THE1-ICASE*IPATH*THE2)


 3    PSY(I)=PSYR*180./PI
      IF(PSY(I).LT.0.) PSY(I)=PSY(I)+360.
      IF(PSY(I).GT.360.) PSY(I)=PSY(I)-360.
      IF(CLOSE.GT.CLOSEN) CLOSEN=CLOSE
      RETURN
      END
C
```

```
C
C
      SUBROUTINE SUB2(X,I)
      DIMENSION X(1)
C*****************************************************************
C    THIS ROUTINE CALCULATES THE COUPLER POINT CO-ORDINATES AND THE
C     INCLINATION OF THE COUPLER LINK WITH THE Y-AXIS.
C
C     PHY,PHYR--CRANK INPUT ANGLES
C      PSYR,PSY-FOLLOWER ANGLES
C      XX,YY-COUPLER POINT CO-ORDINATES.
C      ALPH,ALP-INCLINATION OF COUPLER LINK WITH Y-AXIS
C
      COMMON /REQD/ XD(20);YD(20),ANG(20),PHY(20),PSY(20)
      COMMON /SYNS/ XX(20),YY(20),ALPH(20)
C
      PI=4.*ATAN(1.)
      PHYR=X(I+10)*PI/180.
      PSYR=PSY(I)*PI/180.
      X(9)=X(9)*PI/180.
      AM=X(4)*COS(X(9))+X(3)*COS(PSYR+X(9))-X(1)*COS(PHYR+X(9))
      AN=X(4)*SIN(X(9))+X(3)*SIN(X(9)+PSYR)-X(1)*SIN(PHYR+X(9))
      QX=X(7)+X(1)*COS(PHYR+X(9))+AM*X(5)/X(2)
      QY=X(8)+X(1)*SIN(PHYR+X(9))+AN*X(5)/X(2)
      ALP=ATAN(ABS(AN/AM))
      ALPH(I)=ALP*180./PI
C
      IF(AM.LT.0.0.AND.AN.GT.0.0) ALPH(I)=180.-ALPH(I)
      IF(AM.LT.0.0.AND.AN.LT.0.0)ALPH(I)=180.+ALPH(I)
      IF(AM.GE.0.0.AND.AN.LT.0.0) ALPH(I)=360.-ALPH(I)
      ALPH(I)=ALPH(I)+X(10)-90.
      IF(ALPH(I).LT.0.0) ALPH(I)=ALPH(I)+360.
      IF(ALPH(I).GT.360.) ALPH(I)=ALPH(I)-360.
      ALP=ALPH(I)*PI/180.
C
      XX(I)=QX-X(6)*SIN(ALP)
      YY(I)=QY+X(6)*COS(ALP)
      X(9)=X(9)*180./PI
      RETURN
      END
C
C
C
      SUBROUTINE EQUAL(X,PSI,NEQUS)
      DIMENSION X(1),PSI(1)
C  NO EQUALITY CONSTRAINTS
      RETURN
      END
C
```

```
C
C
C
      SUBROUTINE CONST(X,NCONS,FHI)
      DIMENSION X(1),PHI(1),XYX(20)
C   *****************************************************************
C    THIS ROUTINE CALCULATES THE CONSTRAINT FUNCTION VALUES ON THE SYSTEM
C     CONSTRAINTS TO ENSURE THE PROPER TYPE OF MECHANISM,CONOTRAINTO ON
C     LINK LENGTHS THE FRAME ORIENTATION AND THE CLOSURE OF THE MECHANISM.
C      NCONS-NUMBER OF INEQUALITY CONSTRAINTS
C      PHI-INEQUALITY CONSTRAINT FUNCTION VALUE.
C      XXMAX,XXMIN--UPPER AND LOWER BOUNDS ON LINK LENGTHS.
C
      COMMON /CLOSURE/ CLOSEN
      COMMON /CLINK/ XXMIN,XXMAX
      COMMON /TYPE/ MTYPE,KTYPE,NP,ICASE,NPATH(20)
C
      PI=4.*ATAN(1.)
       MN=NP-1
      MNM=MN-1
      SUM=X(1)+X(2)+X(3)+X(4)
      XM=AMAX1(X(1),X(2),X(3),X(4))
      XL=AMIN1(X(1),X(2),X(3),X(4))
C   CONSTRAINTS COMMON FOR ALL TYPES
      DO 1 I=1,4
C    CONSTRAINTS ON LINK LENGTHS
       PHI(I)=X(I)-XXMIN
       PHI(I+4)=XXMAX-X(I)
      PHI(9)=X(6)
C
C   CONSTRAINT ON FRAME ORIENTATION
      PHI(10)=360.-ABS(X(9))


C   CONSTRAINT TO ENSURE THE CLOSURE OF THE FOUR BAR
      PHI(11)=1.-CLOSEN
C     CONSTRAINT ON THE ORIENTATION OF COUPLER LINK ANGLE-X(10)
      PHI(12)=360.-ABS(X(10))
C    CONSTRAINT TO ENSURE PROPER GRASHOF CRITERION
      PHI(13)=SUM-2.*(XL+XM)
```

```
      GO TO(11,12,13) MTYPE
C     CONSTRAINTS FOR CRANK ROCKER
 11   DO 2 I=1,3
  2   PHI(13+I)=X(I+1)-X(1)
      GO TO 15
C     CONSTRAINTS FOR DOUBLE CRANK MECHANISM
C
 12   DO 3 I=1,3
  3   PHI(13+I)=X(I)-X(4)
      GO TO 15
 13   IF(X(1).EQ.XM) KTYPE=2
      IF(X(2).EQ.XM) KTYPE=3
      IF(X(3).EQ.XM) KTYPE=4
      IF(X(4).EQ.XM) KTYPE=5
      IF(X(2).EQ.XL.AND.SUM.GT.(2.*(XL+XM))) KTYPE=1
      GO TO (6,7,7,7,7) KTYPE
C
  7   PHI(13)=-PHI(13)
  6   DO 4 I=1,3
  4   PHI(13+I)=0.
 15   CONTINUE
      NDIR=1
C     CONSTRAINTR TO ENSURE THAT COUPLER POSITIONS ARE OCCUPIED IN SEQUENCE
      IF(X(12).GT.X(11)) NDIR=2
      GO TO(21,21,22) MTYPE
C     CONSTRAINTS FOR CRANK ROCKER AND DOUBLE CRANK MECHANISMS
 21   DO 5 I=1,MN
      XYX(I)=X(11)-X(11+I)
      IF(NDIR.EQ.2) XYX(I)=-XYX(I)
  5   CONTINUE
C
      DO 50 I=1,MNM
      PHI(16+I)=XYX(I+1)-XYX(I)
 50   CONTINUE
      PHI(15+NP)=0.
      PHI(16+NP)=0.
      RETURN
C
```

```
22    GO TO(31,31,32,32,31) KTYPE
C     CONSTRAINTS FOR DOUBLE ROCKER TYPES 3,4,AND 7
31    CZI=(X(1)*X(1)+X(4)*X(4)-(X(2)+X(3))**2)/(2.*X(1)*X(4))
      IF(CZI.LT.-1.) CZI=-1.
      IF(CZI.GT.1.) CZI=1.
      GETA=ACOS(ABS(CZI))*(180./PI)
      IF(CZI.LT.0.) GETA=180.-GETA
      DO 51 I=1,NP
       XYX(I)=GETA-X(10+I)
51    CONTINUE
      DO 8 I=1,MN
      PHI(16+I)=XYX(I+1)-XYX(I)
      IF(NDIR.EQ.1.AND.NPATH(1).NE.NPATH(I)) PHI(16+I)=-PHI(16+I)
       IF(NDIR.EQ.2.AND.NPATH(1).EQ.NPATH(I)) PHI(16+I)=-PHI(16+I)
8     CONTINUE
C
      PHI(16+NP)=0.
      RETURN
C
C    CONSTRAINTS FOR DOUBLE ROCKER TYPES 5 AND 6
32    CZI=(X(1)*X(1)+X(4)*X(4)-(X(2)-X(3))**2)/(2.*X(1)*X(4))


      IF(CZI.LT.-1.) CZI=-1.
      IF(CZI.GT.1.) CZI=1.
      ZI=ACOS(ABS(CZI))*(180./PI)
      IF(CZI.LT.0.) ZI=180.-ZI
      GETA=360.-ZI
      DO 9 I=1,NP
       XYX(I)=GETA-X(10+I)
9     CONTINUE
      DO 10 I=1,MN
      PHI(16+I)=XYX(I+1)-XYX(I)
      IF(NDIR.EQ.1.AND.NPATH(1).NE.NPATH(I)) PHI(16+I)=-PHI(16+I)
       IF(NDIR.EQ.2.AND.NPATH(1).EQ.NPATH(I)) PHI(16+I)=-PHI(16+I)
10    CONTINUE
      PHI(16+NP)=0.
      RETURN
      END
C
```

