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Synthesis and analysis of variable, non-uniform stroke piston engine mechanisms

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Abstract

The 4-stroke piston engines powering nearly all automobiles in operation today use a mechanism and thermodynamic cycle identical to the Otto engine designed over a century ago. The basic Otto thermodynamic cycle includes intake, compression, power, and exhaust strokes. The cycle is accomplished using a four link, slider-crank mechanism which consists of an engine block, crank shaft, connecting rod, and piston. This mechanism produces a nearly sinusoidal piston trajectory in which all stokes are identical in length and timing. Power is typically varied by throttling the air as it is drawn into the engine. While this cycle and mechanism have proven to be an efficient and practical way to produce power, it is inconceivable that the first internal combustion engine mechanism is the best possible mechanism for doing so.

Two methods for improving piston engine efficiency that are under study are non-uniform stroke engines and variable stroke engines [1,2,4,5,8]. A non-uniform piston trajectory consists of four strokes, which differ in length both spatially and temporally. The basic shape of the trajectory is short intake and compression strokes followed by longer power and exhaust strokes. This cycle allows more energy to be extracted from the burned fuel and yields greater efficiency. Variable stroke engines allow the operator to vary the stroke length and thus the displacement in order to control power output. This approach promises to be much more efficient then the conventional throttling technique for controlling power.

The above engine configurations have both been realized using a number of different mechanisms. This thesis presents an approach to combine non-uniform and variable stroke mechanisms into single mechanisms that generate a variable, non-uniform piston trajectory. Graph theory and mechanism synthesis are used successfully to conceptualize mechanisms with desirable performance characteristics such as nearly constant compression ratio over the variable range and efficient power transfer from the piston to the crank shaft. Six mechanisms with acceptable piston trajectories and performance characteristics are synthesized and analyzed extensively. This analysis indicates that all six mechanisms are adequate candidates for further development toward a working internal combustion engine with variable, non-uniform stroke characteristics.

Chapter 1: Introduction

The two methods of improving internal combustion engine efficiency presented in this thesis are variable stroke piston trajectory and non-uniform stroke piston trajectory. Both methods have been explored individually in previous studies[1,2,4,5,8]. This thesis will show that both techniques can be employed in a single engine mechanism that takes full advantage of both types of mechanisms.

Non-uniform stroke piston trajectory implies that the piston trajectory will be non-uniform within a single four stroke cycle. An optimum trajectory will be sought that will extract the maximum amount of energy from the burned fuel and convert it into mechanical shaft work. This optimum trajectory will not necessarily be composed of nearly sinusoidal curves that the slider crank mechanism produces, but will consist of a more general curve where the intake, compression, power, and exhaust strokes are not all necessarily the same length, either spatially or temporally.

Variable stroke piston trajectory implies that the length of the stroke will be varied by the engine operator in order to vary the power. An equally descriptive name is variable displacement since the engines displacement will change as the stroke length changes. When full power is needed, maximum stroke length and displacement will be used. When less power is needed, stroke length will be decreased to the amount required to produce the needed power, thus minimizing fuel consumption.

Many mechanism have been explored that can produce both non-uniform and variable piston trajectories. A detailed investigation has been carried out in order to reveal all possible mechanisms that can perform both of these tasks with a single mechanism. The most promising mechanisms have been realized and analyzed.

Chapter 2: Non-Uniform Stroke Piston Trajectory Benefits

Approximately one third of the energy released when an engine burns fuel is lost as the exhaust gas leaves the engine. An optimized non-uniform stroke piston trajectory allows more energy to be extracted from this hot exhaust gas. Non-uniform stroke piston trajectories have been developed using models containing thermodynamic, fluid mechanics, and heat transfer effects[1]. These optimizations are typically performed for a given engine rpm as they generally vary as a function of engine speed. While this method allows sub-optimum trajectories at other engine speeds, the resulting performance may still exceed conventional engines over the entire operating range.

2.1 Thermodynamic power cycle

In a typical internal combustion engine, the exhaust is still at relatively high temperature and pressure when the piston reaches bottom dead center after the power stroke. However, in order for a power cycle to work, the thermodynamic state of the working fluid must be returned to the initial state, and therefore the exhaust gas must be expelled and replaced with fresh intake mixture.

A longer stroke length may seem like the answer to removing a higher percentage of the energy from the burned mixture. With a conventional engine, this would mean that along with a longer power stroke for extracting more energy, the intake stroke would also be longer, drawing more mixture and thus more energy into the engine producing no net gain in efficiency. An obvious solution is too make the power stroke longer then the compression stroke. This solution is impossible to implement with a standard slider crank engine mechanism. However, more complicated mechanisms will be discussed that make much more general piston trajectories possible.

The net gain in power caused by increasing the power stroke length can be seen graphically on a typical P-V diagram shown in Figure 1. Recall that the area inside a P-V diagram is equal to the work produced by the cycle. The shaded area represents the increase in power gained by expanding the gas beyond the conventional bottom dead center (BDC) position to the non-uniform BDC position.

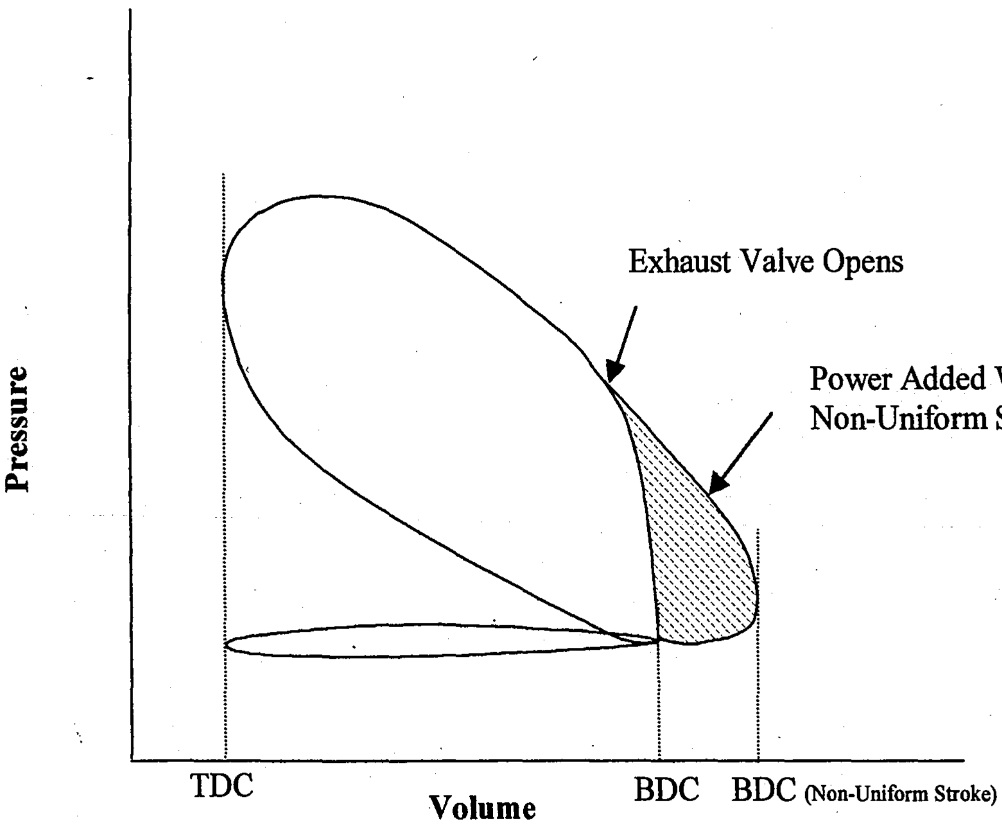


Figure 1: PV Diagram for an Internal Combustion Engine

Note the sudden drop in pressure when the exhaust valve opens. This considerable amount of pressure and energy is wasted because the power stroke is the same length as the compression stroke. By waiting to open the exhaust valve until the volume expands to the larger BDC, more energy is extracted from the fuel.

2.2 Optimized Piston Trajectory

It is clear from the P-V diagram that the exhaust stroke should be longer then the compression stroke. Just how much longer, as well as other details pertaining to the piston trajectory such as time duration of the four strokes is certainly not obvious from the diagram. An optimization analysis has been carried out by Benson[1]. He takes into account factors such as heat transfer coefficients, piston friction, and energy released during the combustion process. Benson's code simulates spark ignition, flame front propagation, and chemical kinetics of the combustion process. The end result of this optimization is a graph of piston position vs. time
that is the optimum piston trajectory for extracting the most possible energy out of the fuel/air mixture.

Note that because combustion, heat transfer, and fluid mechanics are all time dependent processes, the optimum piston trajectory will be unique for any given engine speed. Figure 2 shows Benson's plot of optimum piston trajectory for three different crank speeds. The plot also shows the piston trajectory of a conventional, slider crank mechanism, engine.

In order to fully take advantage of optimum piston trajectory benefits, an engine would have to not only possess non-uniform piston motion within each cycle, but that motion must be variable for different engine speeds. Often designers of non-uniform stroke engines have chosen to simply chose an optimum piston trajectory at an average

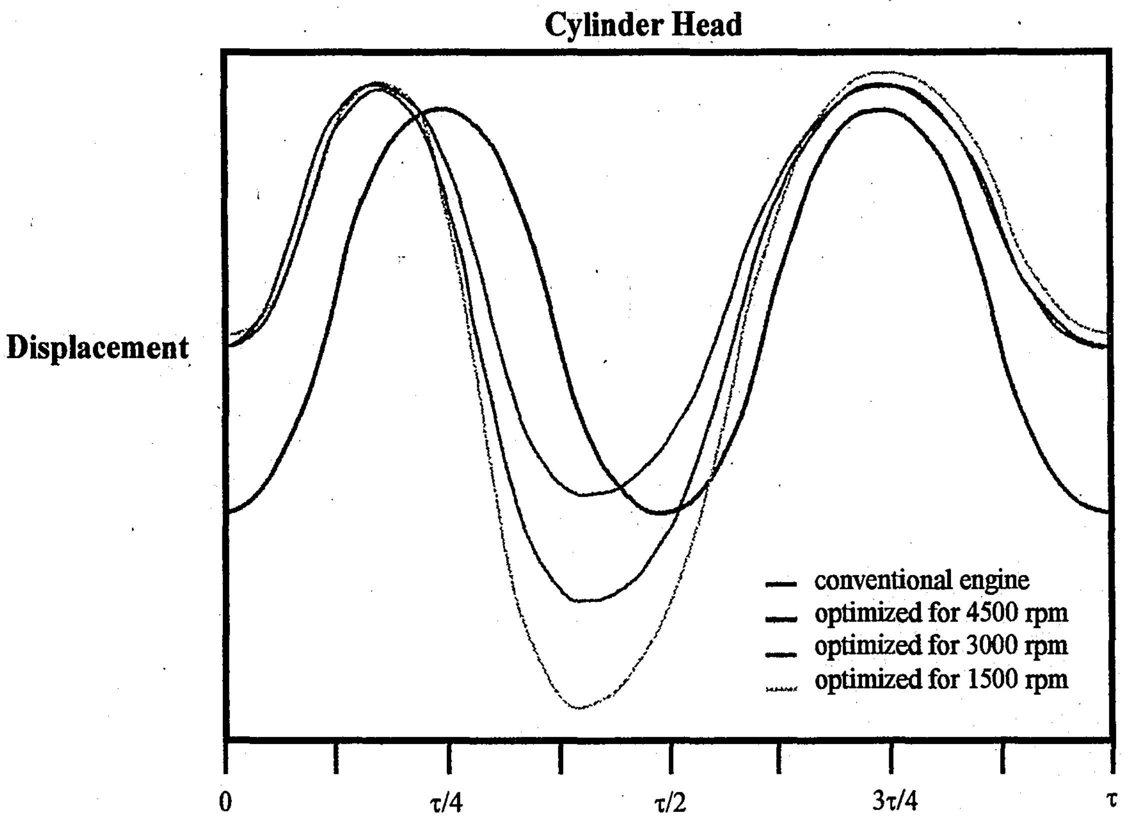


Figure 2: Optimized Piston Trajectories for Different Engine Speeds

engine speed and use that as a design goal for their mechanism's piston trajectory. While not fully optimal, this type of non-uniform fixed stroke engine will have significantly higher efficiencies then a conventional engine.

Chapter 3: Variable Stroke Piston Trajectory Benefits

Because variable stroke engines stroke, displacement, and thus fuel consumption are fully controllable by the operator, they offer the efficiency of small displacement engines as well as the power of large displacement engines. They also operate very efficiently regardless of load since there is no need to throttle the air entering the engine and thus flow restrictions are minimized.

3.1 Problems with Throttling

In order to control the power output of a conventional engine, a throttle plate is placed inline with the air flow to the intake. If the less power is desired, the flow is throttled, diminishing the supply of air to the engine and decreasing the power output. This method, while simple to incorporate, causes loss in efficiency, because the air must be drawn past a constricting throttle plate before it enters the cylinder. This is especially wasteful in automotive applications where the engine spends the vast majority of its life throttled at low power.

Typical highway travel at 55mph requires only approximately 15 horsepower. This may be only ten percent of an engine's maximum power which is needed for accelerating. A more efficient means to vary the power output of an engine is to vary the stroke length, thus varying the engines displacement.

3.2 Advantages of Variable Displacement

A variable stroke engine would operate at a very small stroke length when little power is needed. It would do so unthrottled and thus very efficiently. When more power is needed, the engine would operate at a longer stroke length increasing the volume of fuel/air mix burned with each stroke and increasing the power output. An example of a variable stroke engine's piston trajectory at low, medium, and high power is shown in Figure 3.

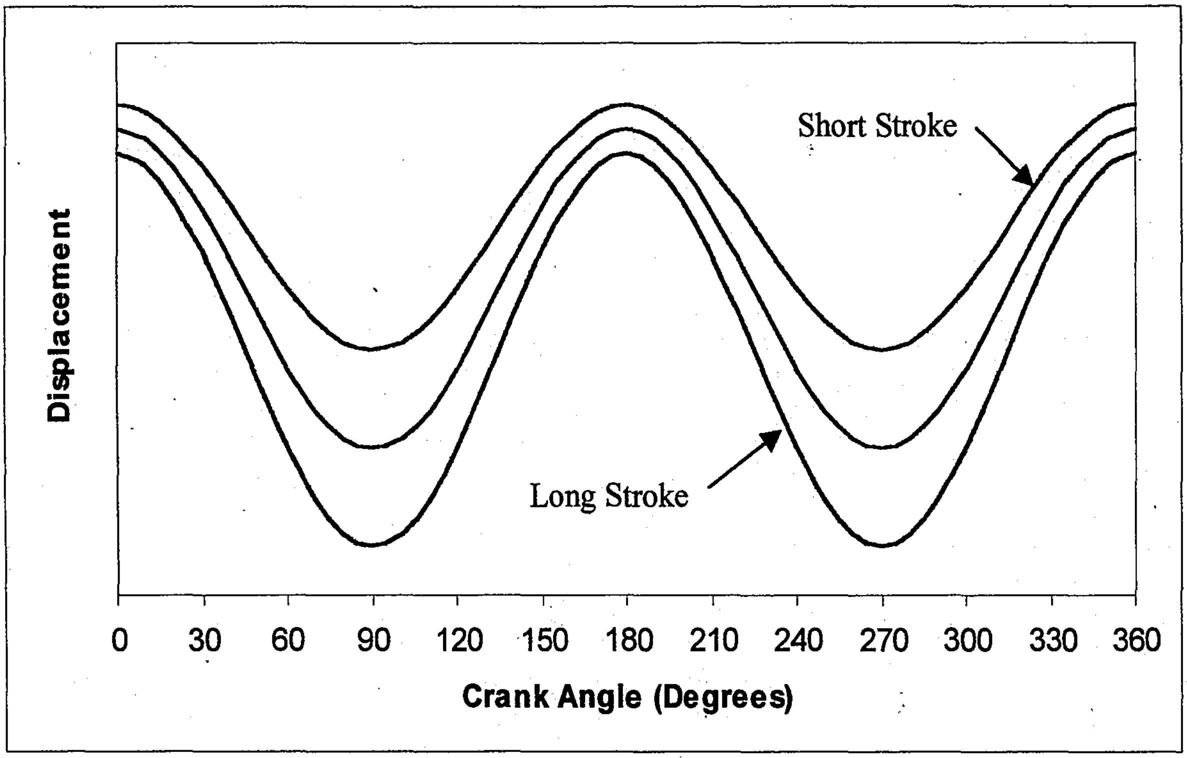


Figure 3: Variable Stroke Piston Trajectories

In order for a variable stroke engine mechanism to work effectively, not only must the mechanism vary the stroke length, but a constant, or nearly constant compression ratio must be maintained. This means that as the BDC position of the piston becomes lower on the cylinder wall, the TDC position must also become lower. Note this detail of the piston trajectories in Figure 3. The need to maintain a constant compression ratio will necessitate a relatively complicated mechanism. Any type of variable crank throw would simply not allow for a constant compression ratio.

A variable stroke engine is truly the best of both worlds. A conventional engine designer will argue that the best way to decrease the fuel consumption of an engine is to decrease the displacement of the engine. This accounts for the trend of decreasing engine size in the automotive industry as government regulations call for more efficient engines. A variable stroke engine does precisely that, decreases the displacement of the engine when high power is not needed. Furthermore, the best way to increase the power of an engine is to increase the displacement. While turbo-charged and multi-valve engines do have increased power for small engines, they do not have the low end torque nor as broad a torque band as larger engines. Simply put, there's no replacement for displacement when maximum torque and power is the goal.

Chapter 4: Graph Theory and Mechanism Synthesis

The complicated types of piston trajectories described in the preceding two chapters can obviously not be accomplished with a standard slider crank mechanism. More complicated mechanisms with more links, more types of joints, and even multiple degrees of freedom are needed to accomplish the desired piston motions. Two techniques will be used for developing the desired mechanisms, graph theory and mechanism synthesis. Graph theory is utilized for initial mechanism selection and combining mechanisms while mechanism synthesis is utilized for determining specific link lengths as well as gear ratios and gear shapes.

4.1 Graph Theory

Graph theory is a technique for representing mechanisms in a very clear, unique, and distinguishable way based on the mechanisms structure and the connectivity of its links[4]. Graphs are very helpful with distinguishing between two mechanisms that may look similarly but have different connectivity. They are also useful in determining when two mechanisms have identical connectivity even though they look differently.

The graph of a mechanism is drawn by first marking a dot for every link in the mechanism. The dots are typically arranged in a closed geometric shape such as a square, rectangle or octagon. Next the dots are connected with lines in the same arrangement as the mechanisms links are connected with joints. Each line between two dots represents a joint between two links. The lines are usually labeled to identify the type of joint, R for revolute joint, P for prismatic joint, G for gear joint, and so forth.

Figure 4 shows a schematic of a variable stroke engine mechanism above with its representative graph below.

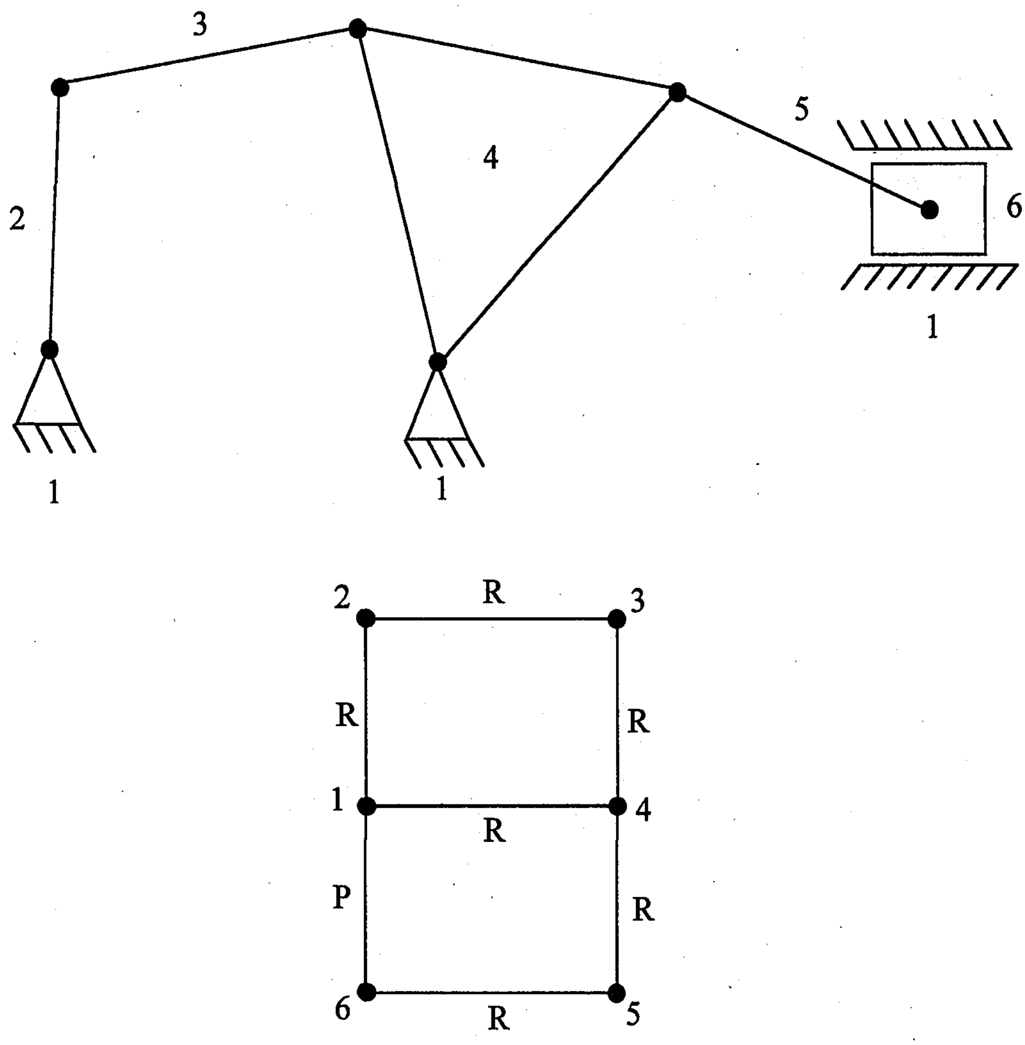


Figure 4: Six-Link Variable Stroke Engine Mechanism and Graph

The graph in Figure 4 portrays the mechanism in a very simple way that represents the mechanisms structure without displaying any information about the link lengths or shapes. This form of representation make classifying and identifying mechanisms much easier then looking at schematics. By using graphs, an engineer does not have to bother with drawing out how a mechanism looks in the early conceptual stage of design. Simply by sketching the graph, much can be learned about the mechanism without bothering with the details and complications that the actual physical mechanisms entails.

