Fall Semester 2019

Name of Student: $\qquad$
Lab Section Number: $\qquad$

Project 1. Upload to Gradescope before 8:00 am on Monday, September 16th. A formal report is not required, however, credit will be given for a detailed presentation and clearly drawn figures.

Straight-line generators played an important role in machinery before the advent of high precision machining (see Chapter 1, pages 39 and 40). The best-known straight-line generator is the Watt parallel motion linkage, see Figure 1.24(a), page 39, which James Watt designed for the early double-acting steam engine, see Figure 1 below. The most important feature of the Watt four-bar linkage is that the path traced by the coupler point M generates an approximate straight line over a considerable distance which will allow point L on the piston to travel up and down inside the cylinder.


Figure 1. A schematic diagram of the early steam engine. (Not drawn to scale).

The origin of the fixed Cartesian reference frame XY is chosen as the shaft at the ground bearing $\mathrm{O}_{2}$. The ground link $\mathrm{O}_{2} \mathrm{O}_{4}$ is inclined at the angle $\beta=15^{\circ}$ and the ground link $\mathrm{O}_{2} \mathrm{O}_{6}$ is inclined at the angle $\psi=60^{\circ}$ from the horizontal X -axis. The distance $\mathrm{O}_{2} \mathrm{O}_{4}=200 \mathrm{~mm}$ and the distance $\mathrm{O}_{2} \mathrm{O}_{6}=400 \mathrm{~mm}$. The horizontal distance between the Y -axis and the centerline of the double-acting cylinder is 93.5 mm and the vertical distance from the X -axis to the ground at the bottom of the cylinder is 320 mm . The great beam CD is chosen as the input (link 2) with the length $\mathrm{CD}=336 \mathrm{~mm}$. The length $\mathrm{O}_{2} \mathrm{C}=\mathrm{O}_{2} \mathrm{D}=168 \mathrm{~mm}$ and the length $\mathrm{O}_{2} \mathrm{~A}=84 \mathrm{~mm}$. The length of the coupler link 3 is $\mathrm{AB}=60 \mathrm{~mm}$ and the length of link 4 is $\mathrm{O}_{4} \mathrm{~B}=90 \mathrm{~mm}$. The location of the coupler point M is $\mathrm{AM}=\mathrm{BM}=30 \mathrm{~mm}$. The lengths of links $5,7,8$, and 9 are $\mathrm{DE}=350 \mathrm{~mm}, \mathrm{LM}=200 \mathrm{~mm}, \mathrm{BM}^{\prime}=76 \mathrm{~mm}$, and $\mathrm{M}^{\prime} \mathrm{C}=58 \mathrm{~mm}$. The radius of the fixed sun gear is $\rho_{\mathrm{S}}=42 \mathrm{~mm}$ and the radius of the planet gear (link 6) is $\rho_{\mathrm{P}}=36 \mathrm{~mm}$.

Assume that for the range of the input angle $156^{\circ} \leq \theta_{2} \leq 203^{\circ}$, the angular velocity of the great beam is a constant $10 \mathrm{rad} / \mathrm{sec}$ counterclockwise.
(i) Determine the mobility of the double-acting steam engine shown in Figure 1. Does the Kutzbach criterion give the correct answer for the mobility? Explain why or why not.
(ii) Does the Watt four-bar linkage $\mathrm{O}_{2} \mathrm{AB} \mathrm{O}_{4}$ satisfy Grashof's law? Explain why or why not.
(iii) Write a computer program, using an appropriate vector loop equation and the Newton-Raphson technique, to obtain the posture variables $\theta_{3}$ and $\theta_{4}$ for the given range of the input angle. Present the posture variables in a tabular format and also plot these variables against the range of the input angle. Determine the input angle when the coupler point M is on the X -axis (as shown in Figure 1).
(iv) Write symbolic equations for the first-order and second-order kinematic coefficients of links 3 and 4. Include these equations in your computer program and obtain numerical values for these kinematic coefficients. Present your results in a tabular format and show plots of the first and second-order kinematic coefficients against the given range of the input angle.
(v) Supplement your program to compute the position of the coupler point $M$ and the first-order and second-order kinematic coefficients of point M. Present the results in a tabular format. Show plots of the first-order and second-order kinematic coefficients against the given range of the input angle.
(vi) Plot the path of the coupler point $M$ for the given range of the input angle. Specify the total X and Y displacements of point M and the values of the input angle when point M has the maximum X and Y displacements and the minimum X and Y displacements. Tabulate and plot the radius of curvature and the center of curvature of the path traced by the coupler point M .
(vii) Determine the total stroke of this double-acting steam engine, that is, the vertical distance travelled by point L on the piston.
(viii) Tabulate and plot (for the given range of the input angle): (a) the angular velocities and angular accelerations of links 3 and 4 ; and (b) the velocity and acceleration of the coupler point M .

Include a discussion of the important results. Also, include your observations and recommendations to improve this design of this steam engine. The project is intended to be an open-ended kinematics project and your TA can provide more information upon request.

For more information and possible applications of the Watt four-bar linkage, see, for example:
https://en.wikipedia.org/wiki/Watt\'s_linkage\#/media/File:Watts_linkage.gif