```
C
C
      SUBROUTINE RESULT(X)
      DIMENSION ERR1(20),ERR2(20)
      DIMENSION X(1)
C    ******************************************************************
C    THIS ROUTINE PRINTS ALL THE OUTPUT DATA IN A FORMAT WHICH
C      CAN BE UNDERSTOOD EASILY BY ANY USER.
C
C
      COMMON /TYPE/ MTYPE,KTYPE,NP,ICASE,NPATH(20)
      COMMON /ERR/ ERMX1,ERMX2
      COMMON /CLINK/ XXMIN,XXMAX
      COMMON /SYNS/ XX(20),YY(20),ALPH(20)
      COMMON /REQD/ XD(20),YD(20),ANG(20),PHY(20),PSY(20)
      COMMON /CLOSURE/ CLOSEN
      COMMON /ERROR/ ER1(20),ER2(20),Y1,Y2
C
      WRITE(6,1)
      WRITE(6,2)
      IF(MTYPE.EQ.1) WRITE(6,3)
      IF(MTYPE.EQ.2) WRITE(6,4)
      IF(MTYPE.EQ.3.AND.KTYPE.EQ.1) WRITE(6,5)
      IF(MTYPE.EQ.3.AND.KTYPE.EQ.2) WRITE(6,6)
      IF(MTYPE.EQ.3.AND.KTYPE.EQ.3) WRITE(6,7)
      IF(MTYPE.EQ.3.AND.KTYPE.EQ.4) WRITE(6,8)
      IF(MTYPE.EQ.3.AND.KTYPE.EQ.5) WRITE(6,9)
      WRITE(6,10) NP
       WRITE(6,11) ERMX1
      WRITE(6,12) ERMX2
      WRITE(6,13) XXMAX
      WRITE(6,14) XXMIN
      WRITE(6,15) ICASE
      WRITE(6,16)
      WRITE(6,17)
      WRITE(6,18)
      WRITE(6,19)
      WRITE(6,20)
      DO 500 I=1,NP
 500  WRITE(6,21) I,XD(I),YD(I),ANG(I)
      WRITE(6,22)
      WRITE(6,23)
      WRITE(6,24) X(1)
      WRITE(6,25) X(2)
      WRITE(6,26) X(3)
      WRITE(6,27) X(4)
      WRITE(6,28)
        WRITE(6.29)
```

```
      WRITE(6,30) X(5)
      WRITE(6,31) X(6)
       WRITE(6,32) X(10)
      WRITE(6,33)
      WRITE(6,34)
      WRITE(6,35) X(7)
      WRITE(6,36) X(8)
      WRITE(6,37) X(9)
      WRITE(6,38)
      WRITE(6,39)
       WRITE(6,40)
      WRITE(6,41)
      WRITE(6,42)
      WRITE(6,43)
      WRITE(6,44)
      DO 550 I=1,NP
550   WRITE(6,45) I,X(I+10),PSY(I),XX(I),YY(I),ALPH(I)
      WRITE(6,46)
      WRITE(6,47)
      WRITE(6,51)
      WRITE(6,52)
      WRITE(6,53)
      WRITE(6,48)
      DO 560 I=1,NP
      ERR1(I)=SQRT(ER1(I))
      ERR2(I)=SQRT(ER2(I))
560   WRITE(6,49) I,ERR1(I),ERR2(I)
      WRITE(6,50) Y1,Y2
      RETURN
1     FORMAT(1H1,20X,*FOUR-BAR COUPLER POSITION SYNTHESIS*)
2     FORMAT(21X,*---- --- ------- -------- ---------*)
 3    FORMAT(/10X,*CRANK ROCKER*)
4     FORMAT(/10X,*DOUBLE CRANK:*)
5     FORMAT(/10X,*DOUBLE ROCKER TYPE 3*)


6     FORMAT(/10X,*DOUBLE ROCKER TYPE 4*)
7     FORMAT(/10X,*DOUBLE ROCKER TYPE 5*)
8     FORMAT(/10X,*DOUBLE ROCKER TYPE 6*)
9     FORMAT(/10X,*DOUBLE ROCKER TYPE 7*)
10    FORMAT(/10X,I2,* SPECIFIED POSITIONS*)
11    FORMAT(/5X,*MAXIMUM ERROR SPECIFIED FOR COUPLER POINT CO-ORDINATES
     *,=*,F8.4,* INCHES*)
12    FORMAT(/5X,*MAXIMUM ERROR SPECIFIED FOR ORIENTATION OF COUPLER LIN
     *K=*,F8.4,* DEGREES*)
13    FORMAT(/5X,*MAXIMUM PERMISSIBLE VALUE ON LINK LENGTHS............
     *,=*,F8.4,* INCHES*)
14    FORMAT(/5X,*MINIMUM PERMISSIBLE VALUE ON LINK LENGTHS.............
     *,=*,F8.4,* INCHES*)
15    FORMAT(/5X,*INITIAL CLOSURE OF THE MECHANISM.................ICAS
     *E=*,I2)
```

```
16    FORMAT(//5X,*DETAILS OF THE REQUIRED COUPLER PLANE POSITIONS*)
17    FORMAT(5X,*------- -- --- -------- ------- ----- ---------*)
18    FORMAT(/5X,*XD,YD---CO-ORDINATES OF COUPLER POINT IN INCHES*)
19    FORMAT(/5X,*ANGLE---ANGLE MADE BY COUPLER LINK WITH Y-AXIS IN DEGR
     *EES*)
20    FORMAT(/5X,*POSITION*,5X,*XD*,14X,*YD*,14X,*ANGLE*)
21    FORMAT(/5X,I2,10X,F9.4,5X,F9.4,5X,F9.4)
22    FORMAT(1H1,5X,*OPTIMUM DIMENSIONS OF THE MECHANISM*)
23    FORMAT(6X,*------- ---------- -- --- ---------*)
24    FORMAT(/10X,*INPUT LINK(CRANK) LENGTH=*,F8.4,* INCHES*)
25    FORMAT(/10X,*COUPLER LINK LENGTH.....=*,F8.4,* INCHES*)
26    FORMAT(/10X,*FOLLOWER LINK LENGTH....=*,F8.4,* INCHES*)
27    FORMAT(/10X,*FRAME LENGTH............=*,F8.4,* INCHES*)
28    FORMAT(//10X,*COUPLER LINK DETAILS*)
29    FORMAT(10X,*------- ---- -------*)
30    FORMAT(/20X,* X5=*,F8.4,* INCHES*)
31    FORMAT(/20X,* X6=*,F8.4,* INCHES*)
32    FORMAT(/20X,*X10=*,F8.4,* DEGREES*)
33    FORMAT(//10X,*DETAILS OF PIVOT LOCATIONS*)
34    FORMAT(10X,*------- -- ----- ---------*)
35    FORMAT(/20X,*X7=*,F8.4,* INCHES*)
36    FORMAT(/20X,*X8=*,F8.4,* INCHES*)
37    FORMAT(/20X,*X9=*,F8.4,* DEGREES*)
38    FORMAT(//10X,*DETAILS OF SYNTHESIZED POSITIONS*)
39    FORMAT(10X,*------- -- ----------- ---------*)
40    FORMAT(/15X,*PHY---CRANK ANGLE IN DEGREES*)
41    FORMAT(/15X,*PSY---FOLLOWER ANGLE IN DEGREES*)
42    FORMAT(/15X,*X,Y---CO-ORDINATES OF COUPLER POINT IN INCHES*)
43    FORMAT(/15X,*ALPHA---ANGLE MADE BY COUPLER LINK WITH Y-AXIS IN DEG
     *REES*)
44    FORMAT(/5X,*POSITION*,5X,*PHY*,14X,*PSY*,12X,*X*,14X,*Y*,11X,*ALPH
     *A*)
45    FORMAT(/5X,I2,10X,5(F9.4,5X))
46     FORMAT(//10X,*DETAILS OF DEVIATIONS OF SYNTHESIZED POSITIONS FROM
     * DESIRED POSITIONS*)
47    FORMAT(10X,*------- -- ---------- -- ----------- --------- ---- --
     *----- ---------*)
48    FORMAT(/5X,*POSITION*,5X,*ERROR1*,14X,*ERROR2*)
49    FORMAT(/5X,I2,10X,E14.8,5X,E14.8)
50    FORMAT(/10X,*Y1=*,E14.8,5X,*Y2=*,E14.8)
51    FORMAT(/15X,*ERROR1---ERROR DUE TO MISMATCH OF COUPLER POINT IN IN
     *CHES*)
52    FORMAT(/15X,*ERROR2---ERROR IN THE ORIENTATION OF COUPLER LINK IN
     * DEGREES*)
53    FORMAT(/15X,*Y1,Y2---INDIVIDUAL VALUES OF OBJECTIVE FUNCTION*)
      END
```

Graphical Output Main Program (file-FBAR)