In order to utilize the full power of graph theory, the engineer does not just sketch the graphs for mechanisms he thinks might work for the application, he enumerates ALL the possible graphs of a given complexity. A certain complexity is chosen for the mechanism based on constraints such as limiting the number of links in the mechanism to 6, limiting the joint types to revolute, prismatic, and gear joints, limiting the link types to binary, tertiary, and quaternary, and limiting the search to single degree of freedom (dof) mechanisms. Next all possible graphs of the chosen complexity can be generated (or look up in a mechanism atlas). They may number from a few dozen to a few thousand or more. In order to generate all the graphs, the designer uses Grubler's equation of mobility shown below.

$$f = 3(n-1) - 2j1 - j2$$

Equation 1

where
f = number of degrees of freedom
n = number of links
j1 = number of 1 dof joints
j2 = number of 2 dof joints

Using Grubler's equation along with the other constraints, all mechanisms that fit the constraints can be enumerated. Figure 5 shows an example of the enumeration off all 6 bar mechanisms with a single degree of freedom and binary, tertiary, and quaternary links. Joint type has not been considered in this enumeration.

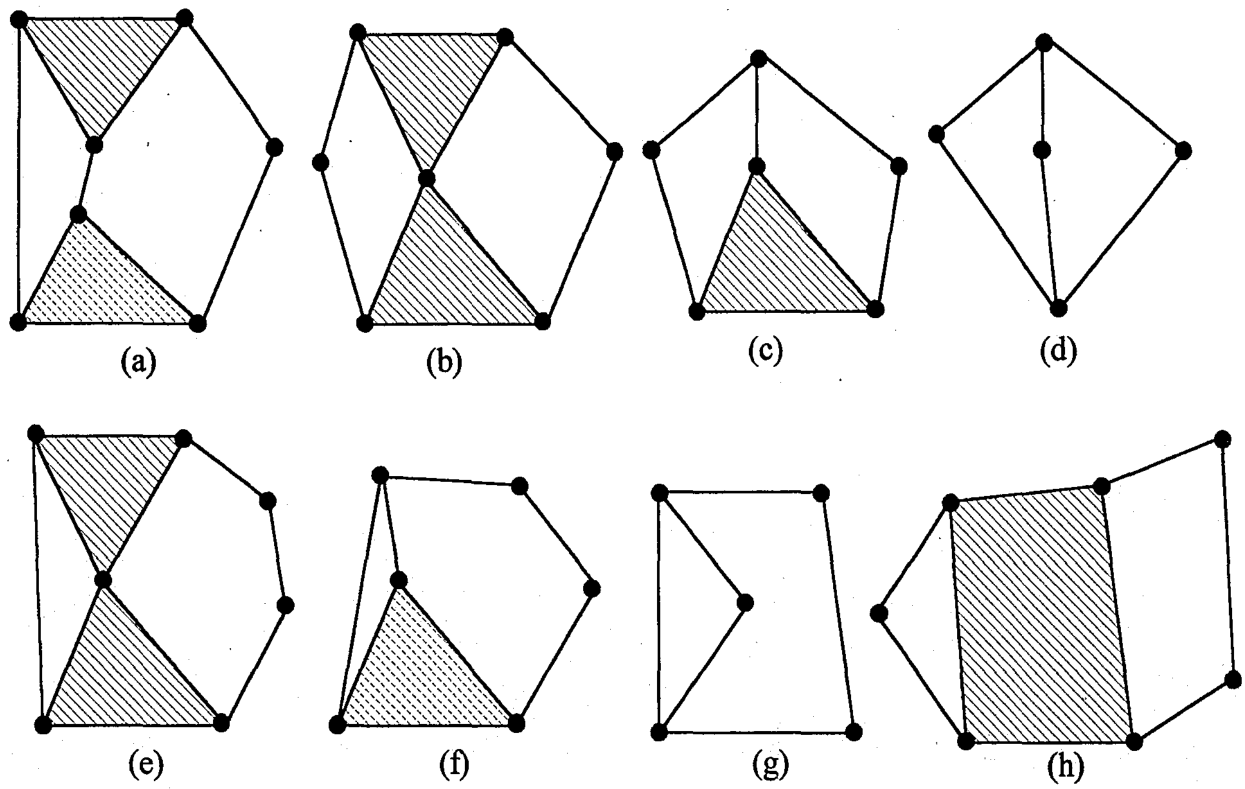


Figure 5: Six-Bar Kinematic Chains

Once all the desired mechanisms have been enumerated, the next step is to "weed out" the mechanisms which are not practical for the application. A set of rules is developed which will be applied to the enumerated graphs. The rules pertain to the connectivity of the mechanism and should be written in such a way that each graph can be accepted, rejected, or ranked in order of how well it is likely to perform the chosen task. This process is discussed in more detail with an example in the following chapter.

Once the graphs have been weeded down to a reasonable number of only the most promising mechanisms, the schematics are sketched and further analysis is performed to determine which will be chosen for the final design. By using graphs, many more mechanisms have been considered then would have been, had another conceptualizing method, such as brainstorming been used. This helps to insure that the best possible mechanism for the job will be chosen.

4.2 Mechanism Synthesis

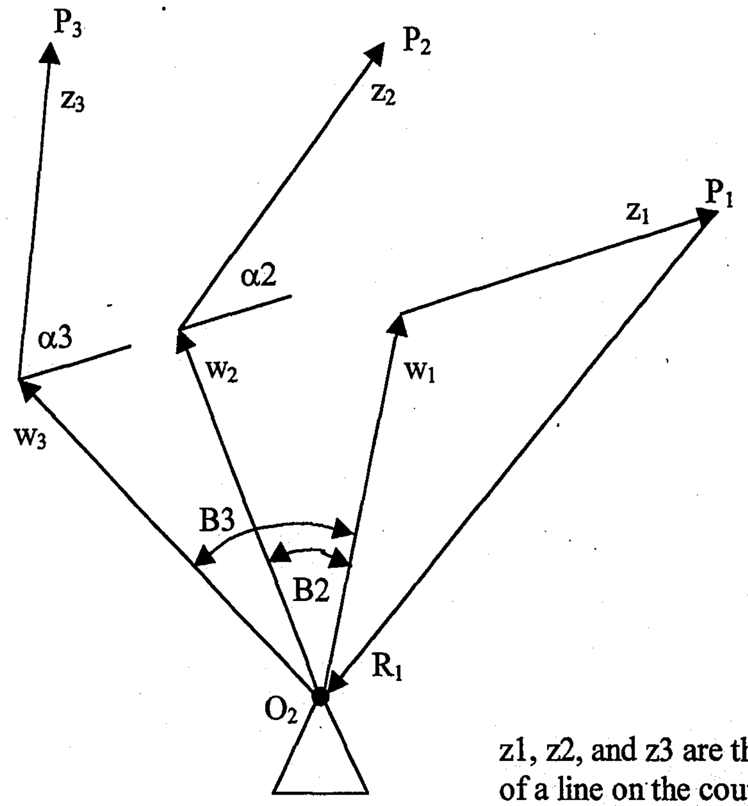
Once a promising mechanism has been chosen from the conceptualization stage of design, the actual link geometry must be determined. Knowing the desired output, in this case the desired piston trajectory, it is the engineers task to determine the linkage geometry the will provide that output. This task is referred to as mechanism synthesis and is typically accomplished by one of three methods, analytic synthesis, graphical synthesis, or by using a mechanism almanac.

4.2.1 Analytic Mechanism Synthesis

Figure 6 shows the setup for an analytic position synthesis problem[6]. The first step is to draw the link which is to have the desired output motion in a number of desired positions. Typically a coupler link is chosen for the output since it provides the most general motion Depending on the required accuracy of the output motion, anywhere from 2 to 5 positions can be used to acquire a valid solution. The vectors z1, z2, and z3 represent three positions of the coupler in Figure 6. Next the rest of the links of the mechanism are drawn with general dimensions. (Since the actual dimensions are unknown and are to be determined) Vectors are now drawn from an arbitrary ground pivot, along the other links, and along the coupler vectors. Figure 6 shows these vectors drawn for one of the unknown links and ground pivot. The other link and ground pivot would be drawn similarly. The vectors are represented with complex number notation such as $R1e^{i\theta}$. Complex vector loop equations are now written and set equal to zero since the loop ends where it started.

Depending on the number of positions required, some of the unknown link rotation angles may be arbitrary and can thus be chosen indiscriminately. The non-linear loop equations must typically be solved numerically for the remaining unknowns. The solution will indicate the remaining link lengths and the fixed pivot positions.

This position synthesis technique is often referred to as motion generation because the mechanisms synthesized will generate a motion that will take the coupler through the specified positions. This type of synthesis is useful for developing a 4 bar mechanism that must produce a specific piston trajectory.



z1, z2, and z3 are three given positions of a line on the coupler link.

w1, w2, and w3 are the associated positions of the grounded crank link

R1, R2, and R3 are the vectors denoting the position of the ground pivot for the crank link

Note: R2 and R3 are not drawn for simplicity

Vector Loop Equations

$w1 + z1 + R1 = 0$

$w2 + z2 + R2 = 0$

$w3 + z3 = R3 = 0$

Vectors written as functions of given angles

$w1 + z1 + R1 = 0$

$we^{iB2} + ze^{i\alpha 2} + R2 = 0$

$we^{i\alpha 3} + ze^{i\alpha 3} + R3 = 0$

Figure 6: Analytic Synthesis Using 3 Specified Positions

4.2.2 Graphical Mechanism Synthesis

Graphical synthesis techniques are somewhat less powerful then analytic synthesis techniques. If something needs to be changed, it is not a simple matter of changing a constant and running through the equations again, the entire problem may have to be redone using a graphical technique. Furthermore, graphical synthesis is generally not as precise as analytic techniques, although with the use of CAD systems they can be made virtually as accurate as necessary. One advantage of graphical synthesis is speed. They can often provide a "quick and dirty" solution which can be very useful as a check for a more sophisticated analytical solution. Often a graphical solution is all that is needed if the problem is well defined. Another advantage of graphical techniques is that they maintain touch with physical reality instead of turning the problem into less meaningful equations. They provide the engineer with a high degree of understanding of the problem and solution.

Figure 7 shows an example of a graphical solution to a problem with three prescribed positions[6]. The problem is to move the box with pivots labeled A and B through the prescribed positions. The basic technique for solving this problem graphically involves first drawing lines connecting the desired pivot points in each of the prescribed positions (blue lines). Next midnormals are drawn and their intersections found (gray lines). The intersections of the midnormals becomes the ground pivots. Finally the actual links can be drawn between the coupler pivots and the ground pivots (red lines).

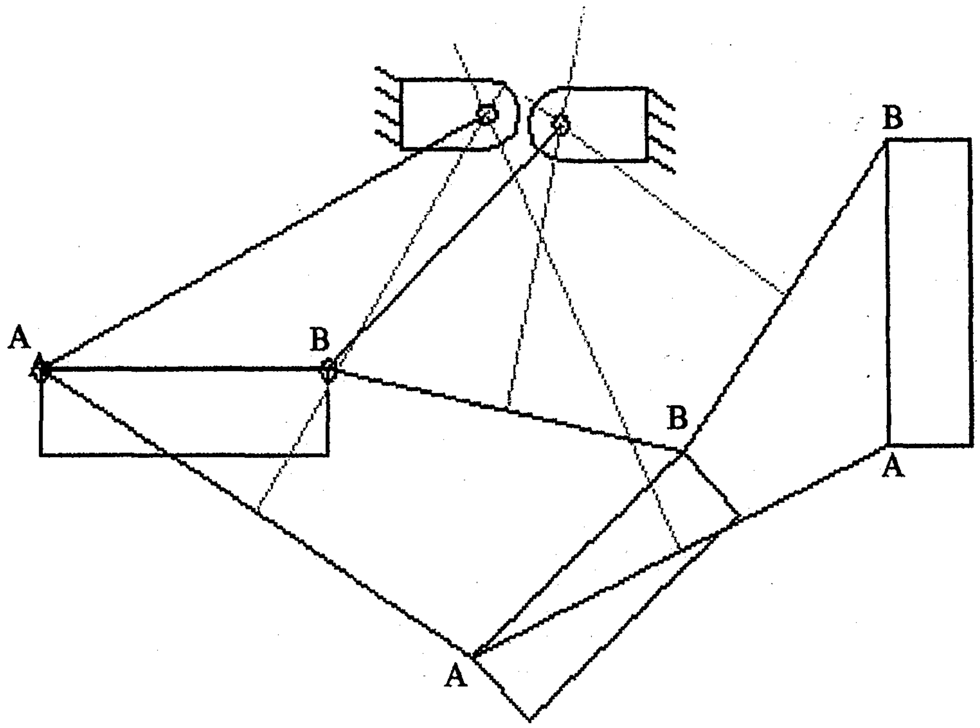


Figure 7: Graphical 3 Position Synthesis

4.3.2 Mechanism Almanacs

A mechanism almanac is a book of mechanisms that shows the motion of various points on each mechanism[7]. Typically multiple coupler curves, representing multiple coupler points, are drawn for a each mechanism. Mechanism almanacs are usually organized in a logical sequence with each mechanism being slightly different from the preceding one. By flipping through a mechanism almanac, an engineer can find a motion path that is similar to his requirements. Often interpolation between coupler points or link lengths is helpful to make the mechanism's motion more closely match the requirements.

This method of finding a mechanism that will produce a required motion is typically the easiest type of synthesis. It is simply using available analysis results in reverse. This is very efficient since it uses work that has already been done rather then "re-inventing the wheel"

Chapter 5: Non-Uniform Stroke Mechanisms

A number of non-uniform stroke mechanisms have been developed in previous studies. Three types in particular will be considered for use as sub mechanisms in variable non-uniform stroke engines. In addition, in order to be sure that the best possible mechanism for the job is chosen, a mechanism search using graph theory has been carried out in order to realize all possible mechanisms that might produce a non-uniform stroke piston trajectory.

5.1 Synthesis of Non-Uniform Stroke Mechanisms

In order to use graph theory to enumerate possible choices for non-uniform stroke mechanisms, a list of constraints must first be chosen. The constraints used for this enumeration is shown in Table 1

	Constraints
1	Limit the number of degrees of freedom to 1
2	Limit # of links to 6
3	Limit joint types to revolute prismatic
4	Limit the number or prismatic joints to 2

Table 1: Constraints for Non-Uniform Stroke Mechanisms

These constraints were chosen so that the mechanisms will be complicated enough to produce the desired trajectory, yet not overly complicated with multiple degrees of freedom or complicated joints. There are 16 graphs that fit the above constraints. They can either be created or looked up in a graph atlas. Figure 8 shows examples of just 8 of the graphs and associated mechanisms.

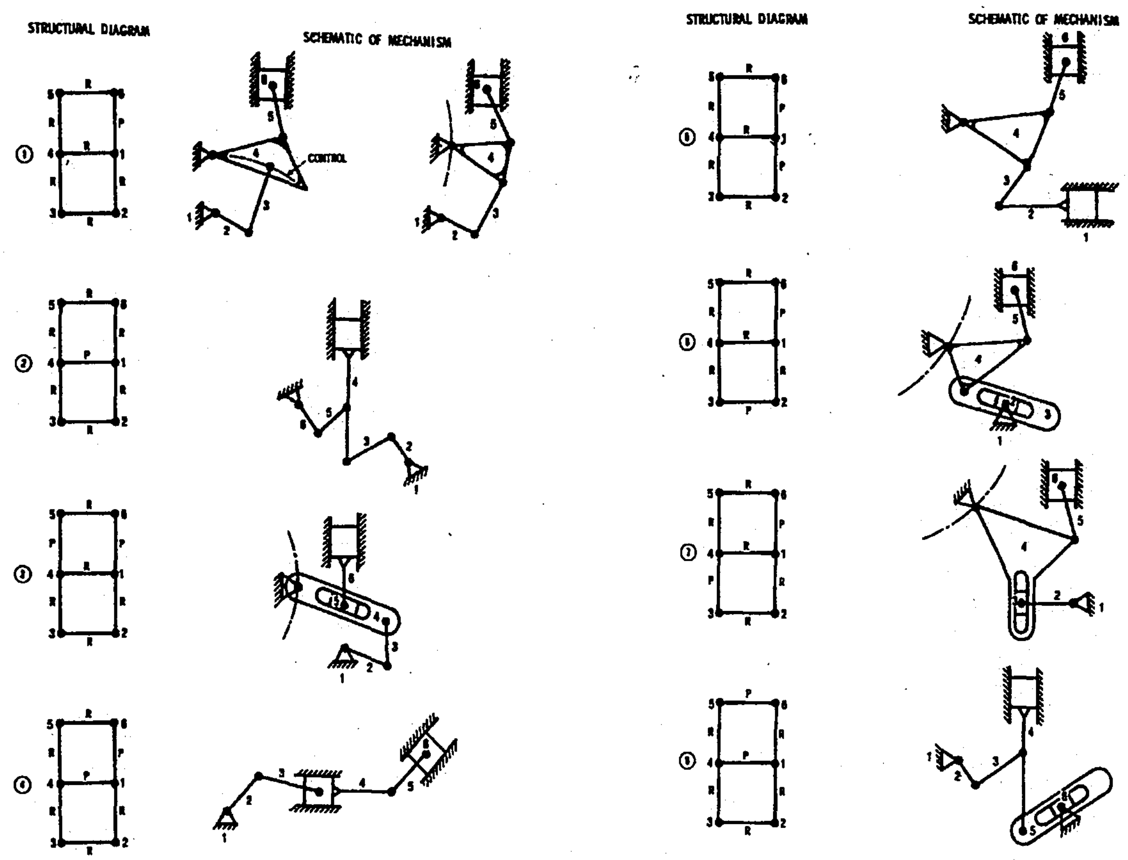


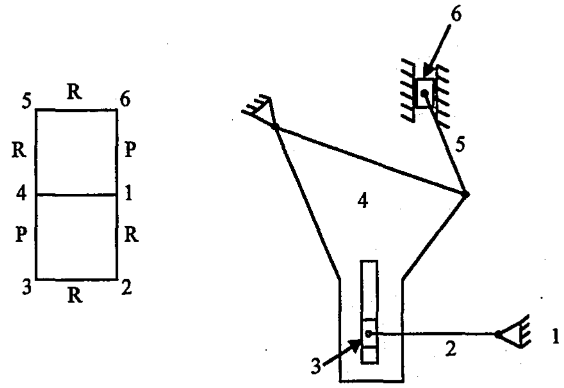
Figure 8: Graphs and Schematics of Possible Non-Uniform Stroke Mechanisms

The 16 mechanisms can be weeded down further by developing heuristic rules based on the connectivity of the graphs and knowledge of what features are important for a non-uniform stroke engine. In order to make the rules easier to apply to the mechanism, it is often useful to go through an identification process where the links are identified in order to better evaluate the mechanism. These identification rules as well as the heuristic rules are shown in Table 2

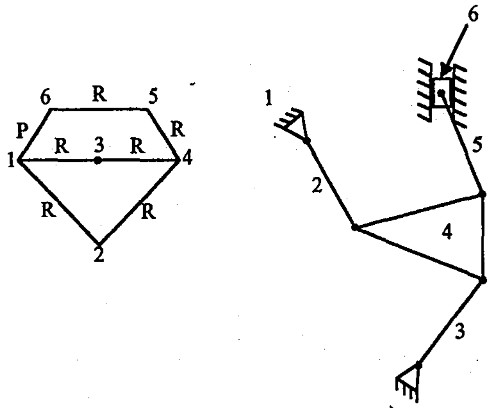
	Identification Rules
1	Link 1 to be the fixed link or Ground
2	A link connected to Ground and only 1 other link by a revolute joints is called the Crank
3	A link connected to Ground with a prismatic joint is called the Piston
4	A link connected to the Piston with a revolute joint is called the Connecting Rod
5	A link connected to Ground, Connecting Rod and another link with a revolute is called the Rocker
6	Any link not fitting under the above rules is called a Connecting Link
7	A loop in a graph that contains Ground and the Crank is the Drive loop
8	A loop in a graph that contains Ground and the Piston is the Output loop
	Heuristic Rules
1	No sliding pairs may exist in the Drive loop to avoid sliding in this high speed loop
2	Connecting Rod must be binary to avoid piston side thrust
3	Crank must be binary to avoid complicated cranks and piston side thrust
4	Piston must be binary to avoid piston side thrust
5	Crank must not be directly attached to the Connecting Rod or non-uniform stroke trajectory would not be possible
6	The Connecting Rod must be joined to a coupler link for the "Double Hump" motion to be possible

Table 2: Heuristic Rules for Non-Uniform Stroke Mechanisms

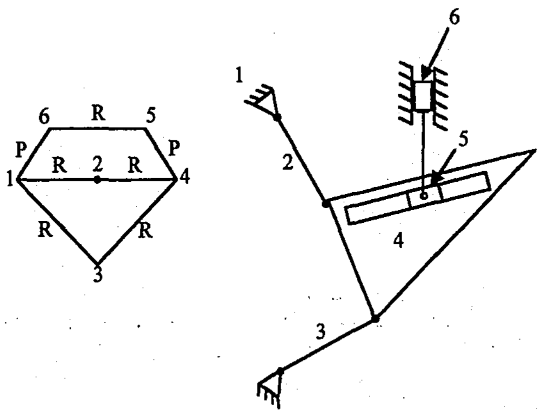
After applying the above rules to the sixteen mechanism graphs, only four graphs are found to be compliant with the rules. These four graphs and schematics are shown in Figure 9. Now that the group of possible mechanisms is down to a manageable number, analysis can be performed on the remaining four mechanisms. After performing basic mechanism analysis on all four, it is determined that only one of them, mechanism 9, will produce a double hump piston trajectory. Mechanism 9 is an Atkinson Cycle linkage which is one of the three original non-uniform stroke mechanisms researched from previous studies. These three mechanisms will now be discussed in more detail.



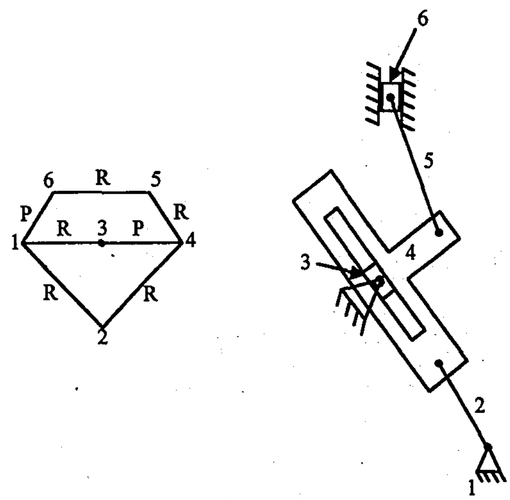
Mechanism #7



Mechanism #9



Mechanism #15



Mechanism #16

Figure 9: Strong Candidates for a Variable Non-Uniform Stroke Mechanism

5.2 Atkinson Cycle Linkage

The Atkinson Cycle linkage is a Stephenson III 6-bar mechanism shown in Figure 10. The linkage consists of a 4-bar crank-rocker mechanism with a connecting rod and piston attached to the coupler of the 4-bar. In order for the piston to move according to the desired double hump piston trajectory, the coupler curve traced by the joint where the connecting rod meets the coupler must be a lamniscate. A lamniscate curve is shaped like a eight and must lie approximately perpendicular to the connecting rod. Each "hump" of the lamniscate will correspond to a stroke for the piston. Two humps per cycle will cause a double hump piston trajectory. The angle of the connecting rod relative to the lamniscate will dictate the relative size of each hump. This is the primary way the shape of the piston trajectory is controlled.

5.2.1 Synthesizing a Lamniscate

In order to make the coupler point of the Atkinson linkage trace out a lamniscate, some form of mechanism synthesis must be employed. Analytic synthesis has been done in previous studies in order to make the piston follow the optimized trajectory as closely as possible. Because this thesis is first attempting to combine non-uniform and variable stroke mechanisms, exactly optimized piston trajectory is not necessary. An exactly optimized non-uniform trajectory would be altered when the variable sub-mechanism is added. In order to get an approximate lamniscate shape, a mechanism almanac is employed[7]. An appropriate lamniscate coupler curve is found and the associated mechanism used for the 4-bar portion of the Atkinson 6-bar. The mechanism is analyzed using complex vector loop equations solved with a Newton-Raphson Scheme performed by Matlab. The mechanism is shown in Figure 11 and the lamniscate and associated piston trajectory are shown in Figure 12.

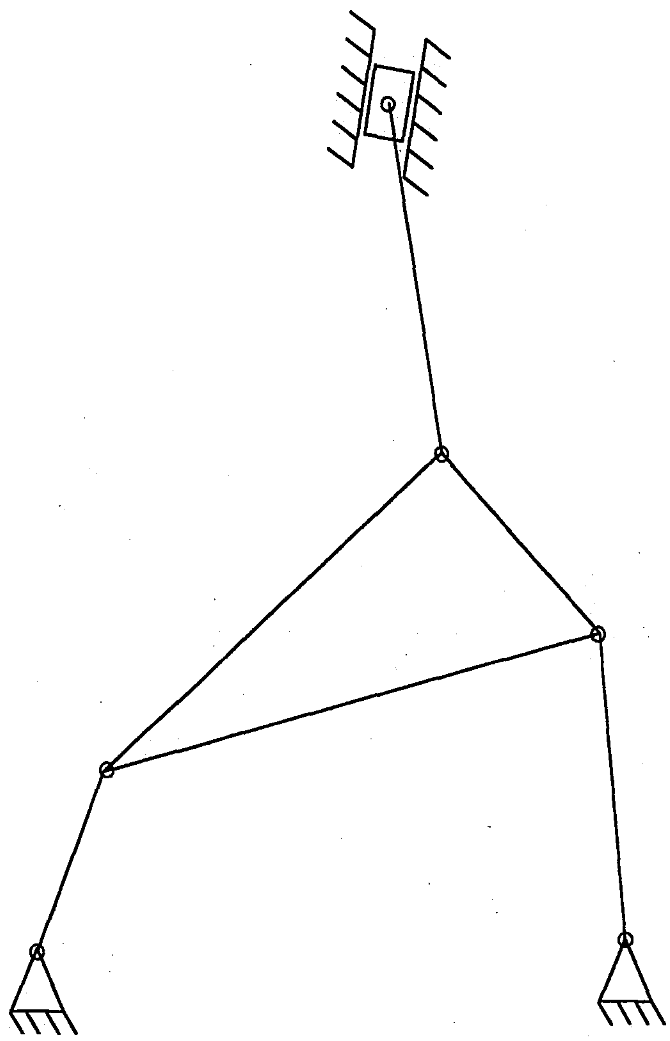


Figure 10: Atkinson Cycle Non-Uniform Stroke Mechanism

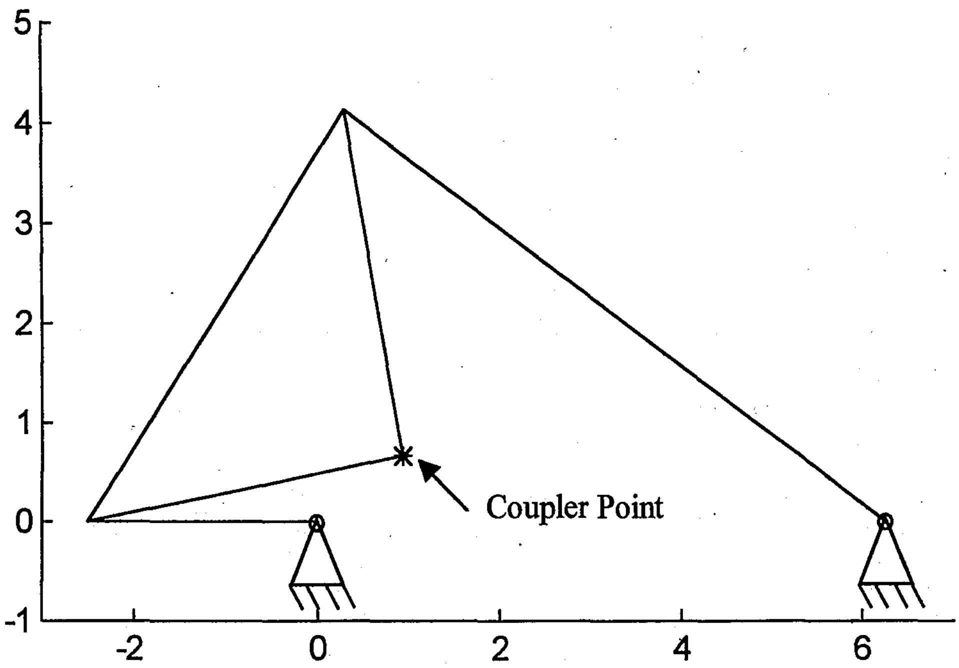


Figure 11: Four Bar Linkage With Lamniscate Coupler Curve

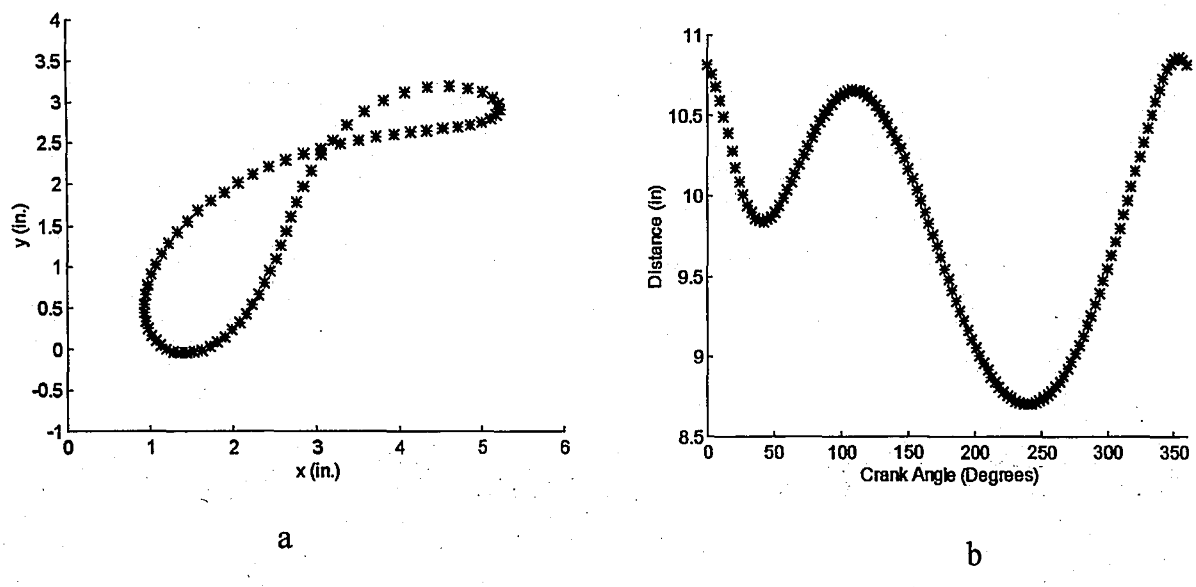


Figure 12: Lamniscate (a) and Associated Piston Trajectory (b) of Atkinson Cycle Linkage

5.2.2 Benefits and Drawbacks of the Atkinson Cycle Linkage

The Atkinson Cycle linkage has a number of characteristics that make it a desirable choice for a non-uniform stroke mechanism. All of the mechanisms joints, except for the piston, are revolute joints. This type of joint is very inexpensive to manufacture and easy to lubricate, maintain, and if necessary replace. There are no gears or cams which are much more expensive to manufacture.

One of the drawbacks of the Atkinson Cycle linkage is its size. The linkage takes up a considerable amount of space relative to the stroke length. Space is a very valuable commodity in automotive applications, particularly in the enormous market of compact cars. Also, the large number of links, six, will cause considerable additional cost over conventional engines. Dynamic balancing for reducing reaction forces will also present a problem. Exact balancing of a six-bar mechanism is generally impossible. Reaction forces can be minimized but will always be present. Although these drawbacks are considerable, they can all be worked around and do not rule out the Atkinson cycle linkage as a possible sub-mechanism for a variable non-uniform stroke engine.

5.3 Planetary Gear Mechanisms

The second mechanism that will be considered for a non-uniform stroke engine is a planetary gear mechanism. A set of planetary gears can produce a double hump piston trajectory in place of the lamniscate of the four-bar linkage. Five different planetary configurations are shown in Figure 13. The trajectory of the coupler point that the connecting rod would be pinned to is displayed. As the figure shows, the double hump trajectory can be accomplished with external gears sets (a & b), or internal gears sets (c, d, and e). All of these gear sets produces a back and forth motion along the horizontal axis that would provide two different length strokes in a single cycle of the planetary gears.

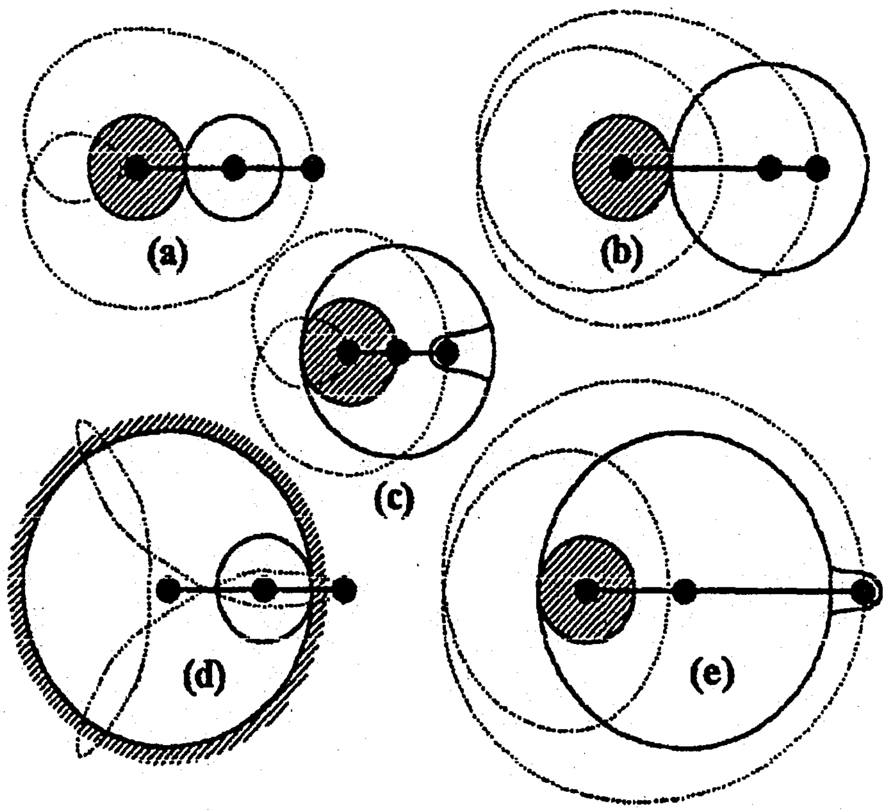


Figure 13: Planetary Gear Configurations

5.3.1 Synthesizing Gear Radius Functions

One of the biggest advantage of using gears for a non-uniform stroke mechanism is that the gears can be cut in a non-circular fashion so that a single gear set will have a varying gear ratio as the gears rotate through one cycle. This makes it possible to come very close to, or even exactly match the desired piston trajectory[5].

Figure 14 shows an external planetary gear mechanism with generally shaped (non-circular) gears.

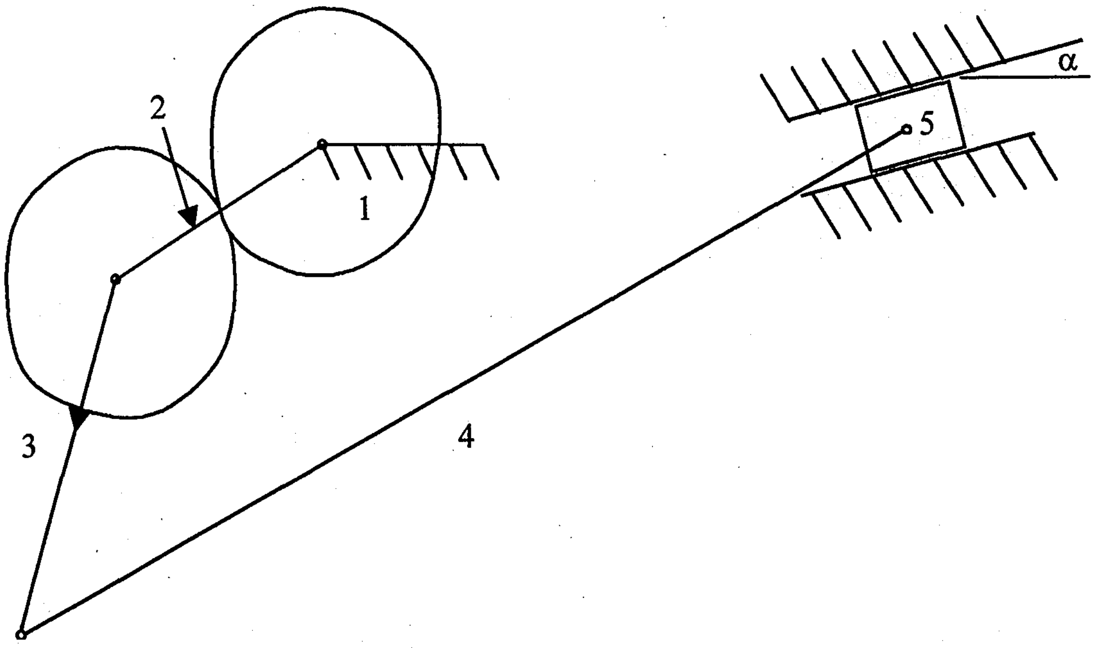


Figure 14: Geared Five-Bar, Non-Uniform Stroke Mechanism

Vector loop equations similar to those discussed in section 5.2 can be written for this geared 5 bar mechanism. In order to solve for the angle of the rotating gear (link 2), as a function of the crank (link 1), the gear ratio must be used. Since a variable gear ratio is allowed, the gear radii will be a functions of the crank angle. These functions shall be referred to as gear radius functions. Further, since the gear radii are variable, an equation which maintains the center to center distance of the gears must be considered so that the gears mesh properly.

Once a relation between the variable gear ratio and the output piston motion is established, additional unknowns such as the length of link 3 and the angle of the cylinder, α must be determined. These unknowns can be chosen arbitrarily keeping in mind considerations such as minimizing link size as well as maintaining a minimum overall link motion envelope. With the gear radius functions the only remaining unknowns, the vector loop and gear mesh equations can be solved numerically for the these functions. This solution technique can require iterations of the arbitrarily chosen unknowns in order to yield an appropriate solution.

5.3.2 Benefits and Drawbacks of Planetary Gear Mechanisms

The greatest benefit of using a planetary gear mechanism for a non-uniform stroke engine is the ability to use a variable gear ratio to exactly match the optimized piston trajectory. The small size and smaller number of links of these mechanism is another advantage, particularly over the Atkinson cycle mechanism which uses a larger, more cumbersome linkage.

The main disadvantage of planetary gear mechanisms is the expense and complexity of the gears. Gears are much more expensive to manufacture then standard linkages, particularly when the gears are mounted in a planetary configuration. They require tight tolerances to assemble and care must be taken to keep them well lubricated and maintained since they wear metal shavings as they operate.

5.4 Wobble-Plate Mechanisms

A final mechanism that can produce a non-uniform piston trajectory is a wobble plate mechanism. A wobble plate, sometimes referred to as a swash plate, is a plate cam which is basically a disk that has a contoured surface. A multi-cylinder wobble plate engine is shown in Figure 15. A follower, link 3, follows the profile of the cam, link 2, as it rotates producing a follower motion that is a direct function of the cam's profile. By integrating a piston, link 4, with the follower, a non-uniform stroke engine can be devised. Since the axis of the piston motion is parallel with the axis of the cam/drive shaft, these types of engines are called axial stroke engines.

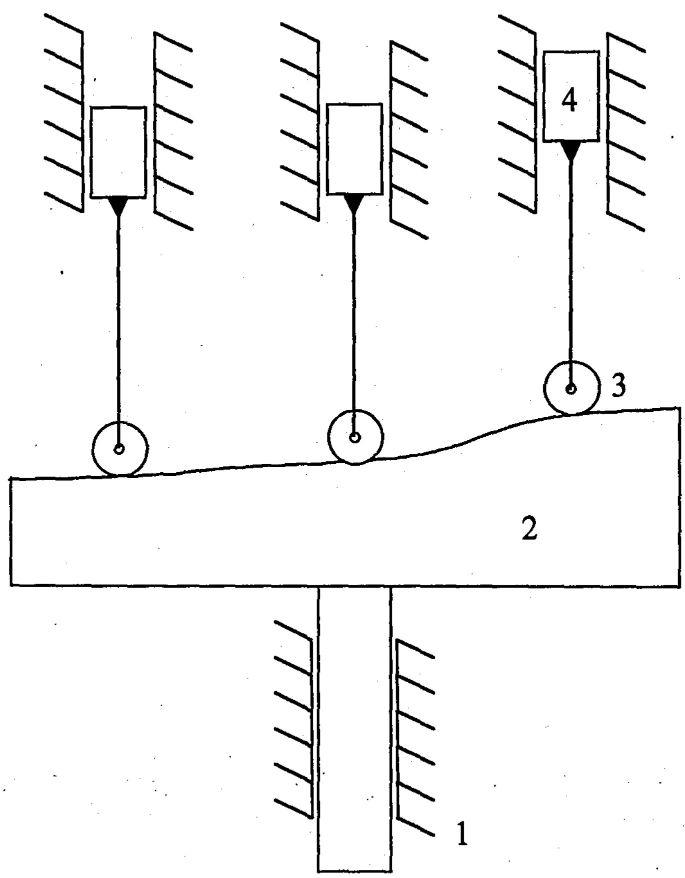


Figure 15: Wobble Plate Engine

Another variation of the wobble plate engine has a bevel gear mechanism in place of the plate cam. This type of mechanism is explored extensively by Yu and Lee [8].