```
      DIMENSION X(20),PHY(20),PSY(20),XD(20),YD(20)
     * ,ANG(20),XS(4),QDX(20),QDY(20),NPATH(20)
      COMMON /GFILE/ IBUF(9000)
C*****************************************************************
C  THIS IS THE GRAPHICAL ANALYSIS PROGRAM DEVELOPED FOR ANALYSING
C  FOUR-BAR MECHANISMS WHOSE COUPLER LINK IS REQUIRED TO PASS
C  THROUGH A NUMBER OF SPECIFIED POSITIONS.THE DATA FROM THE
C  SYNTHESIS PROGRAM WHICH IS BEING EXECUTED BY THE CDC6400 IS THE
C  INPUT FOR THIS PROGRAM.THE GRAPHICAL DISPLAYS THAT ARE OBTAINED
C  BY THIS PROGRAM ARE CONTROLLED THROUGH LIGHT PEN.THIS PROGRAM
C  IS DEVELOPED AS PART OF M.ENG. THESIS.THIS PROGRAM CAN HANDLE
C  ALL TYPES OF THE FOUR-BAR MECHANISMS(CRANK-ROCKER,DOUBLE-CRANK
C  AND DOUBLE-ROCKERS).
C  PROGRAMMER:M.R.GUDAVALLI.   DATE:OCTOBER-1979.
C*******************************************************************
      TYPE 100
100   FORMAT(' ENTER THE DIMENSIONS OF THE MECHANISM-E14.8')
      DO 1 I=1,10
1     READ(5,200) X(I)
200   FORMAT(E14.8)
      TYPE 101
101   FORMAT(' ENTER THE NUMBER OF POSITIONS-I2')
      READ(5,201) NP
201   FORMAT(I2)
      TYPE 102
102   FORMAT(' ENTER THE CRANK INPUT ANGLES-E14.8')
      DO 2 I-1,NP
2     READ(5,202) PHY(I)
202   FORMAT(E14.8)
      CALL TYPE(X,NTYPE)
      IF(NTYPE.GT.2) ICASE=1
      IF(NTYPE.GE.3) GO TO 37
      TYPE 103
103   FORMAT(' ENTER THE VALUE OF ICASE INDICATING MECHANISM CLOSURE')
      READ(5,203) ICASE
203   FORMAT(I2)
```

```
37      IF(NTYPE.GE.3) TYPE 106
106     FORMAT(' ENTER THE VALUES OF NPATH INDICATING THE PHASE OF
     * THE DOUBLE-ROCKER')
        DO 10 I=1,NP
        IF(NTYPE.LE.2) NPATH(I)=1
10      IF(NTYPE.GE.3) READ(5,205) NPATH(I)
205     FORMAT(I2)
        TYPE 104
104     FORMAT(' ENTER THE DESIRED COUPLER POINT CO-ORDINATES AND THE'/
     * ' INCLINATION OF COUPLER LINK WITH Y-AXIS--3F8.3')
        DO 3 I=1,NP
3       READ(5,204) XD(I),YD(I),ANG(I)
204     FORMAT(3F8.3)
        PI=4.*ATAN(1.)
        DR=PI/180.
        RD=180./PI
        PHNC=1.0*DR
        X(9)=X(9)*DR
        X(10)=X(10)*DR
        DO 18 I=1,NP
18      ANG(I)=ANG(I)*DR
        DO 19 I=1,4
19      XS(I)=X(I)*X(I)
C
        TYPE 105
105     FORMAT(' ENTER THE MAXIMUM AND MINIMUM ERRORS-2F5.3')
        READ(5,206) ER1M,ER1N
206     FORMAT(2F6.3)
        TYPE 107
107     FORMAT(' ENTER THE MAXIMUM AND MINIMUM ANGULAR DEVIATIONS-2F5.3')
        READ(5,206) ER2M,ER2N
C
        OBX=X(7)+X(4)*COS(X(9))
        OBY=X(8)+X(4)*SIN(X(9))
        CALL TYPE(X,NTYPE)
666     CONTINUE
        CALL INIT(IBUF,9000)
```

```
      CALL SCAL(0.,0.,1023.,1023.)
      CALL CHECK1(NH)
      CALL SUBP(6)
      CALL TEXT1(NP,ER1M,ER1N,ER2M,ER2N,NTYPE)
      CALL ESUB
      GO TO (6,7,7) ,NH
7     CALL SFAC(X,XMI,XMA,YMI,YMA)
      CALL SCAL(XMI,YMI,XMA,YMA)
C  THIS PART DISPLAYS THE MECHANISM IN DIFFERENT POSITIONS
C*****************************************************************
      CALL SUBP(8)
      DO 5 I=1,NP
      CALL APNT(XD(I)-X(7),YD(I)-X(8),0,-7)
      CALL VECT(X(6)*SIN(ANG(I)),-X(6)*COS(ANG(I)),0,7,1,4)
      XN=XD(I)-X(7)+.05
      YN=YD(I)-X(8)+.05
      CALL APNT(XN,YN,0,-7)
      CALL NMBR(100+I,I,'I2')
5     CONTINUE
      CALL ESUB
      IF(NH.EQ.3) GO TO 7500
      CALL SUBP(4)
      CALL APNT(0.,0.,0,-7,-1,1)
      CALL VECT(OBX-X(7),OBY-X(8),0,7,-1,2)
      DO 4  I=1,NP
      PHIY=PHY(I)*DR
      IPATH=NPATH(I)
C
      CALL GSUB(X,ICASE,IPATH,PHIY,OBX,OBY,AX,AY,BX,BY,
     * QX,QY,PX,PY,PSIY,TAU)
C
      CALL APNT(0.,0.,0,-7,0,1)
      CALL LINKPL(AX,AY,BX,BY,X,OBX,OBY,QX,QY,PX,PY)
4     CONTINUE
      CALL ESUB
C
      GO TO 9999
```

```
C THIS PART DISPLAYS THE DYNAMIC DISPLAY FOR CRANK-ROCKER
C    AND DOUBLE-CRANK MECHANISMS
C**********************************************************
 7500   CALL SUBP(26)
        CALL OFF(26)
        CALL TEXT2
        CALL ESUB
        IF(NTYPE.GE.3) GO TO 347
        CALL CHECK2(1,ND)
        CALL ON(26)
        CALL SCAL(XMI,YMI,XMA,YMA)
        NCOUNT=0
        IPATH=1
        PHIY=PHY(1)*DR
 16     CONTINUE
        CALL SUBP(5)
        CALL APNT(0.,0.,-1,-5,-2,1)
        CALL VECT(OBX-X(7),OBY-X(8),0,7,0,2)
        CALL GSUB(X,ICASE,IPATH,PHIY,OBX,OBY,AX,AY,BX,BY,
     *  QX,QY,PX,PY,PSIY,TAU)
        CALL APNT(0.,0.,0,-7,0,1)
        CALL LINKPL(AX,AY,BX,BY,X,OBX,OBY,QX,QY,PX,PY)
        CALL ESUB
        CALL APNT(PX-X(7),PY-X(8),0,-7)
        IF(NCOUNT.NE.0) CALL VECT(PX-PI1,PY-PI2,0,7,-1,1)
        PI1=PX
        PI2=PY
        CALL SUBP(25)
        CALL TEXT3(PHIY,PSIY,TAU,RD)
        CALL ESUB
        IF(NCOUNT.EQ.361) GO TO 9999
        CALL SCAL(XMI,YMI,XMA,YMA)
        CALL TIME(1)
 500    CALL TIMR(IE)
        IF(IE.NE.0) GO TO 500
        CALL ERAS(5)
        CALL ERAS(25)
```

```
      CALL CMPRS
      IF(ND.EQ.1) PHIY=PHIY+PHNC
      IF(ND.EQ.2) PHIY=PHIY-PHNC
      NCOUNT=NCOUNT+1
      GO TO 16
C  THIS PART DISPLAYS THE DYNAMIC DISPLAY OF  THE MECHANISM
C     FOR ALL TYPES OF DOUBLE-ROCKER MECHANISMS
C   **********************************************************
 347          CALL SUBP(27)
      CALL OFF(27)
      CALL SCAL(0.,0.,1023.,1023.)
      CALL APNT(5.,950.,0,-7)
      CALL TEXT('DOUBLE ROCKER AT UPPER EXTREME POSITION')
      CALL ES[illegible]
      CALL [illegible]29)
      CALL O[illegible]29)
      CALL SCAL(0.,0.,1023.,1023.)
      CALL APNT(5.,950.,0,-7)
      CALL TEXT('DOUBLE ROCKER AT LOWER EXTREME POSITION')
      CALL ESUB
      EE=(X(2)+X(3))**2
      CALL ALIM(X,XS,EE,ZI1)
      EE=(X(2)-X(3))**2
      CALL ALIM(X,XS,EE,ZI2)
      IF(NTYPE.EQ.4.OR.NTYPE.EQ.7) ZI2=-ZI1
      IF(NTYPE.EQ.5.OR.NTYPE.EQ.6) ZI1=ZI2
      IF(NTYPE.EQ.5.OR.NTYPE.EQ.6) ZI2=2.*PI-ZI1
      PHD1=ZI1-PHY(1)*DR
      PHD2=ZI2-PHY(1)*DR
      NSTRT=1
      IF(ABS(PHD2).LT.ABS(PHD1)) NSTRT=2
      NTAG=1
      PHIY=ZI1
      IF(NSTRT.EQ.2) PHIY=ZI2
      IF(NSTRT.EQ.1) CALL ON(27)
      IF(NSTRT.EQ.2) CALL ON(29)
      CALL CHECK2(2,NB)
```

```
      CALL OFF(27)
      CALL OFF(29)
      CALL ON(26)
      IF(NB.EQ.1) IPATH=1
      IF(NB.EQ.2) IPATH=-1
      CALL SCAL(XMI,YMI,XMA,YMA)
716   CONTINUE
      CALL SUBP(7)
      CALL APNT(0.,0.,-1,-7,-2,1)
      CALL VECT(OBX-X(7),OBY-X(8),0,7,0,2)
      CALL GSUB(X,ICASE,IPATH,PHIY,OBX,OBY,AX,AY,BX,BY,QX,QY,PX,PY
     *,PSIY,TAU)
      CALL APNT(0.,0.,0,-7,0,1)
      CALL LINKPL(AX,AY,BX,BY,X,OBX,OBY,QX,QY,PX,PY)
      CALL ESUB
      CALL APNT(PX-X(7),PY-X(8),0,7)
      IF(PHIY.NE.ZI1) CALL VECT(PX-PI1,PY-PI2,0,7,-1,1)
      PI1=PX
      PI2=PY
      TT1=ABS(PHIY-ZI1)
      TT2=ABS(PHIY-ZI2)
      IF(TT1.LE.PHNC.OR.TT2.LE.PHNC) TAU=0.
      CALL SUBP(28)
      CALL TEXT3(PHIY,PSIY,TAU,RD)
      CALL ESUB
      CALL SCAL(XMI,YMI,XMA,YMA)
      CALL TIME(1)
777   CALL TIMR(IE)
      IF(IE.NE.0) GO TO 777
      IF(NTYPE.EQ.5.OR.NTYPE.EQ.6) GO TO 56
      IF(NTAG.EQ.1.AND.NSTRT.EQ.1) PHIY=PHIY-PHNC
      IF(NTAG.EQ.1.AND.NSTRT.EQ.2) PHIY=PHIY+PHNC
      IF(NTAG.EQ.2.AND.NSTRT.EQ.1) PHIY=PHIY+PHNC
      IF(NTAG.EQ.2.AND.NSTRT.EQ.2) PHIY=PHIY-PHNC
      IF(NSTRT.EQ.1.AND.PHIY.LT.ZI2) GO TO 7777
      IF(NSTRT.EQ.2.AND.PHIY.GT.ZI1) GO TO 7777
      IF(NSTRT.EQ.1.AND.PHIY.GT.ZI1) GO TO 9999
      IF(NSTRT.EQ.2.AND.PHIY.LT.ZI2) GO TO 9999
```

```
      CALL ERAS(7)
      CALL ERAS(28)
      CALL CMPRS
      GO TO 716
 56   IF(NTAG.EQ.1.AND.NSTRT.EQ.1) PHIY=PHIY+PHNC
      IF(NTAG.EQ.1.AND.NSTRT.EQ.2) PHIY=PHIY-PHNC
      IF(NTAG.EQ.2.AND.NSTRT.EQ.1) PHIY=PHIY-PHNC
      IF(NTAG.EQ.2.AND.NSTRT.EQ.2) PHIY=PHIY+PHNC
      IF(NSTRT.EQ.1.AND.PHIY.GT.ZI2) GO TO 7777
      IF(NSTRT.EQ.2.AND.PHIY.LT.ZI1) GO TO 7777
      IF(NSTRT.EQ.1.AND.PHIY.LT.ZI1) GO TO 9999
      IF(NSTRT.EQ.2.AND.PHIY.GT.ZI2) GO TO 9999
      CALL ERAS(7)
      CALL ERAS(28)
      CALL CMPRS
      GO TO 716
 7777 CALL SCAL(0.,0.,1023.,1023.)
      IF(NSTRT.EQ.1) CALL ON(29)
      IF(NSTRT.EQ.2) CALL ON(27)
      CALL CHECK2(2,NA)
      CALL OFF(27)
      CALL OFF(29)
      IF(NA.EQ.1) IPATH=1
      IF(NA.EQ.2) IPATH=-1
      CALL SCAL(XMI,YMI,XMA,YMA)
      NTAG=2
      IF(NSTRT.EQ.1) PHIY=ZI2
      IF(NSTRT.EQ.2) PHIY=ZI1
      CALL ERAS(7)
      CALL ERAS(28)
      CALL CMPRS
      GO TO 716
C  THIS PART DISPLAYS THE DESIRED AND SYNTHESIZED POSITIONS
C  ***************************************************************
 6    CALL SFAC1(X,XD,YD,ANG,NP,QDX,QDY,XMI,XMA,YMI,YMA)
      CALL SCAL(XMI,YMI,XMA,YMA)
      CALL SUBP(9)
```

```
        DO 9 I=1,NP
        PHIY=PHY(I)*PI/180.
        IPATH=NPATH(I)
        CALL GSUB(X,ICASE,IPATH,PHIY,QBX,QBY,AX,AY,BX,BY,
     *  QX,QY,PX,PY,PSIY,TAU)
        CALL APNT(XD(I),YD(I),0,-7)
        CALL VECT(QDX(I)-XD(I),QDY(I)-YD(I),0,7,1,4)
        CALL APNT(QX,QY,0,-7)
        CALL VECT(PX-QX,PY-QY,0,7,-1,1)
        XN=XD(I)+.05
        YN=YD(I)+.05
        CALL APNT(XN,YN,0,-7)
        CALL NMBR(200+I,I,'I2')
9       CONTINUE
        CALL ESUB
9999    CALL TIME(15*60)
99      CALL TIMR(IE)
        IF(IE.NE.0) GO TO 99
        CALL ERAS(4)
        CALL ERAS(5)
        CALL ERAS(6)
        CALL ERAS(7)
        CALL ERAS(8)
        CALL ERAS(9)
        CALL ERAS(25)
        CALL ERAS(26)
        CALL ERAS(28)
        CALL ERAS(10)
        CALL ERAS(20)
        CALL CMPRS
        CALL CHECK2(3,NN)
        IF(NN.EQ.1) GO TO 666
        STOP
        END
```

```
      SUBROUTINE CHECK1(NH)
C  THIS ROUTINE REQUESTS THE DESIGNER TO SELECT AN OPTION FOR
C  ANALYSIS USING LIGHT PEN AND RETURNS THE TAG OF LIGHT PEN
C  HIT TO GRAPHICS MAIN ROUTINE
C ***************************************************************
      COMMON /GFILE/ IBUF(1)
      CALL SCAL(0.,0.,1023.,1023.)
      CALL SUBP(1)
      CALL APNT(100.,850.,0,-7)
      CALL TEXT('SELECT ONE OF THE FOLLOWING OPTIONS FOR ANALYSIS')
      CALL APNT(100.,700.,1,7)
      CALL VECT(50.,0.,1,7)
      CALL APNT(160.,700.,1,-7)
      CALL TEXT('STATIC DISPLAY OF DESIRED AND SYNTHESIZED POSITIONS')
      CALL ESUB
      CALL SUBP(2)
      CALL APNT(100.,500.,1,7)
      CALL VECT(50.,0.,1,7)
      CALL APNT(160.,500.,1,-7)
      CALL TEXT('STATIC DISPLAY OF MECHANISM IN DIFFERENT POSITIONS')
      CALL ESUB
      CALL SUBP(3)
      CALL APNT(100.,300.,1,7)
      CALL VECT(50.,0.,1,7)
      CALL APNT(160.,300.,1,-7)
      CALL TEXT('DYNAMIC MOVING DISPLAY OF MECHANISM WITH COUPLER CURV
     *E')
      CALL ESUB
 300  CALL LPEN(MH,NH)
      IF(MH.EQ.0.OR.NH.LT.1.OR.NH.GT.3) GO TO 300
      CALL ERAS(1)
      CALL ERAS(2)
      CALL ERAS(3)
      CALL CMFRS
      RETURN
      END
```