5.4.1 Benefits

Since virtually any contour can be machined into a plate cam, a wobble-plate engine can be designed with a piston trajectory that exactly matches the optimized trajectory. Further, wobble-plate engines have very few moving parts, only the cam and piston. Multi-cylinder engines are achieved be placing multiple cylinders in a radial configuration around the surface of the cam. Finally, variability can be achieved with wobble-plate engines relatively easily. By designing a cam profile that varies in the radial direction, a fully variable, non-uniform stroke engine can be achieved. A mechanism that moves the follower in the radial direction must be added to the engine. By moving the follower back and forth in the radial direction, different profiles will be followed and thus variable piston trajectories will be achieved. A schematic of this type of variable position follower is shown in Figure 16. The actuator mechanism shown lowers the TDC position for longer strokes and is thus capable of maintaining a constant compression ratio.

5.4.2 Drawbacks

Like gearing mechanisms, where the main cost of the mechanism is the gears, the main cost of a wobble-plate mechanism is the plate cam. A vary complicated profile varying in both the angular and radial directions must be machined. The cam must be able to withstand the loads exerted by the pistons, high temperature of an internal combustion engine, and the high speed and friction of the followers. Wear on the cam is of particular concern, especially in a variable stroke wobble-plate engine where the followers will be moving back and forth along the radius of the cam. Excessive wear will occur at the point where the follower and cam are in contact for the majority of the engine's operation.

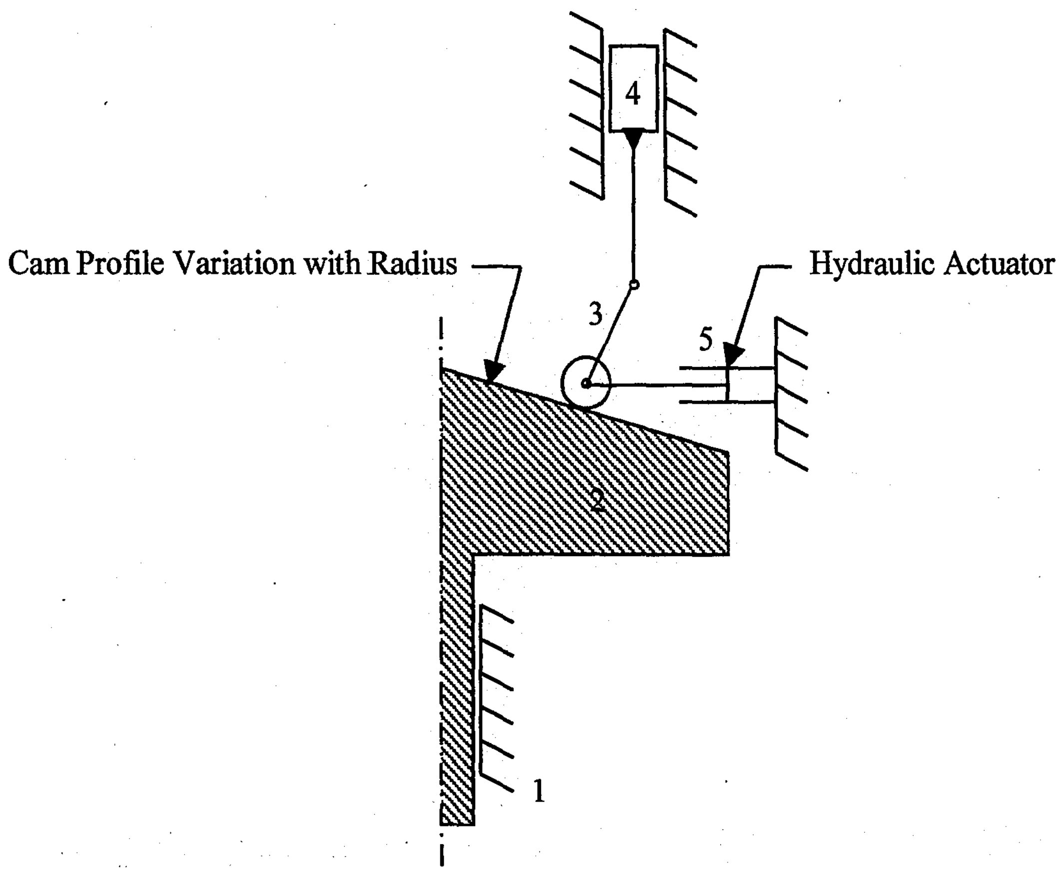


Figure 16: Wobble Plate Engine With Variable Stroke Mechanism

Chapter 6: Variable Stroke Mechanisms

The variable wobble-plate engine has been the first mechanism discussed that produces a variable piston trajectory, one where the stroke length is varied to meet power needs. The operator, or driver in automotive applications, would adjust the position of the follower on the cam in order to control the stroke length and power, presumably with a foot pedal. This chapter discusses three other mechanisms that have been synthesized to allow for variable stroke piston motion.

The following three mechanisms have been synthesized by Freudenstein and Maki[4] using similar techniques to those used in section 5.1 for synthesizing non-uniform stroke engines. Graph theory was used to enumerate six and eight bar mechanisms that had promising characteristics. Heuristic rules ruled out all but three mechanisms the were further developed. Because the mechanisms are all similar eight bar mechanisms, that lack obvious distinctions, they will simply be referred to as variable stroke mechanisms one, two, and three.

6.1 Mechanism 1

The first variable stroke mechanism contains eight links including a piston as well as one additional prismatic joint. It is pictured in both schematic and graph form in Figure 17. The crank, labeled link 2, rotates through the connecting link 3, causing link 4 to oscillate back and forth. The slider, link 5, connecting link 4 to link 6 transmits the force with little sliding motion. Link 6 also rocks back and forth and through connecting link 7, causes the piston to reciprocate. In order to vary the stroke length, the grounded

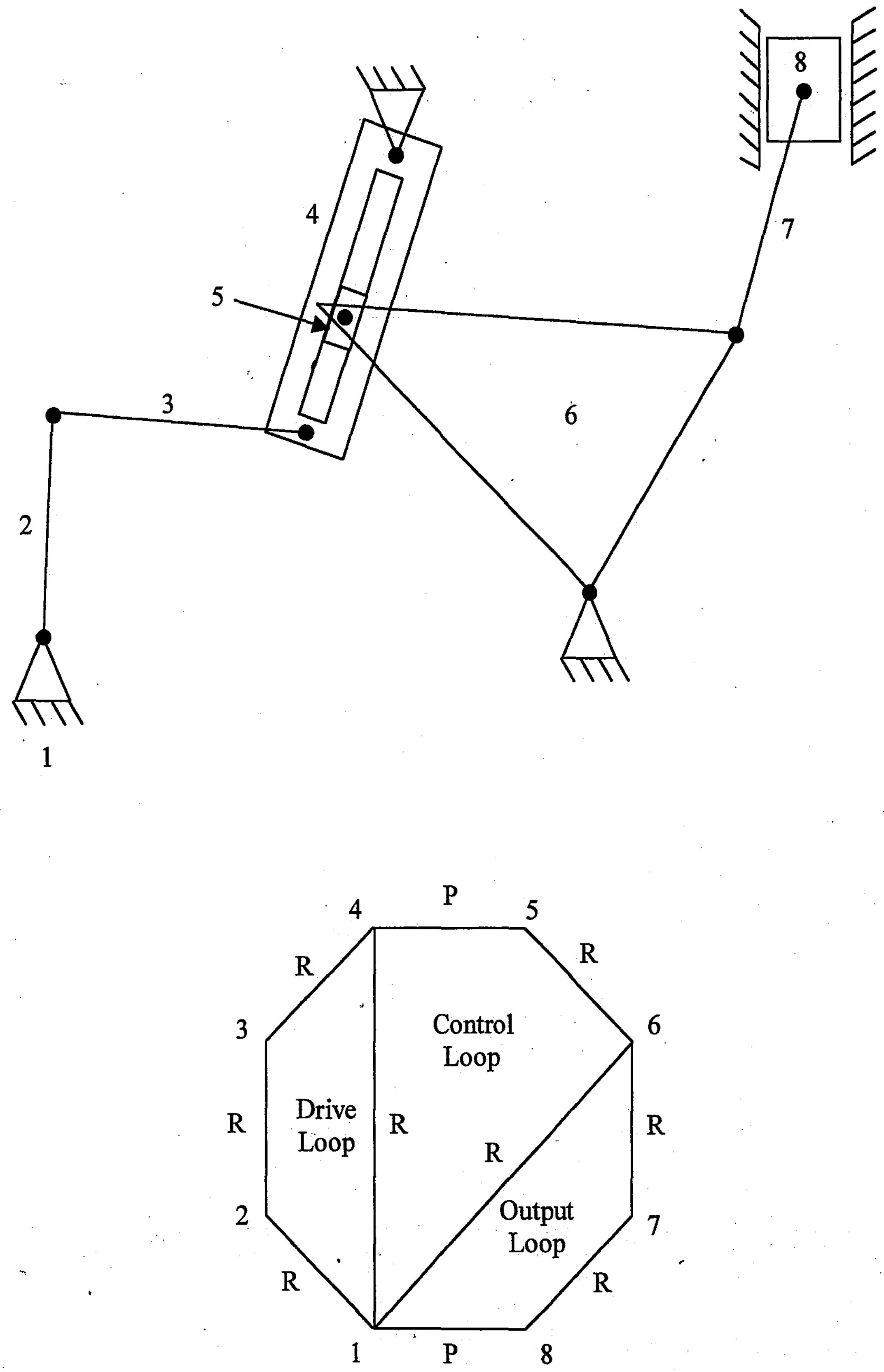


Figure 17: Variable Stroke Mechanism 1

pivot of link 4, hereafter known as the control point, is moved up or down. This causes a change in the position of the slider in link 4 and a change in the transmission arc which transmits motion from link 4 to link 6. This change is carried through the rest of the mechanism and varies the length of the stroke. Thus the stroke is varied by moving the control point which the operator could execute via a cable, hydraulic slider or similar mechanism. An alternate method of varying the stroke of this mechanism is to move the position of the ground pivot of link 6. The net result is the same, a change in the relative position of the slider in the slot of link 4 which changes the magnitude of the rocking motion transferred to link 6.

6.1.1 Benefits

This mechanism has a number of desirable characteristics. Most importantly, the stroke length can be varied while at the same time maintaining a constant compression ratio. This is accomplished by adjusting the precise direction of motion of the control point. If the control point is moved directly along the midline of the range of motion of link 4 (see Figure 18), the stroke will be varied uniformly. In other words, the center of motion of the piston will not move as the stroke is varied. This, in turn, will cause the compression ratio to rise as the stroke increases. By moving the control point at an angle to the midline of link 4, the piston trajectory can be made to move TDC down as BDC moves down, thus keeping the compression ratio approximately constant as stroke length increases.

Another desirable characteristic of mechanism 1 is the ability to keep the adjustable portion of the mechanism isolated from the power transmission portion of the mechanism. This can be seen in the schematic of Figure 17 where links 4 and 6 are connected by slider 5. Adjustability is accomplished by moving the control point up so that the slider contacts link 4 in a different position. Once adjustment is complete, there is very little relative motion between the slider and link 4, due to the perpendicular arrangement of links 4 and 6. This effective de-coupling of the control and power portions of the mechanism is reflected in the graph in Figure 17. Loops drawn connecting ground to the various portions of the mechanism and back to ground display the interconnectivity of the mechanism. The control point, the joint between links 1 and 4, controls the control loop and the stroke length without being integral with either the drive loop or the output loop.

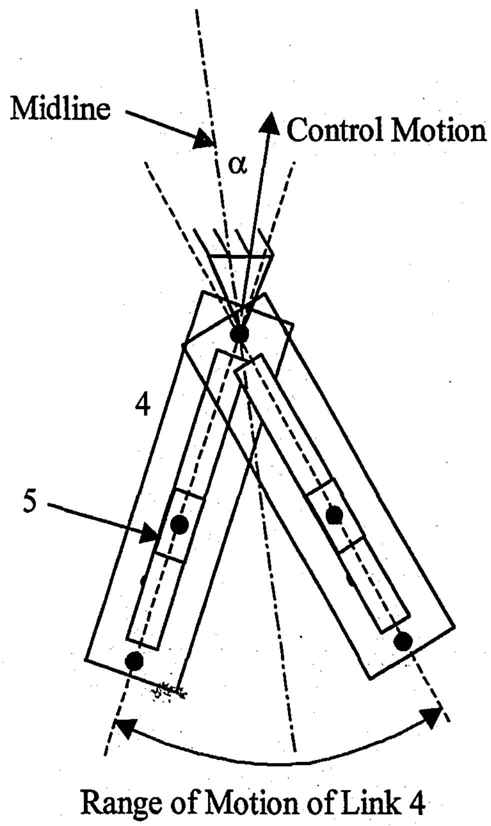


Figure 18: Control Motion of Variable Stroke Mechanism 1

6.1.2 Drawbacks

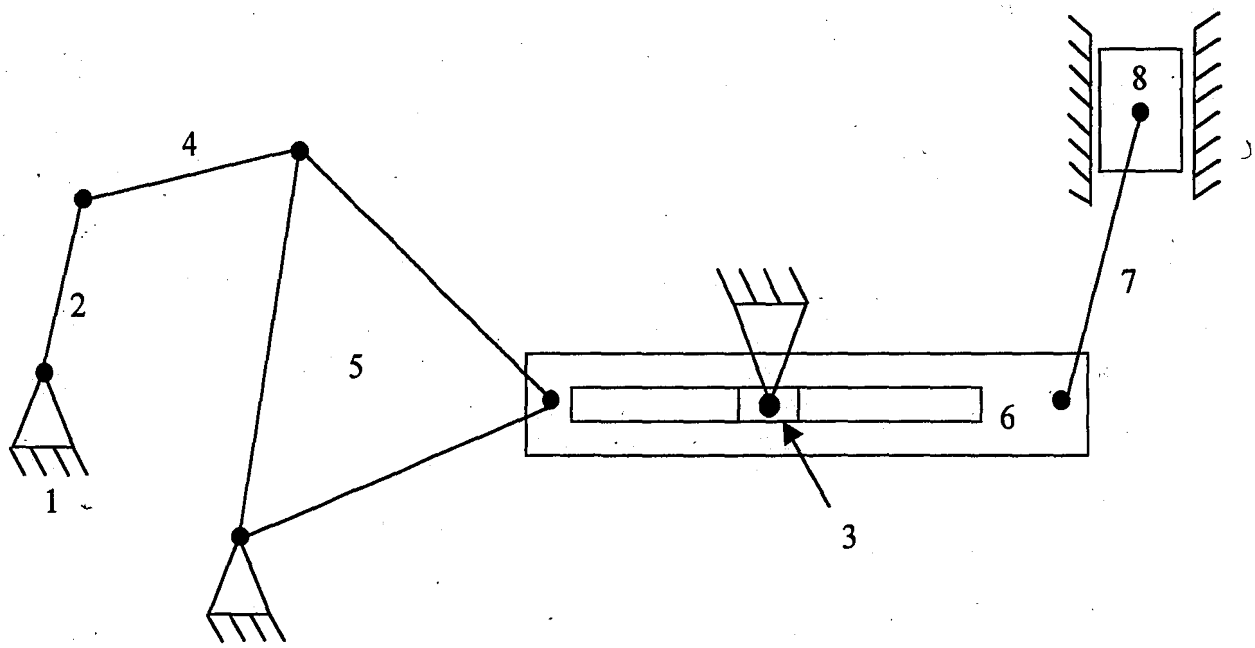
The main drawback of mechanism 1 is its size and complexity. Eight links including two sliding pairs will incur considerable manufacturing costs. The amount of space the large oscillating links require may limit its applications to trucks and larger machinery. The large weight of the engine could abate the advantages of the added power in small cars.

6.2 Mechanism 2

The second variable stroke mechanism also consists of eight links including one sliding pair other then the piston. This mechanism is shown in Figure 19. The basic difference between mechanism 2 and 1 is the control loop of the linkage. Mechanism 2 has a slider (link 3) attached to ground with a revolute joint. This link acts as the control point and is moved right or left in order to vary the stroke. By moving the control point to the left the pivot point of link 6 is moved closer to its driving link, 5, causing the right side of the link to oscillate up and down further and the piston to travel a longer stroke. Moving the control point the right reverses the effect.

6.2.1 Benefits

Like mechanism 1, the control loop of mechanism 2 is separated from the drive and output loops. The control slider is nearly stationary relative to the oscillating link 6 and thus control is possible with little effort. The only time the slider moves along the slot is when the stroke length is varied. The slider does pivot about ground with the high



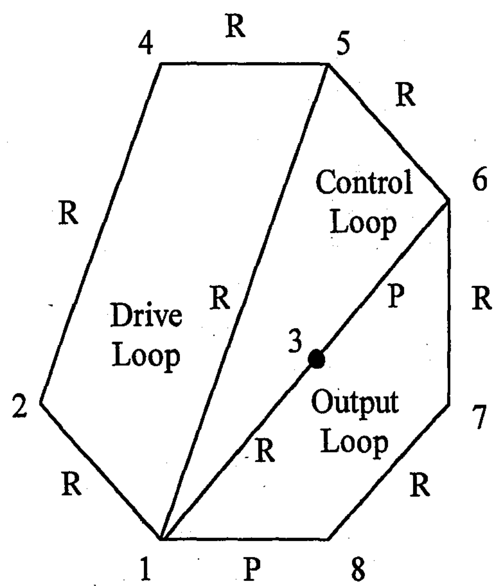


Figure 19: Variable Stroke Mechanism 2

speed of the crank but this motion requires constraints perpendicular to the control direction so again control can be accomplished easily with a cable or hydraulic mechanism. Nearly constant compression ratio is also realizable with this mechanism. By moving the control point slightly down as it moves to the left will lower TDC as BDC lowers and stroke length increases. The control point movement is shown in Figure 20.

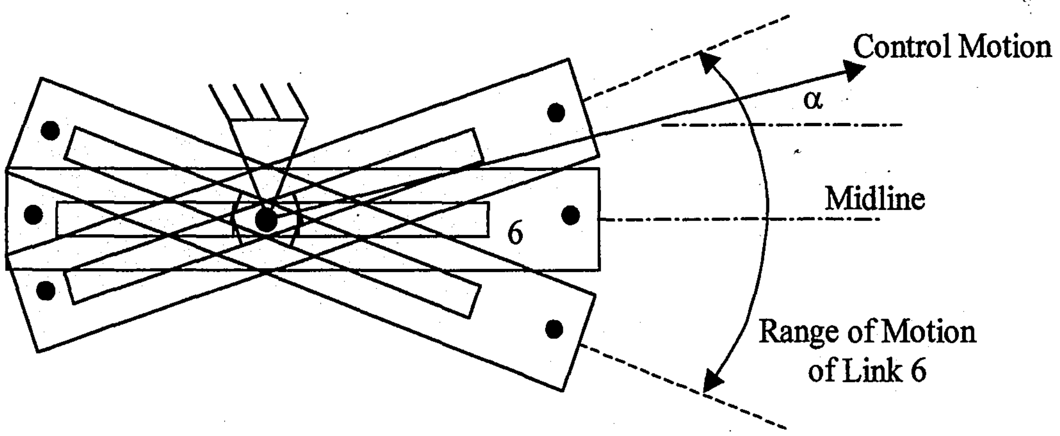


Figure 20: Control Motion of Variable Stroke Mechanism 2

6.2.2 Drawbacks

One drawback of this mechanism is caused by the unusual motion of link 6. This is a coupler link which is not directly attached to ground and is pinned to the connecting rod. This link moves in a very complicated motion including both translation and rotation. This somewhat sporadic motion causes the piston trajectory to have some undesirable characteristics. Smooth, sine wave-like curves are desired for minimum accelerations and shaking forces, but as Figure 21 shows, this mechanism's piston trajectory contains some sections with relatively flat slopes and others with very steep slopes. These steep slopes convert to high accelerations and undesirable forces.

Although this mechanism produces a piston trajectory with a nearly constant compression ratio, the shape of the trajectory is somewhat undesirable. Further, like mechanism 1, mechanism 2 has a large number of links which are expensive, heavy and bulky and my limit it's use to larger applications.

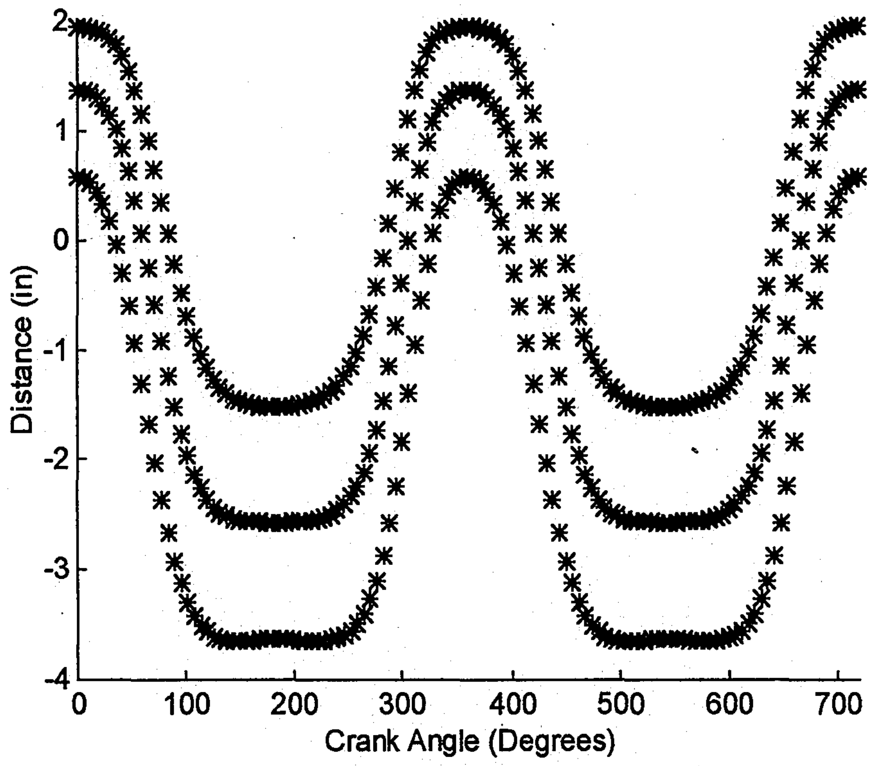


Figure 21: Piston Trajectory at Three Different Stroke Lengths for Variable Mechanism 2

6.3 Mechanism 3

Mechanism 3, shown in Figure 22, has a very similar control loop to mechanism 2. A slider, pivoting on ground acts as the control point and by moving it along the coupler, link 6, variable stroke length is achieved. The main difference is that this coupler is a quaternary link as opposed to the tertiary link of mechanism 2. The basic operation of this mechanism is very similar to that of mechanism 2.

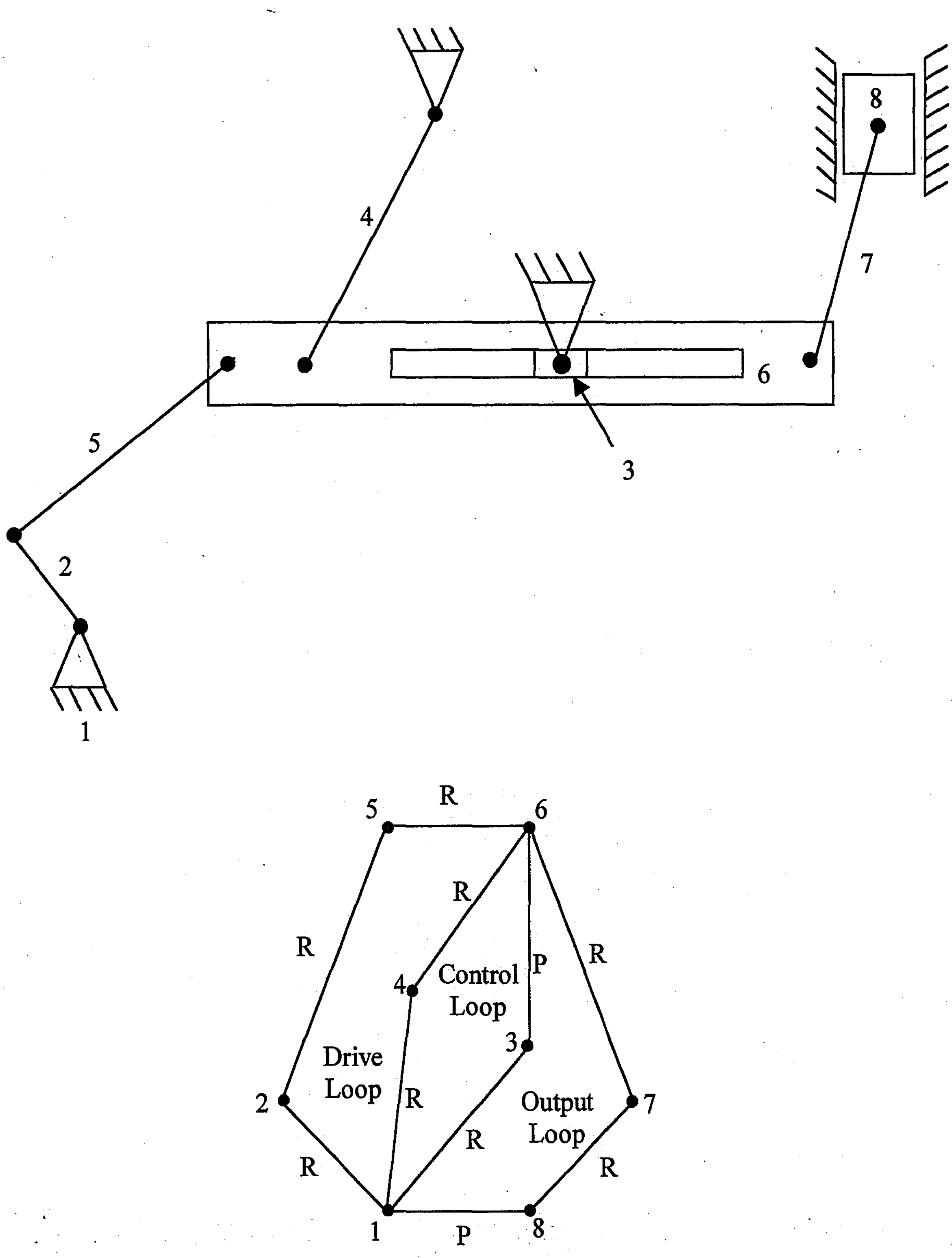


Figure 22: Variable Stroke Mechanism 3

6.3.1 Benefits

Since the control loop of this mechanism is very similar to that of mechanism 2, it has the same benefits in its ability to very the stroke length simply and effectively while maintaining a nearly constant compression ratio.

6.3.2 Drawbacks

The motion of mechanism 3's coupler, link 6, is somewhat less sporadic then mechanism 2's coupler link. The addition of another rocker, link 4, constrains the motion to a degree, but the piston trajectory still contains some undesirable steep slopes and long flats.

Chapter 7:

Synthesizing Variable Non-Uniform Stroke Engines

Now that the details of the workings of both non-uniform stroke and variable stroke engines have been investigated, the next step is to combine the two concepts into a single mechanism that has a variable and non-uniform stroke. This chapter discusses how two mechanisms can be combined into one using graph theory.

7.1

Splicing Graphs of Variable and Non-Uniform Stroke Engines

In order to splice the graphs of two mechanisms, each graph is first drawn in a particular configuration, such as an regular octagon for an eight link mechanism or regular pentagon for a five link mechanism. Figure 23 shows the graphs and schematics of the first variable stroke mechanism and the geared non-uniform stroke mechanism.

In order to splice two graphs while maintaining the integrity of each mechanism, one graph is inserted into one of the sides or corners of the other graph while keeping the rest of the second graph unchanged. In order to maintain a working mechanism with one degree of freedom, it may be necessary to combine links or remove links from one or both mechanisms. Typically the choice of where to insert one graph into the other starts by realizing that both mechanisms should have a common ground, thus links 1 of each mechanism is combined to start one side of the splice. The other side of the splice is determined by knowledge of which links are desired to join the two mechanisms. Figure 24 shows the graph and schematic after splicing the two mechanisms from Figure 23. In

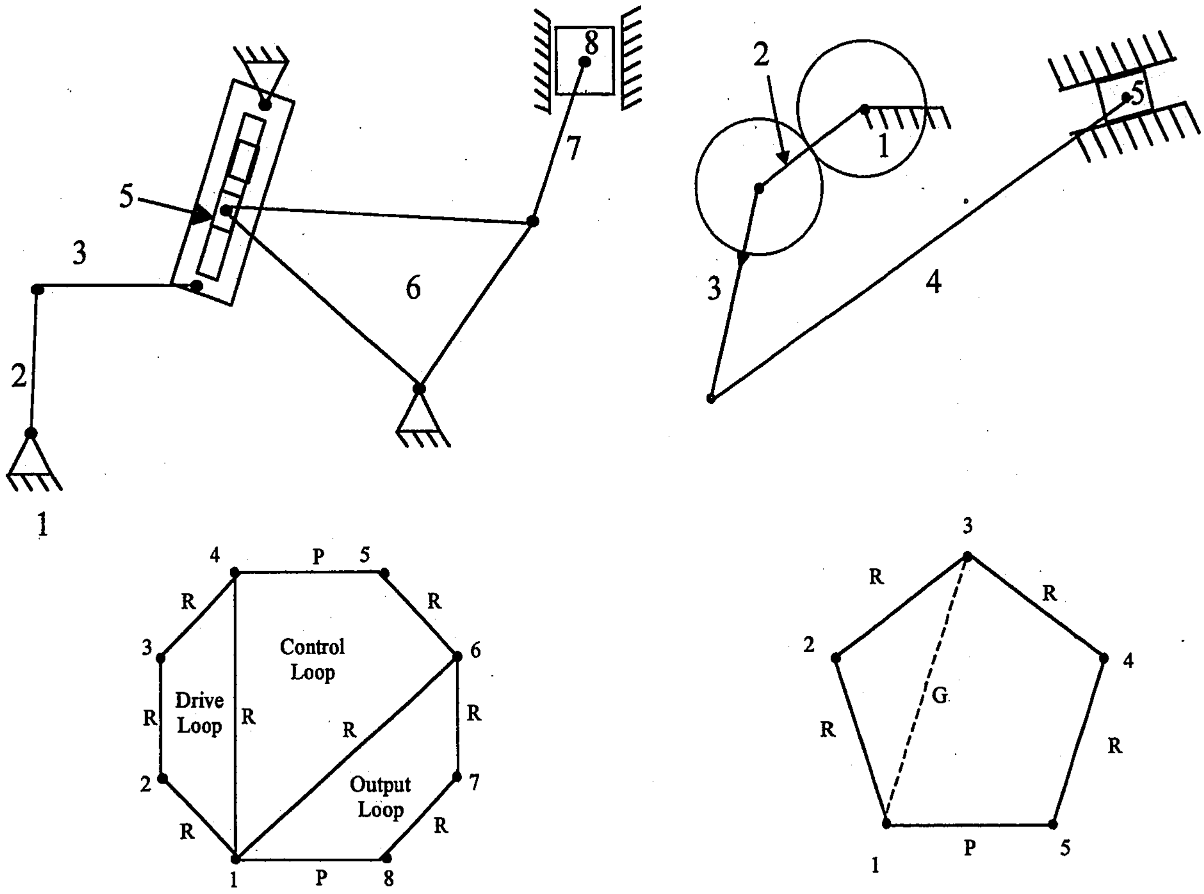


Figure 23: Variable and Non-Uniform Stroke Mechanisms and Graphs

order to maintain a single degree of freedom, link 4 from the non-uniform mechanism and links 3 from the variable stroke mechanism were combined. Also the crank, link 2, from the variable stroke mechanism was removed since link 2 from the non-uniform stroke mechanism performs the job of the crank.

Basically what is done when combining these two mechanism is that the crank of the variable stroke mechanism is replaced with the entire non-uniform stroke mechanism. Previously, a simple rotating crank acted as the input to the variable stroke mechanism. With the spliced mechanism, the double hump trajectory output of the non-uniform

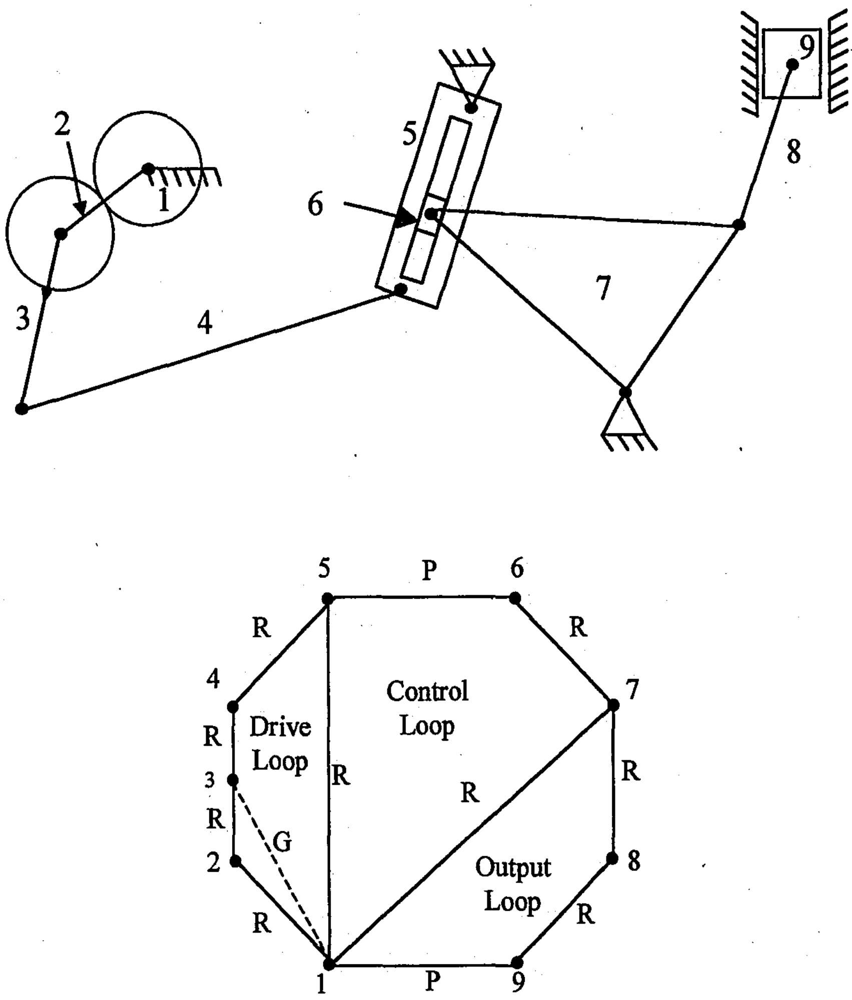


Figure 24: Variable Non-Uniform Stroke Mechanism Derived From Mechanisms in Figure 23

stroke mechanism is the input to the variable stroke mechanism. With this configuration, both the variable and non-uniform stroke characteristics are transferred to the piston trajectory.

Similar methods are used to combine the geared non-uniform stroke mechanism with the other two variable stroke mechanisms. Further, the Atkinson linkage non-uniform stroke mechanism is combined with the three variable stroke mechanism using the same techniques. The variable non-uniform stroke wobble plate engine was discussed in chapter 5.4. Attempting to combine the wobble plate non-uniform stroke mechanism with variable stroke mechanisms 1, 2, or 3 unnecessarily complicates the mechanism since a simple modification to the follower/connecting rod accomplishes the objective.

7.2 Combined Mechanisms

The combined variable non-uniform stroke mechanisms all contain a variable stroke sub-mechanism and a non-uniform stroke sub-mechanism. Each of these sub-mechanism can be modified individually in order to alter the piston trajectory to achieve the desired output. Further, the link joining the two mechanisms can be altered or the relative position of the two sub-mechanisms can be altered to modify the output. The details of how each of the variable non-uniform stroke engines is synthesized and refined to achieve the desired piston trajectory is discussed in the following chapter.

Chapter 8: Variable Non-Uniform Stroke Engines

Each of the six variable non-uniform stroke engines synthesized is named VNUSE 1 through VNUSE 6. The Newton-Raphson Scheme, run in Matlab, is employed to solve the non-linear vector loop equations. The following sections report the synthesis, refinement, and resulting output of the six engines. Benefits and drawbacks will be discussed with emphasis on engine performance and manufacturing considerations.

8.1 Variable Non-Uniform Stroke Engine 1

VNUSE 1 combines variable stroke mechanism 1 and a planetary gearing, non-uniform stroke mechanism. The graphs of the two mechanisms are spliced by inserting the non-uniform mechanism into the crank position of the variable mechanism producing a nine link mechanism. With proper alignment of the two sub-mechanisms a desirable piston trajectory is achieved.

8.1.1 Details of Engine Operation and Performance

A schematic of VNUSE 1 is shown in Figure 25. The non-uniform gearing mechanism containing links 1, 2, and 3 is joined to the variable mechanism via link 4. A double hump motion is produced by the gears and transferred to the rocker, link 5. Link 5 will rock back and forth twice for each rotation of crank shaft 2. This causes a similar rocking motion in link 7. The magnitude of the rocking motion in link 7 is controlled by the variable setting, which changes the position of slider 6 along link 5. The variable double rocking of link 7 is transferred to the piston via a connecting rod.

The stroke length is varied just as it was with the variable mechanism alone. The grounded pivot of link 7, hereafter known as the control point, is moved up or down. This causes a change in the position of the slider in link 6 and a change in the transmission arc which transmits motion from link 5 to link 7. This change is carried through the rest of the mechanism and varies the length of the stroke. Thus the stroke is varied by moving the control point which the operator could execute via a cable, hydraulic slider or similar mechanism.

It was discovered that the stroke could also be varied adequately by moving the pivot position of link 5 instead of link 7. The net result is virtually the same, the position of the slider, 6, along link 5 will be changed, thus changing the amount of arc and

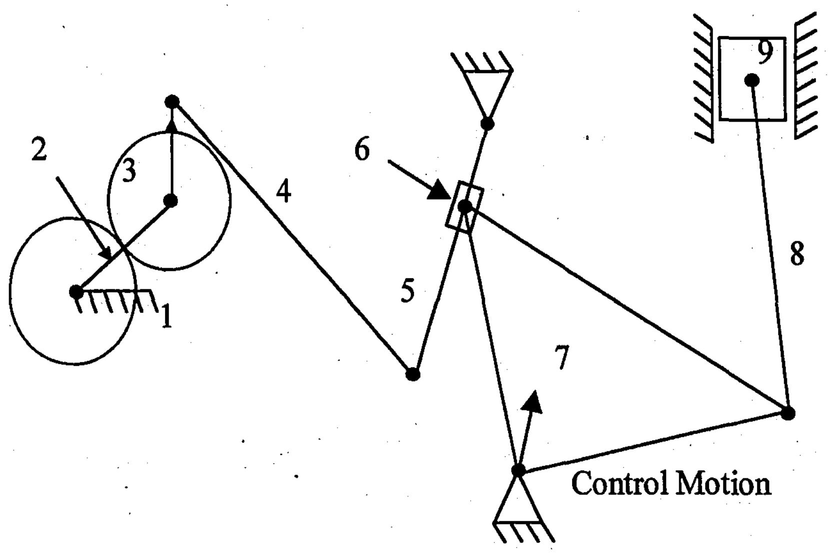


Figure 25: Variable Non-Uniform Stroke Mechanism 1

magnitude of motion that is transferred to link 7. Both methods are capable of maintaining a nearly constant compression ratio as the stroke is varied. VNUSE 1 is shown in three different configurations in Figure 26, with a short, medium, and long piston stroke. The figures show the link positions in 15 degree increments of crank rotation. The actual gears and sliders are not drawn for simplicity. Only lines connecting the joints are shown. The output piston trajectory of each configuration is shown in Figure 27.

8.1.2 Benefits

Virtually all of the benefits of the two sub-mechanisms that make up VNUSE 1 are carried over to the combined mechanism. The particularly important benefits necessary for a practical variable non-uniform stroke engine will be reemphasized. Looking back at VNUSE 1 in Figure 26, Link 7 (green) interfaces with link 5 (red) through the slider, link 6. A critical feature of this interface is that the direction of motion of link 5 at the slider joint is very close to the direction of motion of link 7 at the slider joint.

This described configuration transfers power from link 7 to link 5 with very little movement of the slider. There are two benefits of this configuration. First, little power is wasted in the slider joint. Large displacements in slider joints cause large friction losses, particularly those with lateral thrusts which it the main direction of load slider 6 is carrying. Second, this configuration allows power to be varied using a relatively small force. Since the slider and link 7 see mostly lateral force, only a small force would be required to move the grounded pivot in the direction necessary to vary the stroke.