```
      SUBROUTINE CHECK2(II,NA)
C  THIS ROUTINE REQUESTS THE DESIGNER TO SELECT OPTIONS LIKE
C  DIRECTION OF ROTATION OF   CRANK,PARTICULAR PHASE IN
C  DOUBLE-ROCKER MECHANISMS AND RETURNS THE TAG OF LIGHT PEN
C  HIT TO GRAPHICS MAIN ROUTINE
C ************************************************************
      COMMON /GFILE/ IBUF(1)
      CALL SCAL(0.,0.,1023.,1023.)
      CALL SUBP(1)
      CALL APNT(5.,850.,0,-7,1)
      IF(II.EQ.1)CALL TEXT('SELECT THE DIRECTION OF ROTATION OF CRANK')
      IF(II.EQ.2)CALL TEXT('SPECIFY THE PHASE OF DOUBLE ROCKER')
      IF(II.EQ.3)CALL TEXT('WOULD YOU LIKE TO GO BACK TO ANALYSIS')
      CALL APNT(5.,700.,1,-7)
      CALL VECT(40.,0.,1,7)
      CALL APNT(55.,700.,1,-7)
      IF(II.EQ.1)CALL TEXT('COUNTER CLOCKWISE')
      IF(II.EQ.2)CALL TEXT('PHASE1')
      IF(II.EQ.3)CALL TEXT('YES')
      CALL ESUB
      CALL SUBP(2)
      CALL APNT(5.,500.,1,-7)
      CALL VECT(40.,0.,1,7)
      CALL APNT(55.,500.,1,-7)
      IF(II.EQ.1)CALL TEXT('CLOCKWISE')
      IF(II.EQ.2)CALL TEXT('PHASE2')
      IF(II.EQ.3)CALL TEXT('NO')
      CALL ESUB
  301 CALL LPEN(MA,NA)
      IF(MA.EQ.0.OR.NA.LT.1.OR.NA.GT.2) GO TO 301
      CALL ERAS(1)
      CALL ERAS(2)
      CALL CMPRS
      RETURN
      END
```

```
      SUBROUTINE SFAC1(X,XD,YD,ANG,NP,QDX,QDY,XMI,XMA,YMI,YMA)
      DIMENSION X(20),XD(20),YD(20),ANG(20),QDX(20),QDY(20)
C  THIS ROUTINE SCALES THE SCREEN FOR DESIRED AND SYNTHESIZED
C   POSITIONS OF COUPLER LINK
C ****************************************************************
      DO 2 I=1,NP
      QDX(I)=X(6)*SIN(ANG(I))+XD(I)
      QDY(I)=YD(I)-X(6)*COS(ANG(I))
 2    CONTINUE
      XMI=QDX(1)
      XMA=XD(1)
      YMI=QDY(1)
      YMA=YD(1)
      DO 1 I=1,NP
      XMM=AMIN1(XD(I),QDX(I))
      XML=AMAX1(XD(I),QDX(I))
      YMM=AMIN1(YD(I),QDY(I))
      YML=AMAX1(YD(I),QDY(I))
      IF(XMM.LT.XMI) XMI=XMM
      IF(XML.GT.XMA) XMA=XML
      IF(YMM.LT.YMI) YMI=YMM
      IF(YML.GT.YMA) YMA=YML
 1    CONTINUE
      XMI=XMI-.2*ABS(XMI)
      XMA=XMA*1.2
      YMI=YMI-.2*ABS(YMI)
      YMA=YMA*1.2
      IF(XMI.LE.YMI) YMI=XMI
      IF(YMI.LE.XMI) XMI=YMI
      IF(XMA.GE.YMA) YMA=XMA
      IF(YMA.GE.XMA) XMA=YMA
      RETURN
      END
```

```
      SUBROUTINE ALIM(X,XS,EE,ZI)
C  THIS ROUTINE CALCULATES THE LIMITING ANGLES FOR
C  DOUBLE- ROCKER MECHANISMS
C ***************************************************
      DIMENSION XS(4),X(20)
      PI=4.*ATAN(1.)
      CZI=(XS(1)+XS(4)-EE)/(2.*X(1)*X(4))
      IF(CZI.LT.-1.)CZI=-1.
      IF(CZI.GT.1.)CZI=1.
      ZI=ATAN(ABS(SQRT(1.-CZI*CZI)/CZI))
      IF(CZI.LT.0.) ZI=PI-ZI
      RETURN
      END

      SUBROUTINE TYPE(X,NTYPE)
C  THIS ROUTINE FINDS THE TYPE OF MECHANISM FROM THE
C  DIMENSIONS OF THE MECHANISM
C  GRASHOF FOUR-BAR: L+S.LT.P+Q
C  NON GRASHOF FOUR-BAR:L+S.GTP+Q
C ***************************************************
      DIMENSION X(20)
      XL=AMAX1(X(1),X(2),X(3),X(4))
      XM=AMIN1(X(1),X(2),X(3),X(4))
      SUM=X(1)+X(2)+X(3)+X(4)
      IF(2.*(XL+XM).GT.SUM) GO TO 1
      IF(X(2).EQ.XM) NTYPE=3
      IF(X(1).EQ.XM) NTYPE=1
      IF(X(4).EQ.XM) NTYPE=2
      RETURN
1     IF(XL.EQ.X(1)) NTYPE=4
      IF(XL.EQ.X(2)) NTYPE=5
      IF(XL.EQ.X(3)) NTYPE=6
      IF(XL.EQ.X(4)) NTYPE=7
      RETURN
      END
```

```
      SUBROUTINE SFAC(X,XMI,XMA,YMI,YMA)
C  THIS ROUTINE SCALES THE SCREEN CO-ORDINATES DEPENDING
C  UP ON THE DIMENSIONS OF THE MECHANISM
C ********************************************************
      DIMENSION X(20)
      XMI=-X(1)
      IF(X(7).GT.X(1)) XMI=-X(7)
      XMA=X(4)+X(3)
      YMI=-X(1)
      IF(X(8).GT.X(1)) YMI=-X(8)
      IF(X(9).LT.0..AND.(X(4)*COS(X(9))).GT.ABS(YMI))YMI=
     *-X(4)*COS(X(9))
      YMA=X(1)+X(5)+X(6)
      IF(X(10).GT.180.)YMA=X(1)+X(2)
      IF(XMI.LE.YMI) YMI=XMI
      IF(YMI.LE.XMI) XMI=YMI
      IF(XMA.GE.YMA) YMA=XMA
      IF(YMA.GE.XMA) XMA=YMA
      XMI=XMI*1.2
      YMI=YMI*1.2
      XMA=XMA*1.2
      YMA=YMA*1.2
      RETURN
      END

      SUBROUTINE TEXT2
C  THIS ROUTINE DISPLAYS THE TEXT FOR CRANK ANGLE,
C  FOLLOWER ANGLE AND TRANSMISSION ANGLE
C **************************************************
      COMMON /GFILE/ IBUF(1)
      CALL SCAL(0.,0.,1023.,1023.)
      CALL APNT(680.,200.,0,-7,-1)
      CALL TEXT('CRANK ANGLE       =')
      CALL APNT(680.,150.,0,-7)
      CALL TEXT('FOLLOWER ANGLE    =')
      CALL APNT(680.,100.,0,-7)
      CALL TEXT('TRANSMISSION ANGLE=')
      RETURN
      END
```

```
      SUBROUTINE TEXT3(PHIY,PSIY,TAU,RD)
C  THIS ROUTINE DISPLAYS THE VALUES OF CRANK ANGLE
C   FOLLOWER ANGLE AND TRANSMISSION ANGLE
C *************************************************
      COMMON /GFILE/ IBUF(1)
      PH=PHIY*RD
      PS=PSIY*RD
      TAU=TAU*RD
      IF(PH.GT.360.) PH=PH-360.
      IF(PH.LT.0.) PH=360.+PH
      CALL SCAL(0.,0.,1023.,1023.)
      CALL APNT(945.,200.,0,-7)
      CALL NMBR(60,PH,'F6.2')
      CALL APNT(945.,150.,0,-7)
      CALL NMBR(61,PS,'F6.2')
      CALL APNT(945.,100.,0,-7)
      CALL NMBR(62,TAU,'F6.2')
      RETURN
      END