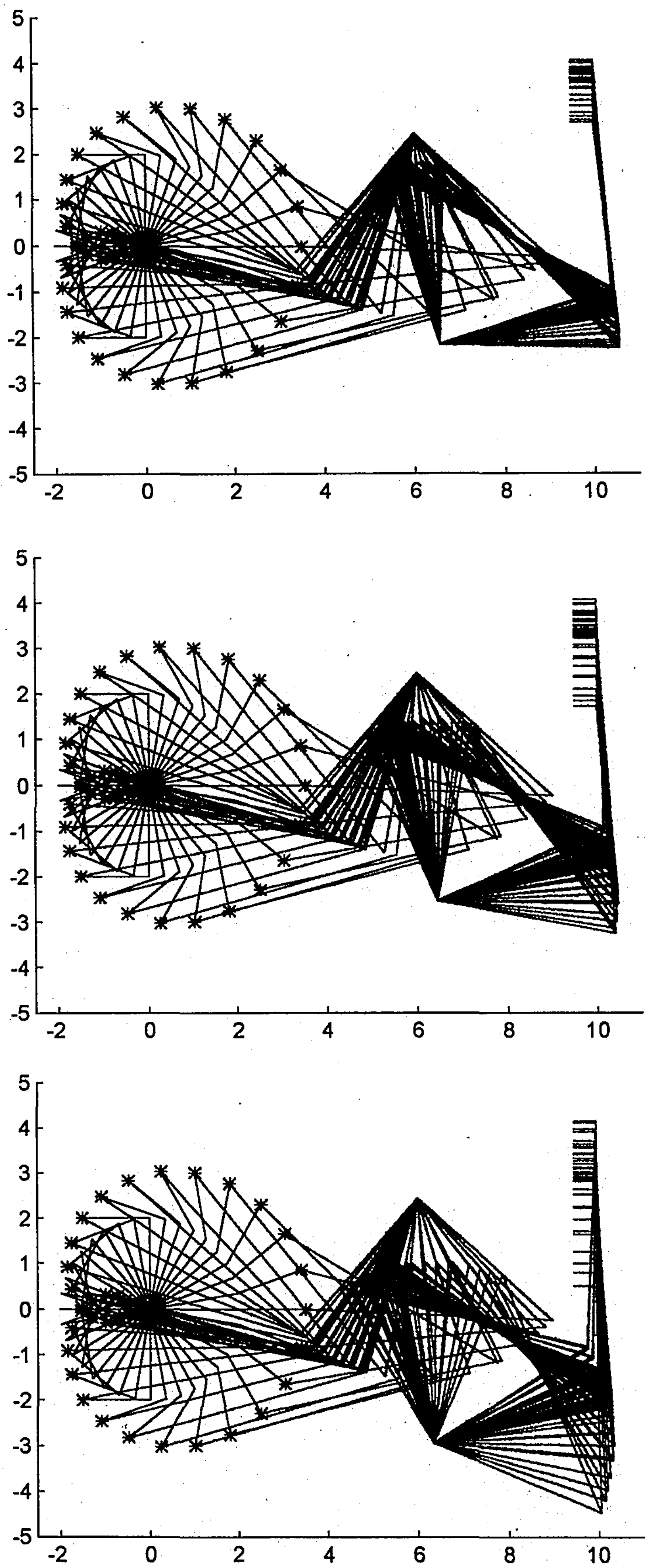


Figure 26: VNUSE 1 in Three Different Stroke Length Configurations

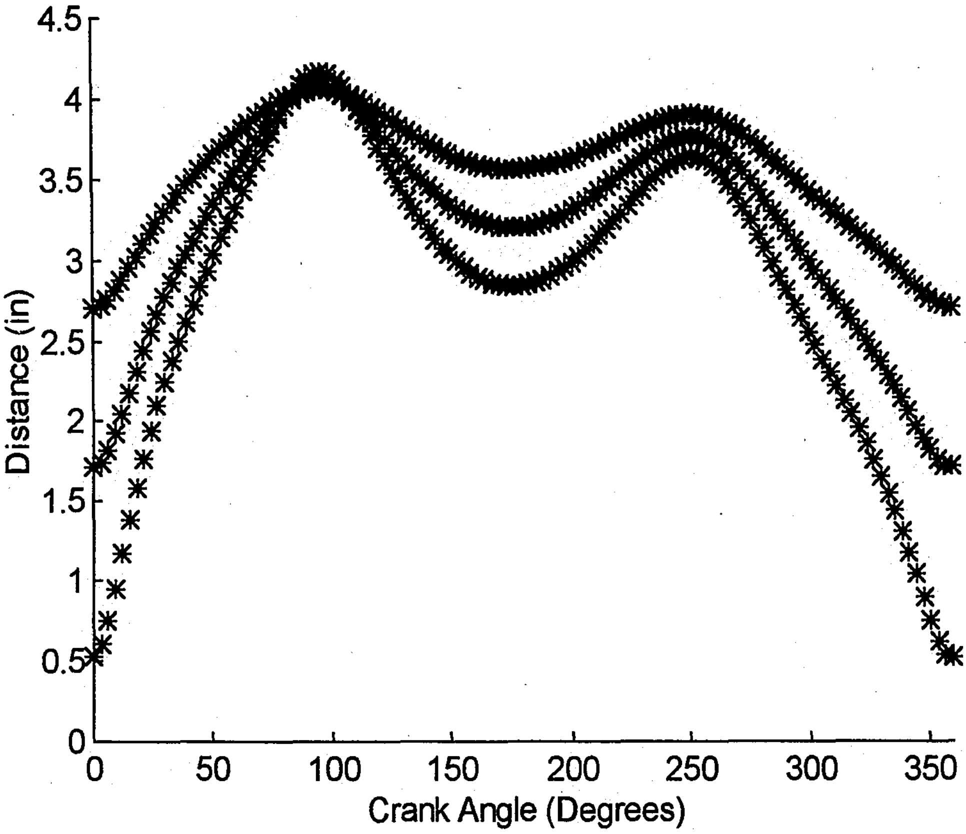


Figure 27: Piston Trajectory of VNUSE 1 With Three Different Stroke Lengths

Perhaps the most crucial element of concern when combining mechanisms is retaining the ability to vary the stroke length while maintaining a nearly constant compression ratio. VNUSE 1 does retain this ability. BDC before compression and TDC after compression define the compression ratio. These two points can be controlled by adjusting the motion of the control point. TDC and BDC can be made to both move down proportionally as stroke length increases, thus maintaining a nearly constant compression ratio. This is shown in Figure 27.

A final benefit of this engine is the ability to attach a second connecting rod and piston to the rocker, link 7. By expanding this link into a triangle symmetric about it's ground pivot, a second connecting rod and piston can be attached as shown in Figure 28.

This second piston must be oriented in the opposite direction of the first piston in order to produce the desired trajectory. The second piston will follow an identical trajectory to the first, just upside down. Employing two pistons per mechanism will greatly decrease the cost and complexity of a multi-cylinder engine. Only half the number of links will be needed since a single adjacent mechanism will only be needed for every two cylinders.

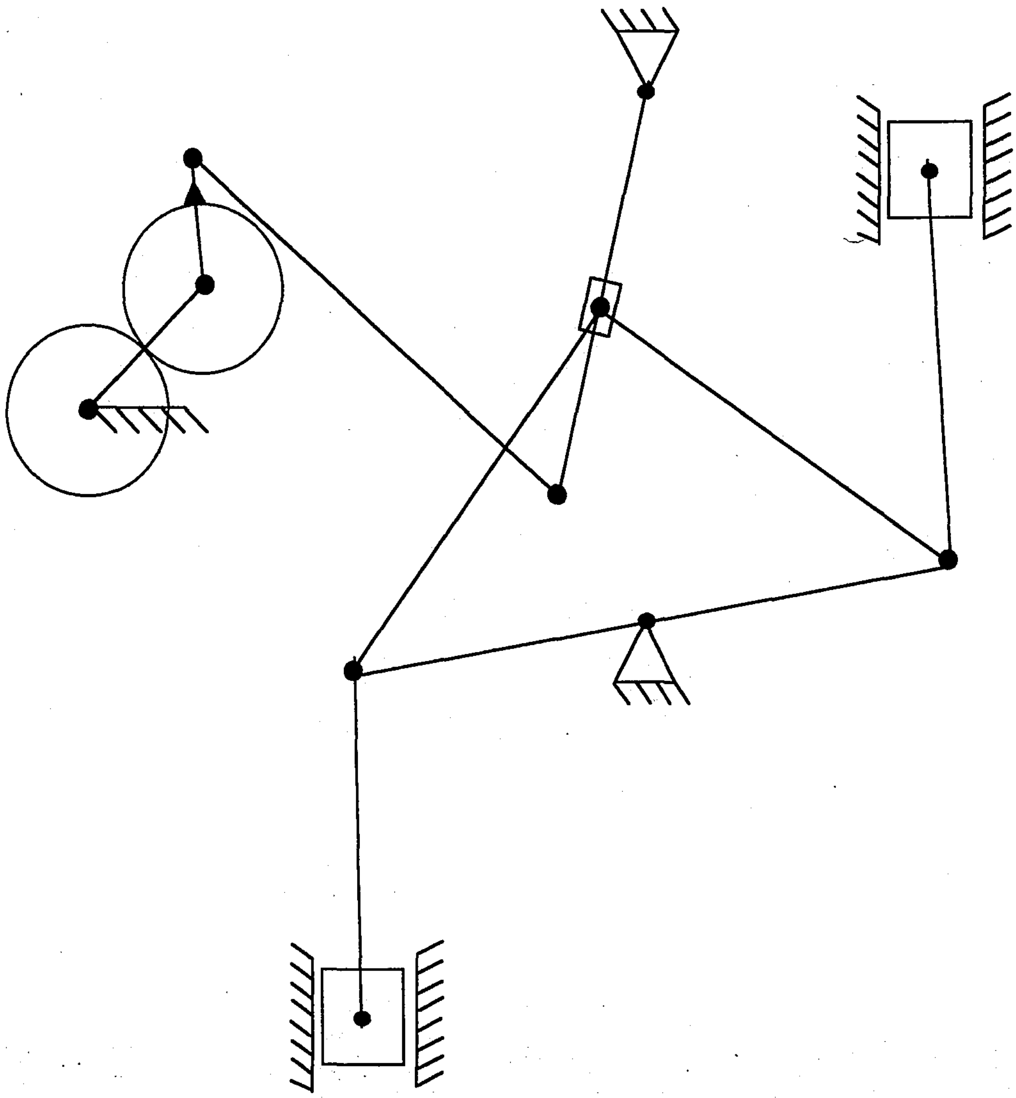


Figure 28: VNUSE 1 With Additional Piston & Connection Rod

8.1.3 Drawbacks

Again, the drawbacks of the two sub-mechanisms are maintained in the combined mechanism. Although this is perhaps the most compact variable non-uniform stroke mechanism analyzed, especially with its two piston configuration, it is still quite complicated. The large size and complexity of this nine link mechanism, containing revolute, prismatic, and gear joints, will make it very expensive to manufacture and maintain. This may limit its market to only large duty applications.

8.2 Variable Non-Uniform Stroke Engine 2

VNUSE 2 combines variable stroke mechanism 1 and an Atkinson cycle, non-uniform stroke mechanism. Again, the graphs of the two mechanisms are spliced by inserting the non-uniform mechanism into the crank position of the variable mechanism. This produces a ten link mechanism. By adjusting the alignment between the lamniscate produced by the Atkinson linkage and the variable mechanism's rocker link, an acceptable piston trajectory is achieved.

8.2.1 Details of Engine Operation and Performance

A schematic of VNUSE 2 is shown in Figure 29. The Atkinson linkage, containing links 1, 2, 3, and 4 is joined to the variable mechanism via link 5. The lamniscate produced by the linkage transfers a double hump motion to the rocker, link 6. The rest of the mechanism is identical to VNUSE 1's variable sub-mechanism. The double hump motion is transferred to the piston while the variable control point allows variation in stroke length while maintaining a nearly constant compression ratio.

VNUSE 2 is shown in three different configurations in Figure 30, with a short, medium, and long piston stroke. The figures show the link positions in 15 degree increments of crank rotation. The output piston trajectory of each configuration is shown in Figure 31.

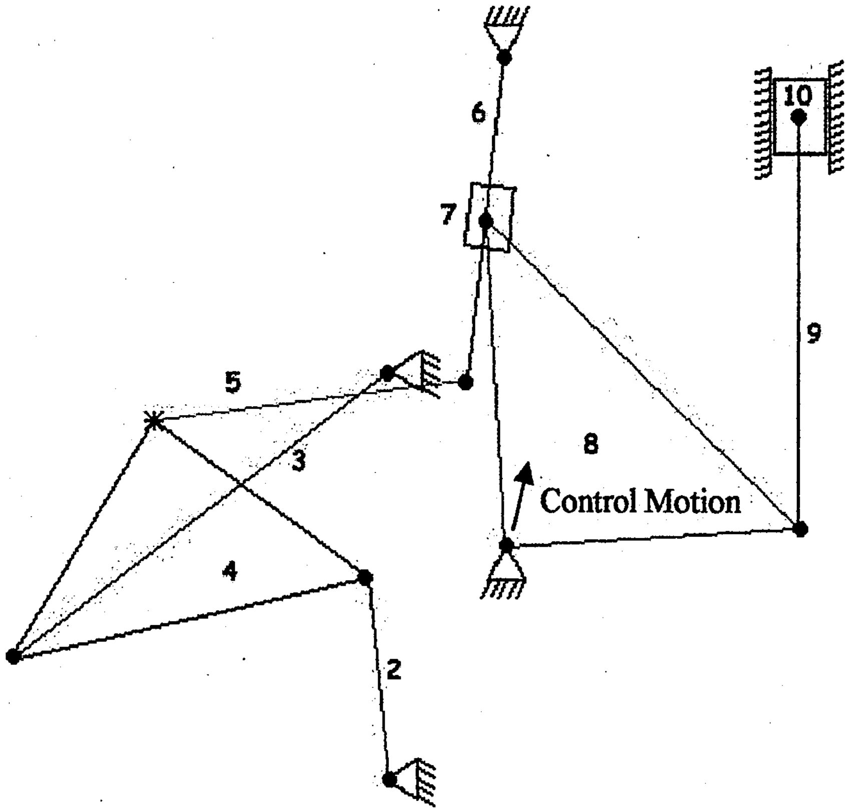


Figure 29: Variable Non-Uniform Stroke Mechanism 2

8.2.2 Benefits

Again, virtually all of the benefits of the two sub-mechanisms that make up VNUSE 2 are carried over to the combined mechanism. The benefits of the variable sub-mechanism were discussed in the previous section. They included desirable transmission angles, maintaining nearly constant compression ratio, as well as the ability to connect two piston's to a single mechanism in order to simplify multi-cylinder engines. Additionally, the Atkinson linkage has the benefit of all revolute joints which are very inexpensive and easy to maintain relative to gears.

8.2.3 Drawbacks

Even more so then VNUSE 1, the size of VNUSE 2 is a large drawback. The Atkinson linkage takes up a large amount of space and cannot be positioned too closely to the variable stroke sub-mechanism because of the long narrow shape of the lamniscate. Positioning the lamniscate, shown as blue stars in Figure 30, too closely to the rocker, shown in red, will result in poor transmission angles and excess friction. The large size of this mechanism will most likely limit its market to only large duty applications

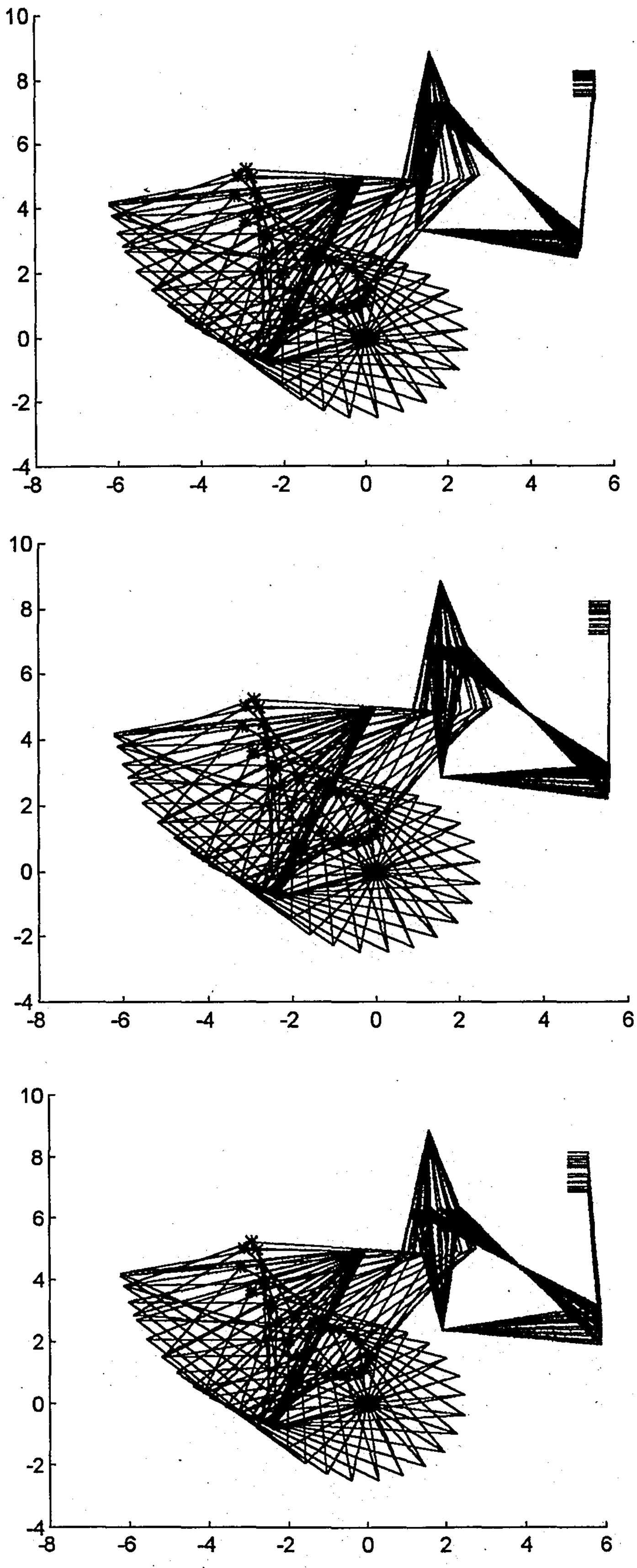


Figure 30: VNUSE 2 in Three Different Stroke Length Configurations

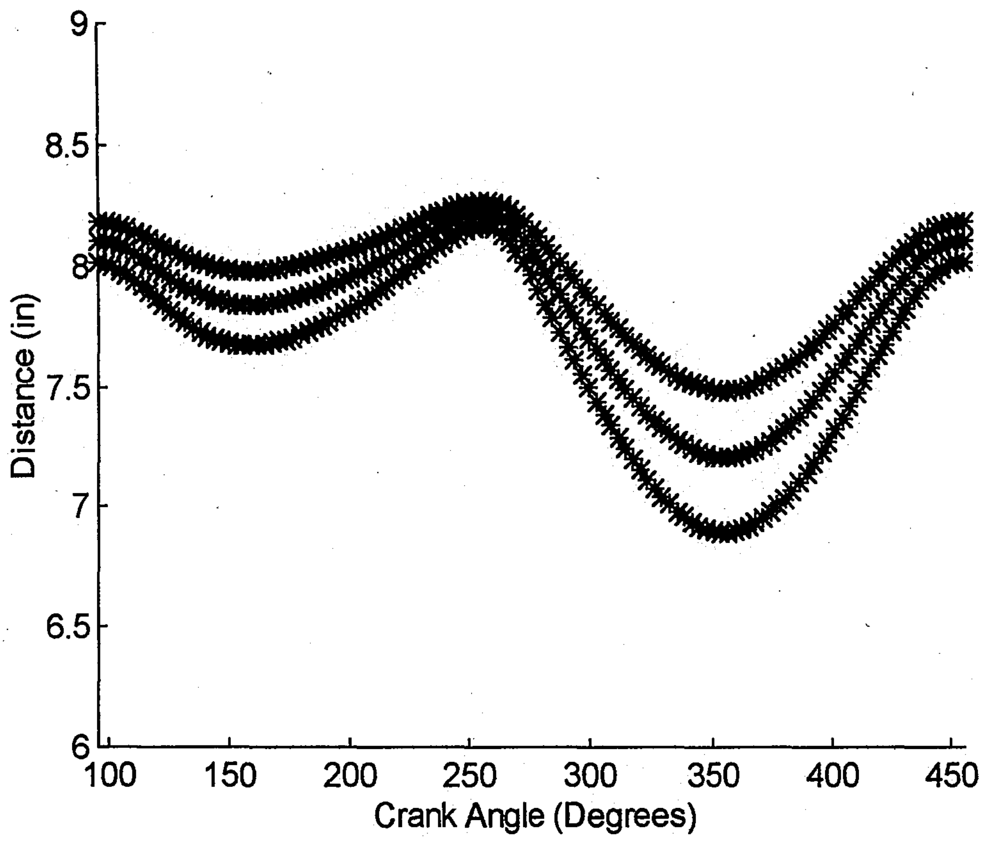


Figure 31: Piston Trajectory of VNUSE 2 With Three Different Stroke Lengths

8.3 Variable Non-Uniform Stroke Engine 3

VNUSE 3 combines variable stroke mechanism 2 and a planetary gearing, non-uniform stroke mechanism. Splicing the gearing mechanism in place of the crank of the variable mechanism produces a nine link mechanism capable of variable, non-uniform piston trajectories.

8.3.1 Details of Engine Operation and Performance

A schematic of VNUSE 3 is shown in Figure 32. The non-uniform gearing mechanism containing links 1, 2, and 3 is joined to the variable mechanism via link 5. A double hump motion is produced by the gears and transferred to the rocker, link 6. Link 6 will rock back and forth twice for each rotation of the crank shaft. The rocker is attached to a coupler/oscillator, link 7, which slides in a slider pivoted to ground. Link 7 moves with a very complicated coupler motion since it is not directly grounded Link 7 is pinned to the connecting rod which is pinned to the piston. The slider, link 4, acts as the control point for the variable portion of the mechanism

The stroke length is varied by moving the control point to the right or left.. By moving the control point to the left, the pivot point of link 6 is moved closer to its driving link, 6, causing the right side of the link to oscillate up and down further and the piston to travel a longer stroke. Moving the control point the right reverses the effect.

VNUSE 3 is shown in three different configurations in Figure 33, with a short, medium, and long piston stroke. The figures show the link positions in 15 degree increments of crank rotation. The output piston trajectory of each configuration is shown in Figure 34.

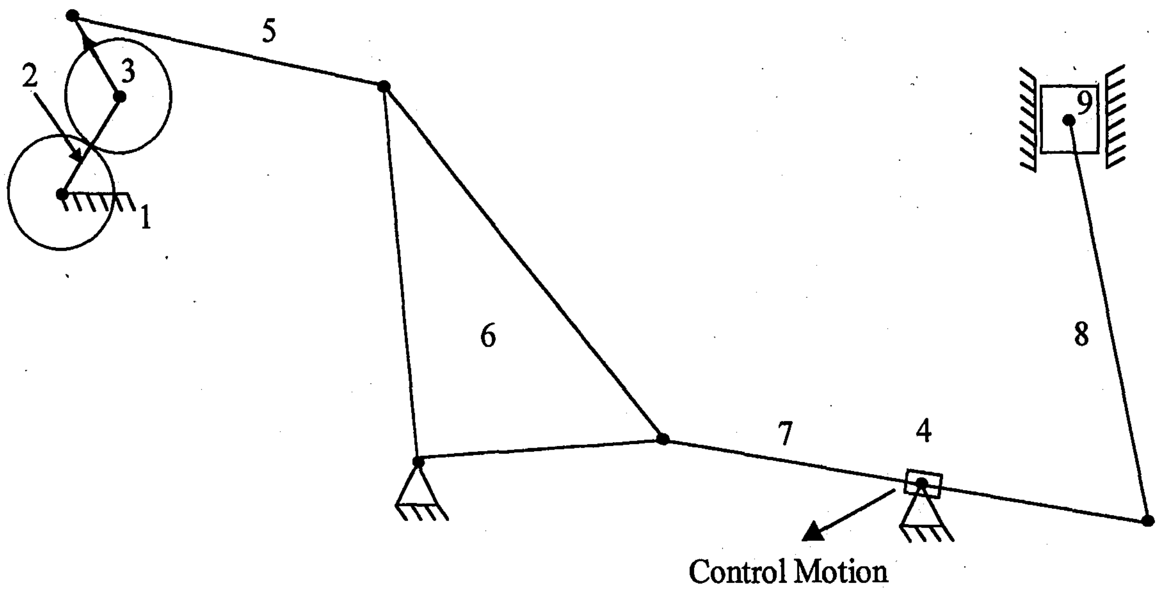


Figure 32: Variable Non-Uniform Stroke Mechanism 3

8.3.2 Benefits

The benefits of using VNUSE 3 are again derived from the sub mechanisms. This mechanism contains a slider control point that moves very little during normal operation. The slider only moves significant amounts when the stroke is actually varied. The direction of the control motion is perpendicular to the force on the slider, thus it is a low friction, low power joint that is easy to move in a controllable manor.

Link 7, the link that the control motion is affecting, moves along a very complicated trajectory. While this adds some complexity to the piston trajectory, it also allows for a very general control of the piston trajectory from the control point. In other words, great variability in piston trajectory is possible with this mechanism. More so in fact then allowed by the simpler variable rocker used in variable mechanism 1. For these

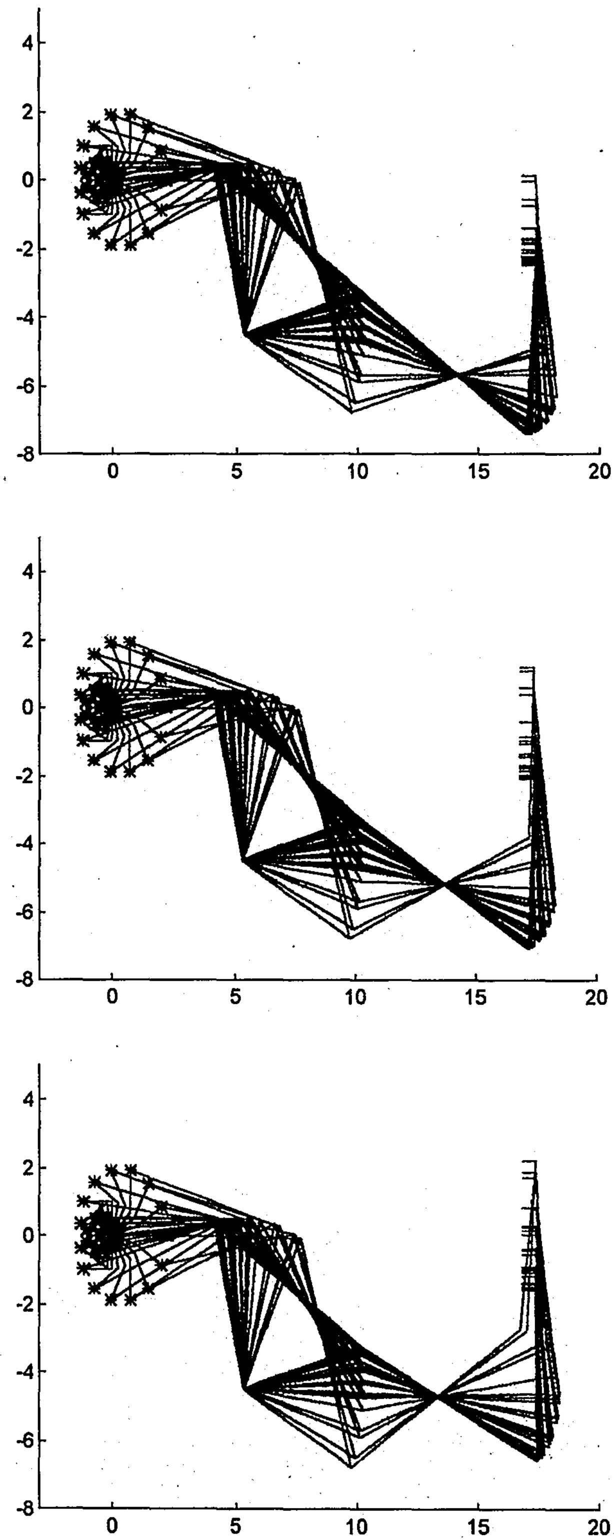


Figure 33: VNUSE 3 in Three Different Stroke Length Configurations

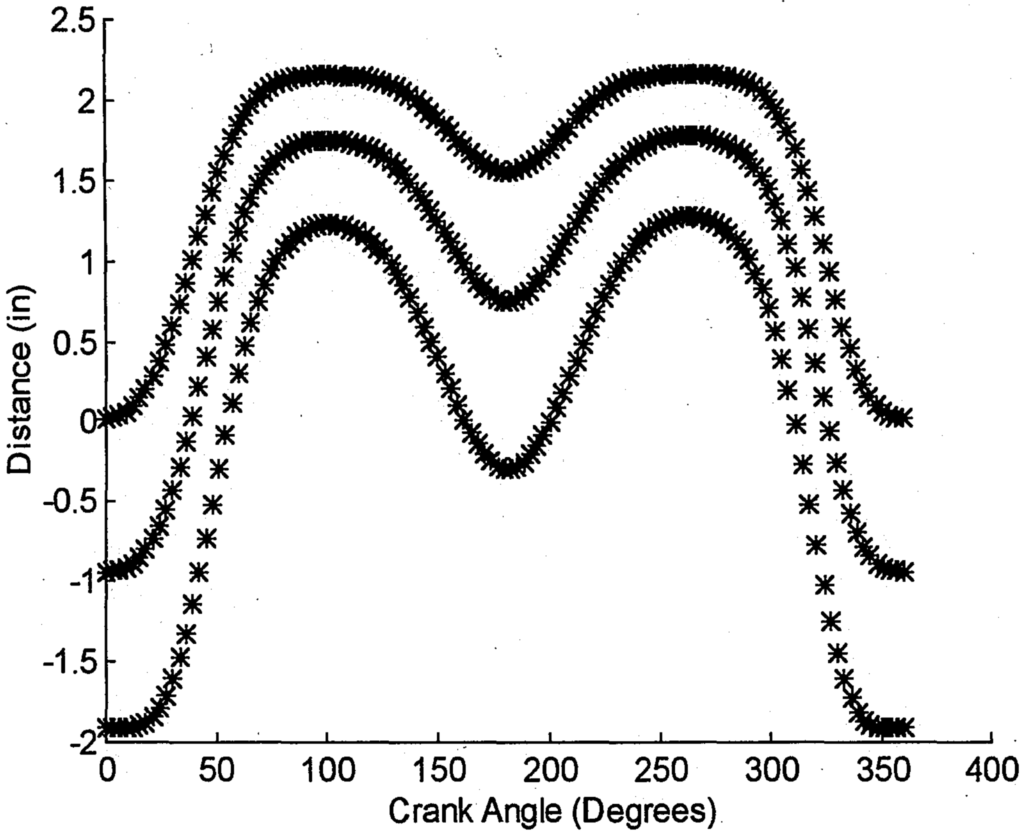


Figure 34: Piston Trajectory of VNUSE 3 With Three Different Stroke Lengths

reasons, very nearly constant compression ratio can be attained with this mechanism. This is accomplished by moving the control point slightly down as it moves to the left. This brings the piston down as the stroke length increases keeping compression ratio nearly constant.

8.3.3 Drawbacks

The main drawback of VNUSE 3 is the complicated motion of its oscillating link # 7. While it's complicated, general motion allows great variability for compression ratio control, its somewhat sporadic motion causes the piston trajectory to have some undesirable characteristics. Smooth, sine wave-like curves are desired for minimum accelerations and shaking forces, but as Figure 34 shows, this mechanism's piston trajectory contains some sections with relatively flat slopes and others with very steep slopes. These steep slopes convert to high accelerations and undesirable forces. Further, the variable portion of this mechanism contains long bulky links which is undesirable for use in the space conscious automotive industry.

8.4 Variable Non-Uniform Stroke Engine 4

VNUSE 4 combines variable stroke mechanism 2 and an Atkinson cycle, non-uniform stroke mechanism. The mechanisms are spliced in the usual manor producing a ten link mechanism. By adjusting the alignment between the lamniscate produced by the Atkinson linkage and the variable mechanism's rocker link, an acceptable output piston trajectory is achieved.

8.4.1 Details of Engine Operation and Performance

A schematic of VNUSE 4 is shown in Figure 35. The Atkinson linkage, containing links 1, 2, 3, and 4 is joined to the variable mechanism via link 5. The lamniscate produced by the linkage transfers a double hump motion to the rocker, link 6. The rest of the mechanism is identical to VNUSE 3's variable sub-mechanism. The double hump motion is transferred to the piston and the variable control point allows variation in stroke length while maintaining a nearly constant compression ratio.

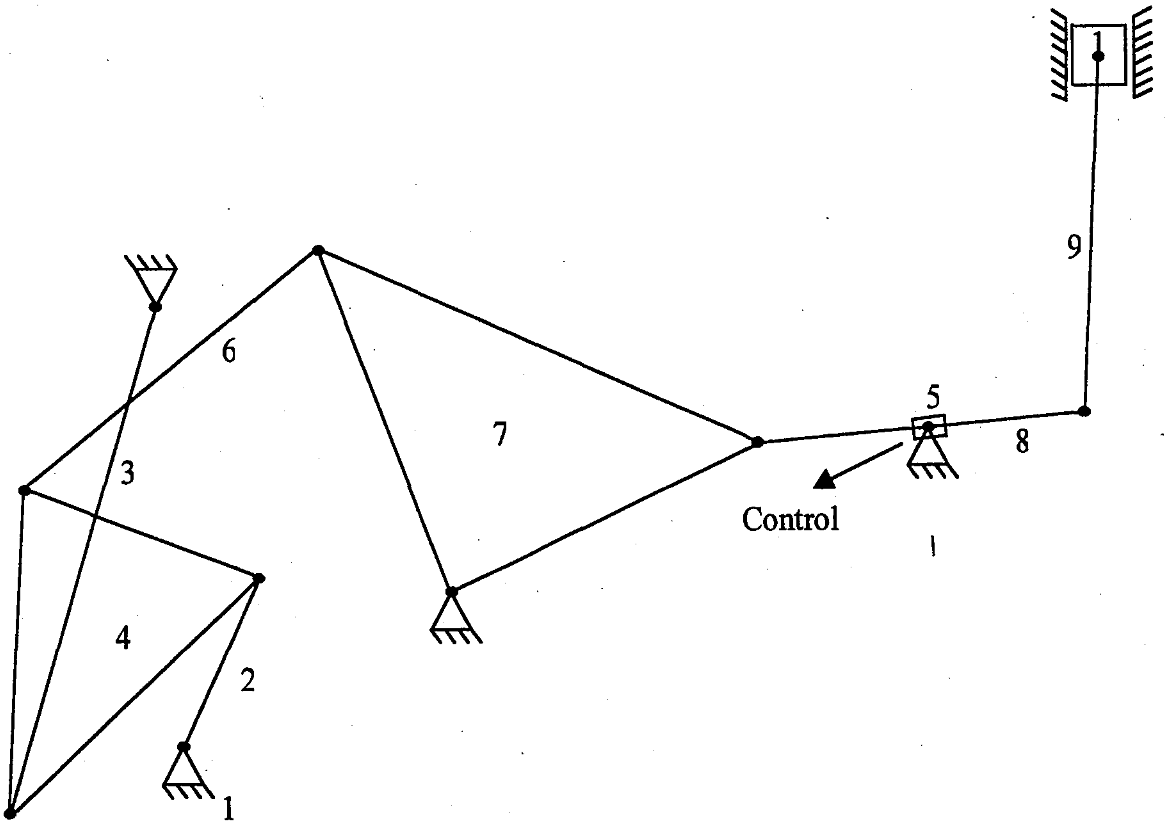


Figure 35: Variable Non-Uniform Stroke Mechanism 4

VNUSE 4 is shown in three different configurations in Figure 36, with a short, medium, and long piston stroke. The figures show the link positions in 15 degree increments of crank rotation. The output piston trajectory of each configuration is shown in Figure 37.

8.4.2 Benefits

The benefits discussed in the previous section including desirable transmission angles, maintaining nearly constant compression ratio, and the high degree of control of the variable sub mechanism are applicable to VNUSE 4. Further, VNUSE 4 utilizes the more inexpensive Atkinson linkage for it's non-uniform mechanism as opposed to VNUSE 3's expensive gearing.

8.4.3 Drawbacks

The main drawbacks of VNUSE 4 are the same as that of VNUSE 3. The oscillating link which causes a somewhat sporadic motion which leads to a undesirable piston trajectory, and large size which limits its applications.

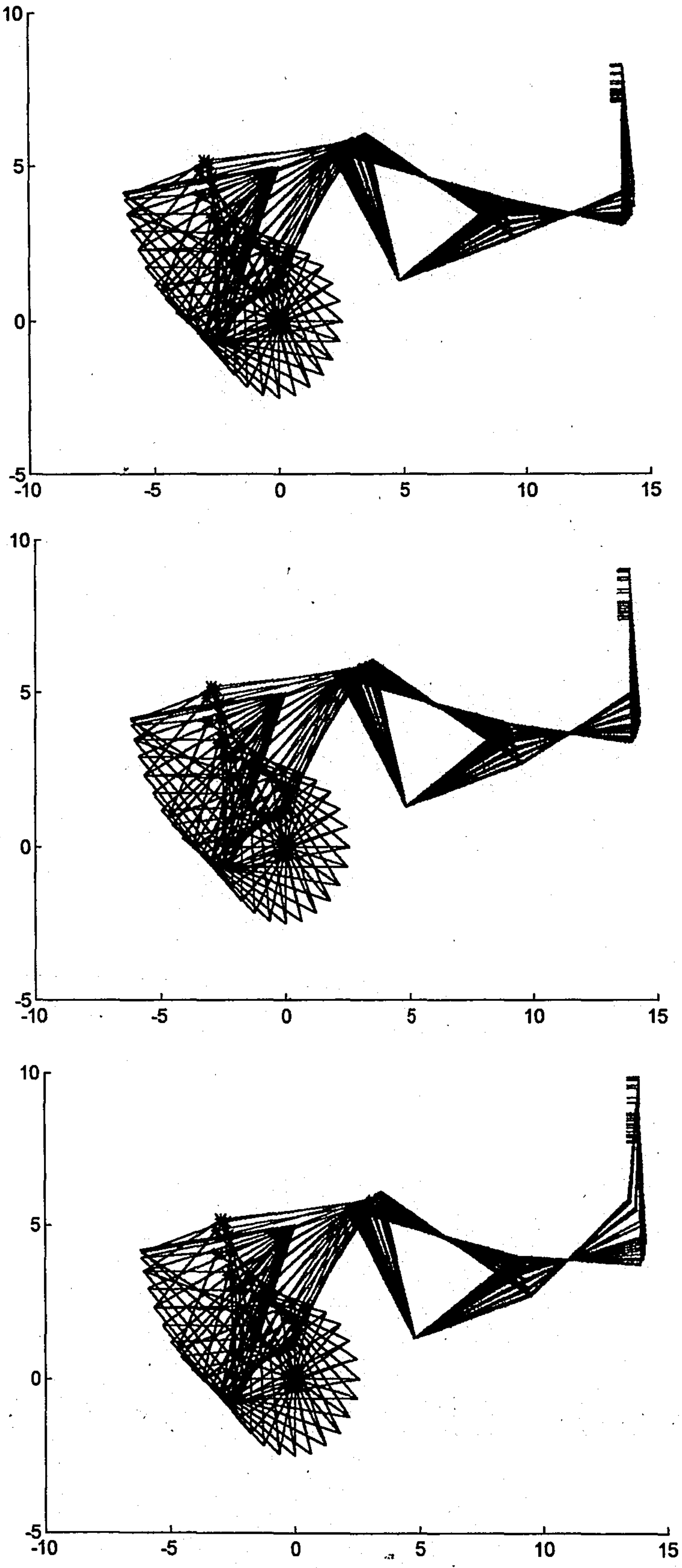


Figure 36: VNUSE 4 in Three Different Stroke Length

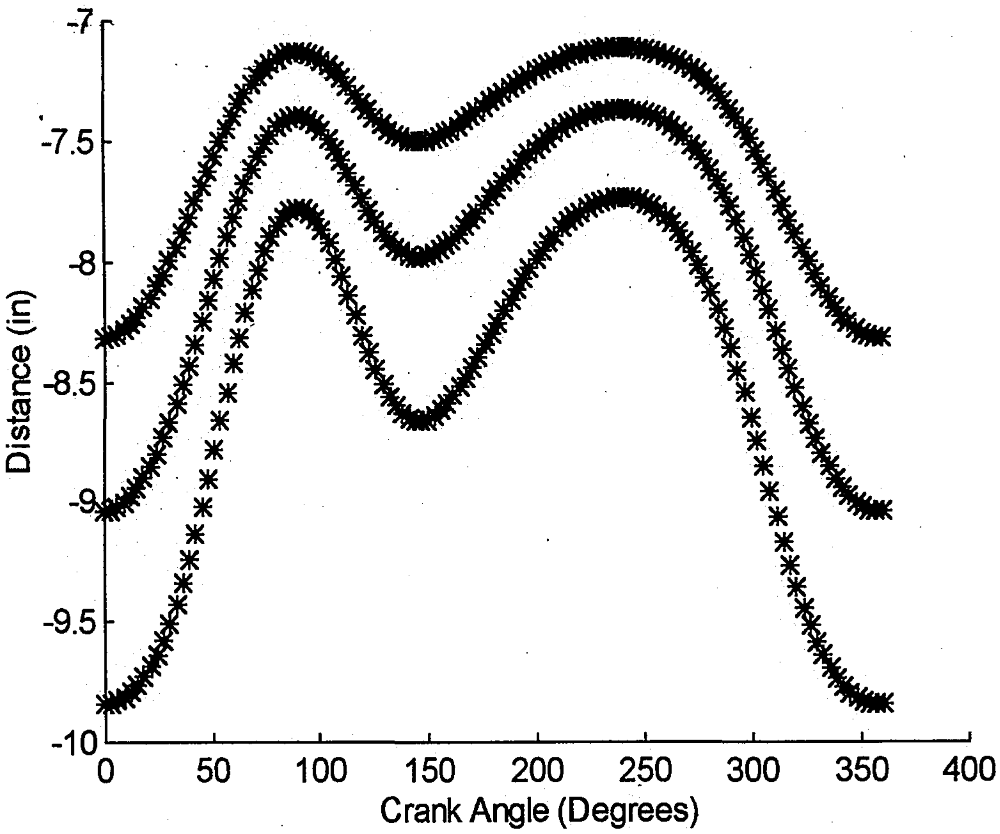


Figure 37: Piston Trajectory of VNUSE 4 With Three Different Stroke Lengths

8.5 Variable Non-Uniform Stroke Engine 5

VNUSE 5 combines variable stroke mechanism 3 and a planetary gearing, non-uniform stroke mechanism. Splicing the gearing mechanism in place of the crank of the variable mechanism produces a nine link mechanism capable of variable, non-uniform piston trajectories.

8.5.1 Details of Engine Operation and Performance

A schematic of VNUSE 5 is shown in Figure 38. The non-uniform gearing mechanism containing links 1, 2, and 3 is joined to the variable mechanism via link 6. A double hump motion is produced by the gears and transferred to a quaternary oscillating link, # 7, which is pinned to a grounded rocker, link 5, and slotted to a control slider, link 4. The opposite end of this oscillating link is pinned to the connecting rod which moves the piston. The oscillator moves up and down, pivoting on the grounded slider similarly to the oscillator in variable mechanism 2. However, because this oscillator is a quaternary link also pinned to rocker 5, it's motion is more constrained then the oscillator in variable mechanism 2. The slider, link 4, acts as the control point for the variable

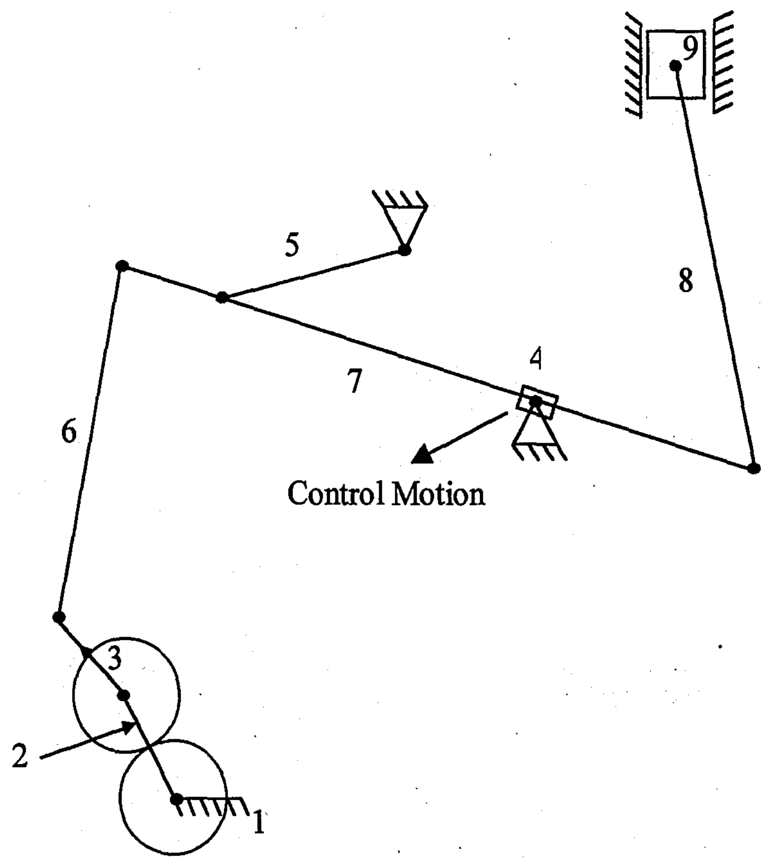


Figure 38: Variable Non-Uniform Stroke Mechanism 5

portion of the mechanism.