      SUBROUTINE LINKPL(AX,AY,BX,BY,X,OBX,OBY,QX,QY,PX,PY)
C   THIS ROUTINE PLOTS THE LINKAGE FROM THE CO-ORDINATES
C       OF ALL THE NODAL POINTS OBTAINED  FROM GSUB.
C   **********************************************************
      DIMENSION X(10)
      COMMON /GFILE/ IBUF(1)
      CALL VECT(AX-X(7),AY-X(8))
      CALL VECT(BX-AX,BY-AY)
      CALL VECT(OBX-BX,OBY-BY)
      CALL APNT(QX-X(7),QY-X(8))
      CALL VECT(PX-QX,PY-QY)
      IF(X(5).GT.X(2).OR.X(5).LT.0.) CALL APNT(QX-X(7),QY-X(8),0,-7)
      IF(X(5).GT.X(2)) CALL VECT(BX-QX,BY-QY)
      IF(X(5).LT.0.) CALL VECT(AX-QX,AY-QY)
      RETURN
      END
```

```
      SUBROUTINE GSUB(X,ICASE,IPATH,PHIY,OBX,OBY,AX,AY,BX,BY
     *,QX,QY,PX,PY,PSIY,TAU)
C  THIS ROUTINE CALCULATES THE CO-ORDINATES OF ALL THE
C  NODAL POINTS IN THE MECHANISM
C ***************************************************
      DIMENSION X(20),XS(4)
      PI=4.*ATAN(1.)
      DO 1 I=1,4
 1    XS(I)=X(I)*X(I)
      PHI=AMOD(PHIY,2.*PI)
C  PHIY-CRANK ANGLE
      IF(PHIY.GT.PI.AND.PHIY.LT.2.*PI) PHI=2.*PI-PHIY
      IF(PHIY.LT.(-PI).AND.PHIY.GT.(-2.*PI))PHI=PHIY+2.*PI
      IF(PHIY.LT.0..AND.PHIY.GT.(-PI))PHI=-PHIY
      EE=XS(1)+XS(4)-2.*X(1)*X(4)*COS(PHI)
      E=SQRT(EE)
      CTAU=(XS(2)+XS(3)-EE)/(2.*X(2)*X(3))
      IF(ABS(CTAU).GT.1.) CTAU=1.
C  TAU-TRANSMISSION ANGLE
      TAU=ATAN(SQRT(1.-CTAU*CTAU)/ABS(CTAU))
      ST1=X(1)*SIN(PHI)/E
      THE1=ATAN(ABS(ST1/SQRT(1.-ST1*ST1)))
      IF(XS(1).GT.(XS(4)+EE)) THE1=PI-THE1
      CT2=(EE+XS(3)-XS(2))/(2.*X(3)*E)
      IF(ABS(CT2).GT.1.) CT2=1.
      THE2=ATAN(ABS(SQRT(1.-CT2*CT2)/CT2))
      IF(CT2.LT.0.) THE2=PI-THE2
      IF(PHIY.LT.0..AND.PHIY.GT.(-PI)) GO TO 9
      IF(PHIY.GT.PI.AND.PHIY.LT.2.*PI) GO TO 9
C  PSIY-FOLLOWER ANGLE
      PSIY=PI-(THE1+ICASE*IPATH*THE2)
      GO TO 10
 9    PSIY=PI+(THE1-ICASE*IPATH*THE2)
 10   IF(PSIY.LT.0.) PSIY=PSIY+2.*PI
      IF(PSIY.GT.2.*PI) PSIY=PSIY-2.*PI
      AX=X(7)+X(1)*COS(PHIY+X(9))
      AY=X(8)+X(1)*SIN(PHIY+X(9))
      BX=OBX+X(3)*COS(PSIY+X(9))
      BY=OBY+X(3)*SIN(PSIY+X(9))
```

```
      AM=BX-AX
      AN=BY-AY
      QX=AX+X(5)*AM/X(2)
      QY=AY+X(5)*AN/X(2)
      ALP=ATAN(ABS(AN/AM))
      IF(AM.LT.0.0.AND.AN.GE.0.0)ALP=PI-ALP
      IF(AM.LT.0.0.AND.AN.LT.0.0)ALP=PI+ALP
      IF(AM.GE.0.0.AND.AN.LT.0.0)ALP=2.*PI-ALP
      ALP=ALP-PI/2.+X(10)
C  PX,PY-CO-ORDINATES OF COUPLER POINT
      PX=QX-X(6)*SIN(ALP)
      PY=QY+X(6)*COS(ALP)
      RETURN
      END


      SUBROUTINE TEXT1(NP,ER1M,ER1N,ER2M,ER2N,NTYPE)
      COMMON /GFILE/ IBUF(1)
C  THIS ROUTINE DISPLAYS THE MESSAGES PERTAINING TO THE
C  MECHANISMTYPE, NUMBER OF POSITIONS BEING SYNTHESIZED
C  AND THE MAXIMUM AND MINIMUM ERRORS AND ANGULAR DEVIATIONS
C ----------------------------------------------------------

      CALL SCAL(0.,0.,1023.,1023.)
      CALL APNT(700.,750.,0,-7,1)
      IF(NTYPE.EQ.1) CALL TEXT('CRANK ROCKER')
      IF(NTYPE.EQ.2) CALL TEXT('DOUBLE CRANK')
      IF(NTYPE.EQ.3) CALL TEXT('DOUBLE ROCKER TYPE 3')
      IF(NTYPE.EQ.4) CALL TEXT('DOUBLE ROCKER TYPE 4')
      IF(NTYPE.EQ.5) CALL TEXT('DOUBLE ROCKER TYPE 5')
      IF(NTYPE.EQ.6) CALL TEXT('DOUBLE ROCKER TYPE 6')
      IF(NTYPE.EQ.7) CALL TEXT('DOUBLE ROCKER TYPE 7')
      CALL APNT(690.,700.,0,-7,-1)
      CALL NMBR(50,NP,'I2')
      CALL APNT(740.,700.,0,-7)
      CALL TEXT('SPECIFIED POSITIONS')
      CALL APNT(25.,30.,0,-7)
      CALL TEXT('MAX. ERROR=')
      CALL APNT(200.,30.,0,-7)
```

```
CALL NMBR(51,ER1M,'F5.3')
CALL APNT(25.,5.,0,-7)
CALL TEXT('MIN. ERROR=')
CALL APNT(200.,5.,0,-7)
CALL NMBR(52,ER1N,'F5.3')
CALL APNT(430.,30.,0,-7)
CALL TEXT('MAX. ANGULAR DEVIATION=')
CALL APNT(780.,30.,0,-7)
CALL NMBR(53,ER2M,'F4.2')
CALL APNT(430.,5.,0,-7)
CALL TEXT('MIN. ANGULAR DEVIATION=')
CALL APNT(780.,5.,0,-7)
CALL NMBR(54,ER2N,'F4.2')
CALL APNT(700.,950.)
CALL VECT(50.,0.,0,7,1,4)
CALL APNT(760.,950.,0,-7)
CALL TEXT('DESIRED')
CALL APNT(700.,900.)
CALL VECT(50.,0.,0,7,-1,1)
CALL APNT(760.,900.,0,-7)
CALL TEXT('SYNTHESIZED')
RETURN
END
```

```
      DO 9 I=1,NP
      PHIY=PHY(I)*PI/180.
      IPATH=NPATH(I)
      CALL GSUB(X,ICASE,IPATH,PHIY,QBX,QBY,AX,AY,BX,BY,
     * QX,QY,PX,PY,PSIY,TAU)
      CALL APNT(XD(I),YD(I),0,-7)
      CALL VECT(QBX(I)-XD(I),QBY(I)-YD(I),0,7,1,4)
      CALL APNT(QX,QY,0,-7)
      CALL VECT(PX-QX,PY-QY,0,7,-1,1)
      XN=XD(I)+.05
      YN=YD(I)+.05
      CALL APNT(XN,YN,0,-7)
      CALL NMBR(200+I,I,'I2')
9     CONTINUE
      CALL ESUB
9999  CALL TIME(15*60)
99    CALL TIMR(IE)
      IF(IE.NE.0) GO TO 99
      CALL ERAS(4)
      CALL ERAS(5)
      CALL ERAS(6)
      CALL ERAS(7)
      CALL ERAS(8)
      CALL ERAS(9)
      CALL ERAS(25)
      CALL ERAS(26)
      CALL ERAS(28)
      CALL ERAS(10)
      CALL ERAS(20)
      CALL CMPRS
      CALL CHECK2(3,NN)
      IF(NN.EQ.1) GO TO 666
      STOP
      END
```

```
      SUBROUTINE CHECK1(NH)
C  THIS ROUTINE REQUESTS THE DESIGNER TO SELECT AN OPTION FOR
C  ANALYSIS USING LIGHT PEN AND RETURNS THE TAG OF LIGHT PEN
C  HIT TO GRAPHICS MAIN ROUTINE
C *************************************************************
      COMMON /GFILE/ IBUF(1)
      CALL SCAL(0.,0.,1023.,1023.)
      CALL SUBP(1)
      CALL APNT(100.,850.,0,-7)
      CALL TEXT('SELECT ONE OF THE FOLLOWING OPTIONS FOR ANALYSIS')
      CALL APNT(100.,700.,1,7)
      CALL VECT(50.,0.,1,7)
      CALL APNT(160.,700.,1,-7)
      CALL TEXT('STATIC DISPLAY OF DESIRED AND SYNTHESIZED POSITIONS')
      CALL ESUB
      CALL SUBP(2)
      CALL APNT(100.,500.,1,7)
      CALL VECT(50.,0.,1,7)
      CALL APNT(160.,500.,1,-7)
      CALL TEXT('STATIC DISPLAY OF MECHANISM IN DIFFERENT POSITIONS')
      CALL ESUB
      CALL SUBP(3)
      CALL APNT(100.,300.,1,7)
      CALL VECT(50.,0.,1,7)
      CALL APNT(160.,300.,1,-7)
      CALL TEXT('DYNAMIC MOVING DISPLAY OF MECHANISM WITH COUPLER CURV
     *E')
      CALL ESUB
300   CALL LPEN(MH,NH)
      IF(MH.EQ.0.OR.NH.LT.1.OR.NH.GT.3) GO TO 300
      CALL ERAS(1)
      CALL ERAS(2)
      CALL ERAS(3)
      CALL CMPRS
      RETURN
      END
```

```
      SUBROUTINE CHECK2(II,NA)
C  THIS ROUTINE REQUESTS THE DESIGNER TO SELECT OPTIONS LIKE
C  DIRECTION OF ROTATION OF   CRANK,PARTICULAR PHASE IN
C  DOUBLE-ROCKER MECHANISMS AND RETURNS THE TAG OF LIGHT PEN
C  HIT TO GRAPHICS MAIN ROUTINE
C *************************************************************
      COMMON /GFILE/ IBUF(1)
      CALL SCAL(0.,0.,1023.,1023.)
      CALL SUBP(1)
      CALL APNT(5.,850.,0,-7,1)
      IF(II.EQ.1)CALL TEXT('SELECT THE DIRECTION OF ROTATION OF CRANK')
      IF(II.EQ.2)CALL TEXT('SPECIFY THE PHASE OF DOUBLE ROCKER')
      IF(II.EQ.3)CALL TEXT('WOULD YOU LIKE TO GO BACK TO ANALYSIS')
      CALL APNT(5.,700.,1,-7)
      CALL VECT(40.,0.,1,7)
      CALL APNT(55.,700.,1,-7)
      IF(II.EQ.1)CALL TEXT('COUNTER CLOCKWISE')
      IF(II.EQ.2)CALL TEXT('PHASE1')
      IF(II.EQ.3)CALL TEXT('YES')
      CALL ESUB
      CALL SUBP(2)
      CALL APNT(5.,500.,1,-7)
      CALL VECT(40.,0.,1,7)
      CALL APNT(55.,500.,1,-7)
      IF(II.EQ.1)CALL TEXT('CLOCKWISE')
      IF(II.EQ.2)CALL TEXT('PHASE2')
      IF(II.EQ.3)CALL TEXT('NO')
      CALL ESUB
 301  CALL LPEN(MA,NA)
      IF(MA.EQ.0.OR.NA.LT.1.OR.NA.GT.2) GO TO 301
      CALL ERAS(1)
      CALL ERAS(2)
      CALL CMFRS
      RETURN
      END
```

```
      SUBROUTINE SFAC1(X,XD,YD,ANG,NP,QDX,QDY,XMI,XMA,YMI,YMA)
      DIMENSION X(20),XD(20),YD(20),ANG(20),QDX(20),QDY(20)
C  THIS ROUTINE SCALES THE SCREEN FOR DESIRED AND SYNTHESIZED
C   POSITIONS OF COUPLER LINK
C ****************************************************************
      DO 2 I=1,NP
      QDX(I)=X(6)*SIN(ANG(I))+XD(I)
      QDY(I)=YD(I)-X(6)*COS(ANG(I))
 2    CONTINUE
      XMI=QDX(1)
      XMA=XD(1)
      YMI=QDY(1)
      YMA=YD(1)
      DO 1 I=1,NP
      XMM=AMIN1(XD(I),QDX(I))
      XML=AMAX1(XD(I),QDX(I))
      YMM=AMIN1(YD(I),QDY(I))
      YML=AMAX1(YD(I),QDY(I))
      IF(XMM.LT.XMI) XMI=XMM
      IF(XML.GT.XMA) XMA=XML
      IF(YMM.LT.YMI) YMI=YMM
      IF(YML.GT.YMA) YMA=YML
 1    CONTINUE
      XMI=XMI-.2*ABS(XMI)
      XMA=XMA*1.2
      YMI=YMI-.2*ABS(YMI)
      YMA=YMA*1.2
      IF(XMI.LE.YMI) YMI=XMI
      IF(YMI.LE.XMI) XMI=YMI
      IF(XMA.GE.YMA) YMA=XMA
      IF(YMA.GE.XMA) XMA=YMA
      RETURN
      END
```

```
      SUBROUTINE ALIM(X,XS,EE,ZI)
C  THIS ROUTINE CALCULATES THE LIMITING ANGLES FOR
C  DOUBLE- ROCKER MECHANISMS
C ***************************************************
      DIMENSION XS(4),X(20)
      PI=4.*ATAN(1.)
      CZI=(XS(1)+XS(4)-EE)/(2.*X(1)*X(4))
      IF(CZI.LT.-1.)CZI=-1.
      IF(CZI.GT.1.)CZI=1.
      ZI=ATAN(ABS(SQRT(1.-CZI*CZI)/CZI))
      IF(CZI.LT.0.) ZI=PI-ZI
      RETURN
      END

      SUBROUTINE TYPE(X,NTYPE)
C  THIS ROUTINE FINDS THE TYPE OF MECHANISM FROM THE
C  DIMENSIONS OF THE MECHANISM
C  GRASHOF FOUR-BAR: L+S.LT.P+Q
C  NON GRASHOF FOUR-BAR:L+S.GTP+Q
C ***************************************************
      DIMENSION X(20)
      XL=AMAX1(X(1),X(2),X(3),X(4))
      XM=AMIN1(X(1),X(2),X(3),X(4))
      SUM=X(1)+X(2)+X(3)+X(4)
      IF(2.*(XL+XM).GT.SUM) GO TO 1
      IF(X(2).EQ.XM) NTYPE=3
      IF(X(1).EQ.XM) NTYPE=1
      IF(X(4).EQ.XM) NTYPE=2
      RETURN
1     IF(XL.EQ.X(1)) NTYPE=4
      IF(XL.EQ.X(2)) NTYPE=5
      IF(XL.EQ.X(3)) NTYPE=6
      IF(XL.EQ.X(4)) NTYPE=7
      RETURN
      END
```

```
      SUBROUTINE SFAC(X,XMI,XMA,YMI,YMA)
C  THIS ROUTINE SCALES THE SCREEN CO-ORDINATES DEPENDING
C  UP ON THE DIMENSIONS OF THE MECHANISM
C ****************************************************
      DIMENSION X(20)
      XMI=-X(1)
      IF(X(7).GT.X(1)) XMI=-X(7)
      XMA=X(4)+X(3)
      YMI=-X(1)
      IF(X(8).GT.X(1)) YMI=-X(8)
      IF(X(9).LT.0..AND.(X(4)*COS(X(9))).GT.ABS(YMI))YMI=
     *-X(4)*COS(X(9))
      YMA=X(1)+X(5)+X(6)
      IF(X(10).GT.180.)YMA=X(1)+X(2)
      IF(XMI.LE.YMI) YMI=XMI
      IF(YMI.LE.XMI) XMI=YMI
      IF(XMA.GE.YMA) YMA=XMA
      IF(YMA.GE.XMA) XMA=YMA
      XMI=XMI*1.2
      YMI=YMI*1.2
      XMA=XMA*1.2
      YMA=YMA*1.2
      RETURN
      END