The stroke length is varied by moving the control point to the right or left.. By moving the control point to the left, the pivot point of link 7 is moved closer to its driving link, #6, causing the right side of the link to oscillate up and down further and the piston to travel a longer stroke. Moving the control point the right reverses the effect.

VNUSE 5 is shown in three different configurations in Figure 39, with a short, medium, and long piston stroke. The figures show the link positions in 15 degree increments of crank rotation. The output piston trajectory of each configuration is shown in Figure 40.

8.5.2 Benefits

The motion of the quaternary oscillator link, # 7, is one of the main benefits of this mechanism. This link performs a similar job to the oscillating link in the previous two engine mechanisms, however, it has an important difference. It is pinned to a rocker link in addition to the links that the previous oscillator is joined to. At first glance, this additional joint might be suspect of removing a necessary degree of freedom from the mechanism. This is not the case since link 6 has also changed from a tertiary rocker to a binary coupler, thus keeping the total number of degrees of freedom equal to one.

The rocker, link 5, causes link 7 to move with a smoother motion then the oscillators in the previous two engines. The net effect is a more desirable, sinusoidal shaped piston trajectory. This slightly more constrained motion does not take away from the ability to control the stroke length and compression ratio with the control point. All of the benefits previously stated concerning this variable sub-mechanism are still

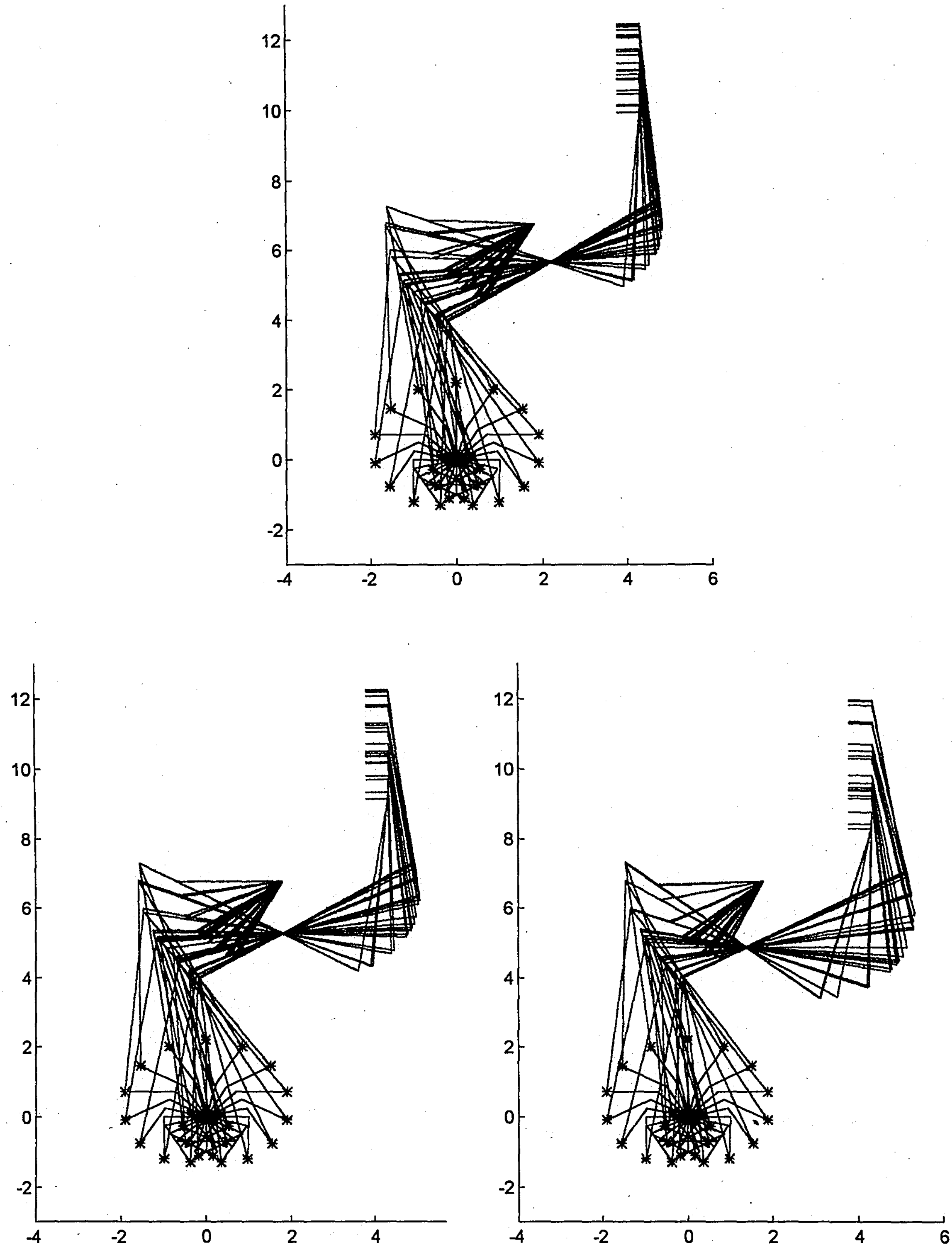


Figure 39: VNUSE 5 in Three Different Stroke Length Configurations

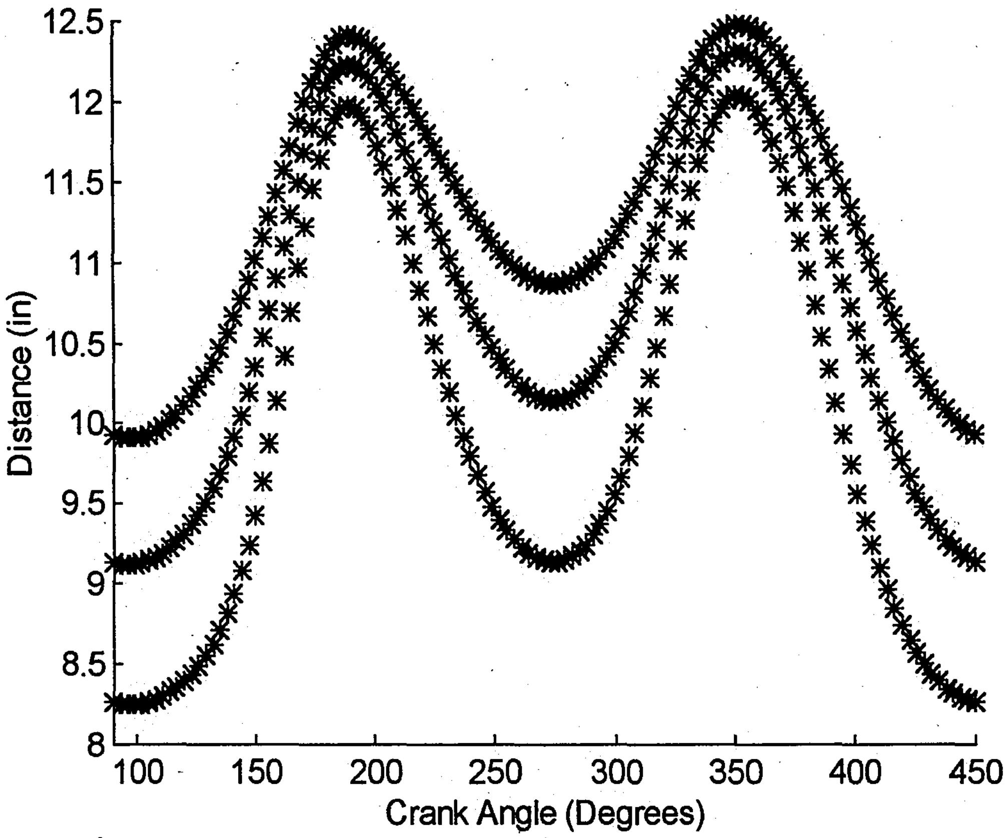


Figure 40: Piston Trajectory of VNUSE 5 With Three Different Stroke Lengths

applicable as well as the benefits associated with the geared non-uniform stroke mechanism.

8.5.3 Drawbacks

There are no additional drawbacks to this mechanism other then the ones previously discussed concerning the individual sub-mechanisms.

8.6 Variable Non-Uniform Stroke Engine 6

VNUSE 6 combines variable stroke mechanism 3 and an Atkinson cycle, non-uniform stroke mechanism. The mechanisms are spliced in the usual manor producing a ten link mechanism capable of variable, non-uniform piston trajectories.

8.6.1 Details of Engine Operation and Performance

A schematic of VNUSE 6 is shown in Figure 41. The Atkinson linkage, containing links 1, 2, 3, and 4 is joined to the variable mechanism via link 7. The lamniscate produced by the linkage transfers a double hump motion to the oscillator, link 8. The rest of the mechanism is identical to VNUSE 5's variable sub-mechanism. The double hump motion is transferred to the piston and the variable control point allows

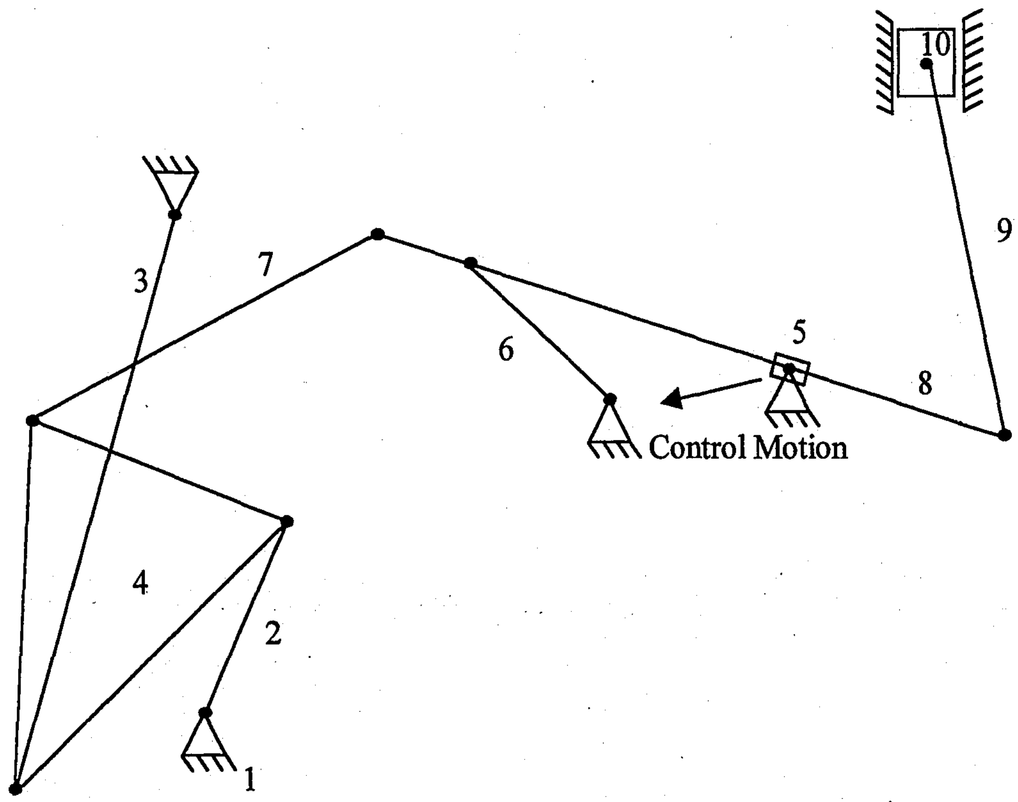


Figure 41: Variable Non-Uniform Stroke Mechanism 6

variation in stroke length while maintaining a nearly constant compression ratio.

VNUSE 6 is shown in three different configurations in Figure 42, with a short, medium, and long piston stroke. The figures show the link positions in 15 degree increments of crank rotation. The output piston trajectory of each configuration is shown in Figure 43.

8.6.2 Benefits

The benefits discussed in the previous section including a more smoother oscillator motion, desirable transmission angles, and maintaining nearly constant compression ratio are applicable to VNUSE 6. Further, VNUSE 6 utilizes the more inexpensive Atkinson linkage for it's non-uniform mechanism as opposed to VNUSE 5's expensive gearing.

8.6.3 Drawbacks

There are no additional drawbacks to this mechanism other then the ones previously discussed concerning the individual sub-mechanisms.

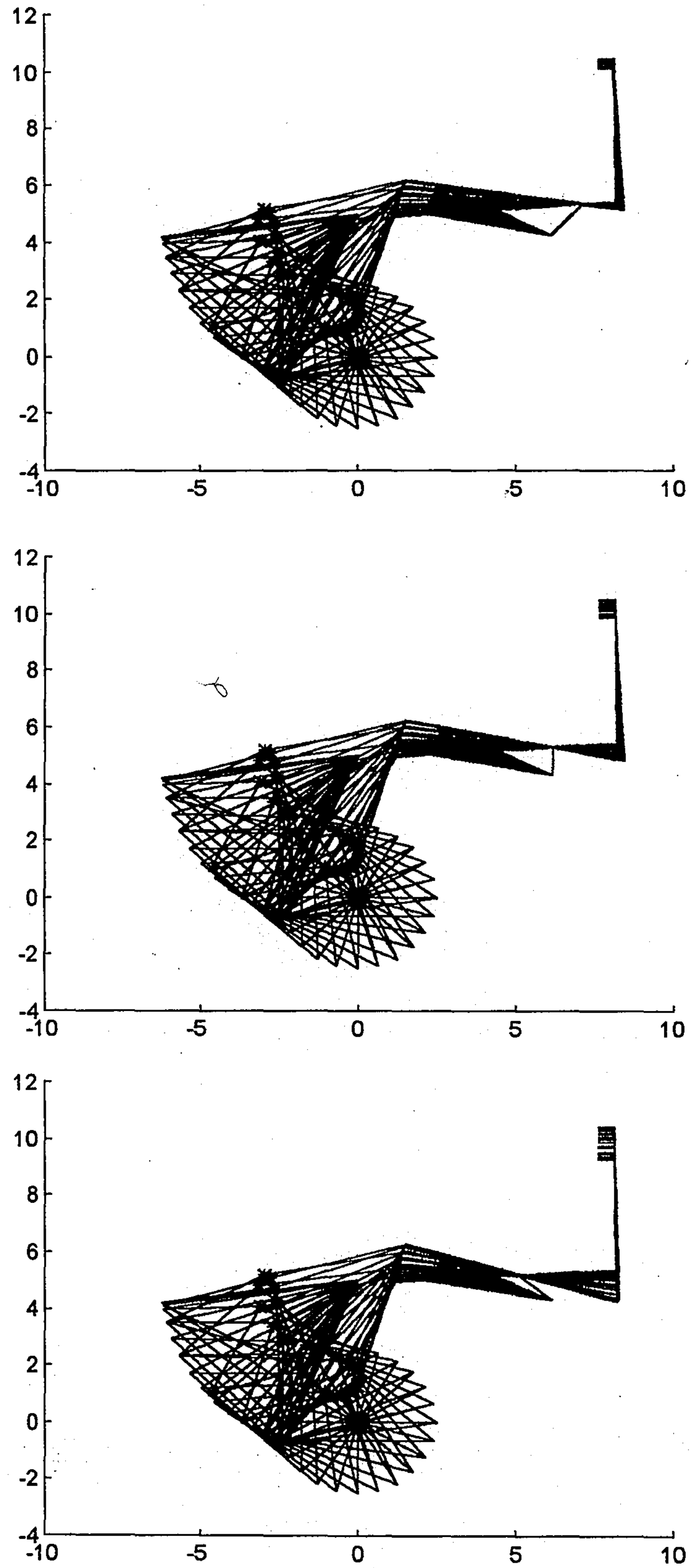


Figure 42: VNUSE 6 in Three Different Stroke Length Configurations

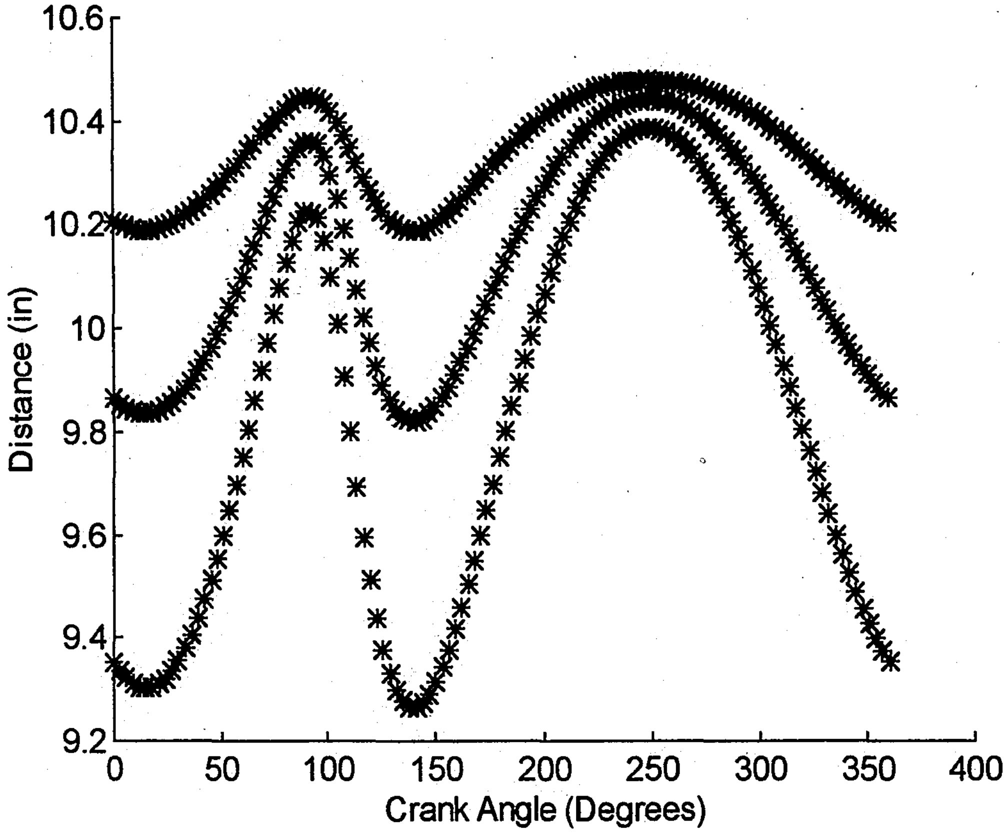


Figure 43: Piston Trajectory of VNUSE 6 With Three Different Stroke Lengths

Chapter 9: Conclusions and Recommendations

Six mechanisms that can generate variable, non-uniform stroke piston trajectories have been realized and analyzed. Each of these mechanisms have been refined to a degree that they produce a desirable trajectory with efficient power transfer from the piston to the crank shaft, as well as maintain a nearly constant compression ratio over the variable range. These engines all benefit from increased efficiencies derived from each of their sub-mechanisms. The non-uniform trajectory increases efficiency by extracting more energy from the burned fuel, while the variable trajectory allows decreased displacement when low power is needed, thus increasing efficiency. The basic drawbacks of all these mechanism is their great size and complexity that makes them expensive and difficult to employ in many applications.

In order to proceed further with developing any of these mechanism into actual working internal combustion engines a more detailed machinery design analysis must be performed. In addition to choosing one of the six mechanism and detailing the design to minimize space requirements, it is recommended that future work be done on resolving some other major difficulties. These difficulties include balancing, lubrication, and cylinder wear.

The large number of links associated with these complex mechanisms makes balancing extremely difficult and in general makes perfect balance with zero reaction forces impossible. However, a great reduction in reaction forces is possible with the use of balancing masses and further balancing can be accomplished with the use of additional balancing shafts if deemed necessary.

Lubrication also presents a problem, especially for the large number of oscillating links. Since oscillating links do not rotate continuously in the same direction, they require special care to lubricate. A crank link that rotates in the same direction continuously uses the inertia of the rotating lubricant to keep the lubricant in place in the bearing. Since oscillating links change direction, the beneficial inertia force drops to zero at every direction change, leaving the joint poorly lubricated.

A final issue arising with variable piston stroke is uneven cylinder wear. The ability to vary the stroke length causes the piston to contact different areas of the cylinder for different amounts of time. This will cause the cylinder to wear excessively in the areas of the most often used stroke length, and minimal wear to occur in the areas of less often used stroke lengths. This uneven wear will lead to increased friction, sealing problems, and possibly piston damage. Although a major problem, this issue can be resolved by requiring engine overhauls at somewhat more often intervals then conventional engines.

The problems mentioned above, although great, are by no means insurmountable. With continued work on solutions to these problems, a feasible, variable, non-uniform stroke engine can be developed that will exhibit great gains in efficiency and performance over conventional piston engines.

This thesis has demonstrated the effectiveness of graph theory in it's traditional role of conceptualizing mechanisms to perform complex tasks. Further demonstrated, is the capability of using graph theory to combine two mechanisms that perform individual tasks into a single mechanism that performs both tasks. The joining of variable and non-uniform piston trajectories has been a successful utilization of graph theory in this role.

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Vita

The author was born in Meadowbrook Pennsylvania on December 17, 1975 to Virgil and Diane Banowetz. He earned his Bachelors of Science in Mechanical Engineering from Lehigh University in May, 1998. The author then continued his education at Lehigh, specializing in mechanisms and dynamics as well as working as a Teaching Assistant. In 1999, he was a co-recipient of the Mechanical Engineering Teaching Assistant of the Year Award. He will receive his Masters degree in Mechanical Engineering in January, 2000.

END OF TITLE