      SUBROUTINE TEXT2
C  THIS ROUTINE DISPLAYS THE TEXT FOR CRANK ANGLE,
C  FOLLOWER ANGLE AND TRANSMISSION ANGLE
C ***********************************************
      COMMON /GFILE/ IBUF(1)
      CALL SCAL(0.,0.,1023.,1023.)
      CALL APNT(680.,200.,0,-7,-1)
      CALL TEXT('CRANK ANGLE       =')
      CALL APNT(680.,150.,0,-7)
      CALL TEXT('FOLLOWER ANGLE    =')
      CALL APNT(680.,100.,0,-7)
      CALL TEXT('TRANSMISSION ANGLE=')
      RETURN
      END
```

```
      SUBROUTINE TEXT3(PHIY,PSIY,TAU,RD)
C  THIS ROUTINE DISPLAYS THE VALUES OF CRANK ANGLE
C   FOLLOWER ANGLE AND TRANSMISSION ANGLE
C *************************************************
      COMMON /GFILE/ IBUF(1)
      PH=PHIY*RD
      PS=PSIY*RD
      TAU=TAU*RD
     /IF(PH.GT.360.) PH=PH-360.
      IF(PH.LT.0.) PH=360.+PH
      CALL SCAL(0.,0.,1023.,1023.)
      CALL APNT(945.,200.,0,-7)
      CALL NMBR(60,PH,'F6.2')
      CALL APNT(945.,150.,0,-7)
      CALL NMBR(61,PS,'F6.2')
      CALL APNT(945.,100.,0,-7)
      CALL NMBR(62,TAU,'F6.2')
      RETURN
      END

      SUBROUTINE LINKPL(AX,AY,BX,BY,X,OBX,OBY,QX,QY,PX,PY)
C   THIS ROUTINE PLOTS THE LINKAGE FROM THE CO-ORDINATES
C       OF ALL THE NODAL POINTS OBTAINED  FROM GSUB.
C  *********************************************************
      DIMENSION X(10)
      COMMON /GFILE/ IBUF(1)
      CALL VECT(AX-X(7),AY-X(8))
      CALL VECT(BX-AX,BY-AY)
      CALL VECT(OBX-BX,OBY-BY)
      CALL APNT(QX-X(7),QY-X(8))
      CALL VECT(PX-QX,PY-QY)
      IF(X(5).GT.X(2).OR.X(5).LT.0.) CALL APNT(QX-X(7),QY-X(8),0,-7)
      IF(X(5).GT.X(2)) CALL VECT(BX-QX,BY-QY)
      IF(X(5).LT.0.) CALL VECT(AX-QX,AY-QY)
      RETURN
      END
```

```
      SUBROUTINE GSUB(X,ICASE,IPATH,PHIY,OBX,OBY,AX,AY,BX,BY
     *,QX,QY,PX,PY,PSIY,TAU)
C  THIS ROUTINE CALCULATES THE CO-ORDINATES OF ALL THE
C  NODAL POINTS IN THE MECHANISM
C ****************************************************
      DIMENSION X(20),XS(4)
      PI=4.*ATAN(1.)
      DO 1 I=1,4
 1    XS(I)=X(I)*X(I)
      PHI=AMOD(PHIY,2.*PI)
C  PHIY-CRANK ANGLE
      IF(PHIY.GT.PI.AND.PHIY.LT.2.*PI) PHI=2.*PI-PHIY
      IF(PHIY.LT.(-PI).AND.PHIY.GT.(-2.*PI))PHI=PHIY+2.*PI
      IF(PHIY.LT.0..AND.PHIY.GT.(-PI))PHI=-PHIY
      EE=XS(1)+XS(4)-2.*X(1)*X(4)*COS(PHI)
      E=SQRT(EE)
      CTAU=(XS(2)+XS(3)-EE)/(2.*X(2)*X(3))
      IF(ABS(CTAU).GT.1.) CTAU=1.
C  TAU-TRANSMISSION ANGLE
      TAU=ATAN(SQRT(1.-CTAU*CTAU)/ABS(CTAU))
      ST1=X(1)*SIN(PHI)/E
      THE1=ATAN(ABS(ST1/SQRT(1.-ST1*ST1)))
      IF(XS(1).GT.(XS(4)+EE)) THE1=PI-THE1
      CT2=(EE+XS(3)-XS(2))/(2.*X(3)*E)
      IF(ABS(CT2).GT.1.) CT2=1.
      THE2=ATAN(ABS(SQRT(1.-CT2*CT2)/CT2))
      IF(CT2.LT.0.) THE2=PI-THE2
      IF(PHIY.LT.0..AND.PHIY.GT.(-PI)) GO TO 9
      IF(PHIY.GT.PI.AND.PHIY.LT.2.*PI) GO TO 9
C  PSIY-FOLLOWER ANGLE
      PSIY=PI-(THE1+ICASE*IPATH*THE2)
      GO TO 10
 9    PSIY=PI+(THE1-ICASE*IPATH*THE2)
 10   IF(PSIY.LT.0.) PSIY=PSIY+2.*PI
      IF(PSIY.GT.2.*PI) PSIY=PSIY-2.*PI
      AX=X(7)+X(1)*COS(PHIY+X(9))
      AY=X(8)+X(1)*SIN(PHIY+X(9))
      BX=OBX+X(3)*COS(PSIY+X(9))
      BY=OBY+X(3)*SIN(PSIY+X(9))
```

```
      AM=BX-AX
      AN=BY-AY
      QX=AX+X(5)*AM/X(2)
      QY=AY+X(5)*AN/X(3)
      ALP=ATAN(ABS(AN/AM))
      IF(AM.LT.0.0.AND.AN.GE.0.0)ALP=PI-ALP
      IF(AM.LT.0.0.AND.AN.LT.0.0)ALP=PI+ALP
      IF(AM.GE.0.0.AND.AN.LT.0.0)ALP=2.*PI-ALP
      ALP=ALP-PI/2.+X(10)
C  PX,PY-CO-ORDINATES OF COUPLER POINT
      PX=QX-X(6)*SIN(ALP)
      PY=QY+X(6)*COS(ALP)
      RETURN
      END

      SUBROUTINE TEXT1(NP,ER1M,ER1N,ER2M,ER2N,NTYPE)
      COMMON /GFILE/ IBUF(1)
C  THIS ROUTINE DISPLAYS THE MESSAGES PERTAINING TO THE
C  MECHANISMTYPE, NUMBER OF POSITIONS BEING SYNTHESIZED
C  AND THE MAXIMUM AND MINIMUM ERRORS AND ANGULAR DEVIATIONS
C ----------------------------------------------------------------

      CALL SCAL(0.,0.,1023.,1023.)
      CALL APNT(700.,750.,0,-7,1)
      IF(NTYPE.EQ.1) CALL TEXT('CRANK ROCKER')
      IF(NTYPE.EQ.2) CALL TEXT('DOUBLE CRANK')
      IF(NTYPE.EQ.3) CALL TEXT('DOUBLE ROCKER TYPE 3')
      IF(NTYPE.EQ.4) CALL TEXT('DOUBLE ROCKER TYPE 4')
      IF(NTYPE.EQ.5) CALL TEXT('DOUBLE ROCKER TYPE 5')
      IF(NTYPE.EQ.6) CALL TEXT('DOUBLE ROCKER TYPE 6')
      IF(NTYPE.EQ.7) CALL TEXT('DOUBLE ROCKER TYPE 7')
      CALL APNT(690.,700.,0,-7,-1)
      CALL NMBR(50,NP,'I2')
      CALL APNT(740.,700.,0,-7)
      CALL TEXT('SPECIFIED POSITIONS')
      CALL APNT(25.,30.,0,-7)
      CALL TEXT('MAX. ERROR=')
      CALL APNT(200.,30.,0,-7)
```

```
CALL NMBR(51,ER1M,'F5.3')
CALL APNT(25.,5.,0,-7)
CALL TEXT('MIN. ERROR=')
CALL APNT(200.,5.,0,-7)
CALL NMBR(52,ER1N,'F5.3')
CALL APNT(430.,30.,0,-7)
CALL TEXT('MAX. ANGULAR DEVIATION=')
CALL APNT(780.,30.,0,-7)
CALL NMBR(53,ER2M,'F4.2')
CALL APNT(430.,5.,0,-7)
CALL TEXT('MIN. ANGULAR DEVIATION=')
CALL APNT(780.,5.,0,-7)
CALL NMBR(54,ER2N,'F4.2')
CALL APNT(700.,950.)
CALL VECT(50.,0.,0,7,1,4)
CALL APNT(760.,950.,0,-7)
CALL TEXT('DESIRED')
CALL APNT(700.,900.)
CALL VECT(50.,0.,0,7,-1,1)
CALL APNT(760.,900.,0,-7)
CALL TEXT('SYNTHESIZED')
RETURN
END
```