Lab #3 - Slider-Crank Lab

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INTRODUCTION

In this laboratory we will investigate the kinematics of some simple mechanisms used to convert rotary motion into oscillating linear motion and vice-versa. The first of these is the slider-crank - a mechanism widely used in engines to convert the linear thrust of the pistons into the useful rotary motion of the drive-shaft. In this lab you will measure the linear acceleration of the piston of a lawn mower engine at various rotation rates of the drive shaft. The results exemplify a simple relation between speed and acceleration for kinematically restricted motions, which you will discover. An adjustable slider-crank apparatus and a computer simulation will show you some effects of changing the proportions of the slider-crank mechanism on piston velocity and acceleration. Other linkages and cam mechanisms may also be used for linear-rotary motion conversion and some of these will be included in the lab.

Linear momentum balance allows us to relate the forces acting on a body to its acceleration ($\underline{\mathbf{F}} = m\underline{\mathbf{a}}$). Thus a knowledge of the acceleration $\underline{\mathbf{a}}$ of a piston permits analysis of the total force $\underline{\mathbf{F}}$ acting on it. Knowledge of these forces is crucial if one is to choose the right material, proportions, and operating conditions for a new design.

PRELAB QUESTIONS

Read through the laboratory instructions and then answer the following questions:

1. What data will you collect from the lawn-mower engine and what will you simulate on the computer?

2. Which parameter(s) can be varied on the adjustable slider-crank? Which are fixed?

3. Derive an equation relating the piston displacement x to the crankshaft speed, ω, time, t, connecting rod length, L, and crank radius R. (Hint: Use trigonometry).

SLIDER-CRANK KINEMATICS & INTERNAL COMBUSTION ENGINES

Figure 3.1 shows a sketch of the slider-crank mechanism. The point A is on the piston, line AB (with length L) is the *connecting rod*, line BC (with length R) is the crank, and point C is on the *crankshaft*. In an engine, a mixture of gasoline and air in the cylinder is ignited in an exothermic (heat producing) reaction. As a result, the pressure in the cylinder rises, forcing the piston out. The force transmitted through the connecting rod has a moment about the center of the crankshaft, causing the shaft to rotate. An exhaust valve releases the gas pressure once the piston is extended. Inertia of machinery (often a flywheel) connected to the crankshaft (as well as forcing from other pistons in multi-cylinder engines) forces the

piston back up the cylinder. In a standard "four-cycle" engine the crankshaft makes another full revolution before another ignition (to bring in fresh air and compress it before ignition).

In this experiment the crankshaft is driven by an electric motor. The piston is driven by this crankshaft rotation at a more or less constant rate. The same motion results as when the combustion process takes place. As the crankshaft rotates the piston moves in the positive and negative x direction. The basic measurements in this lab are the position and velocity of the piston in the x direction (which happens to be vertical in the laboratory). These measurements can be compared to those calculated by hand (if you are energetic) or to the results of a computer simulation. The simulation and the adjustable crank will allow you to see some of the effects of varying the ratio of connecting rod length L to crank length R.
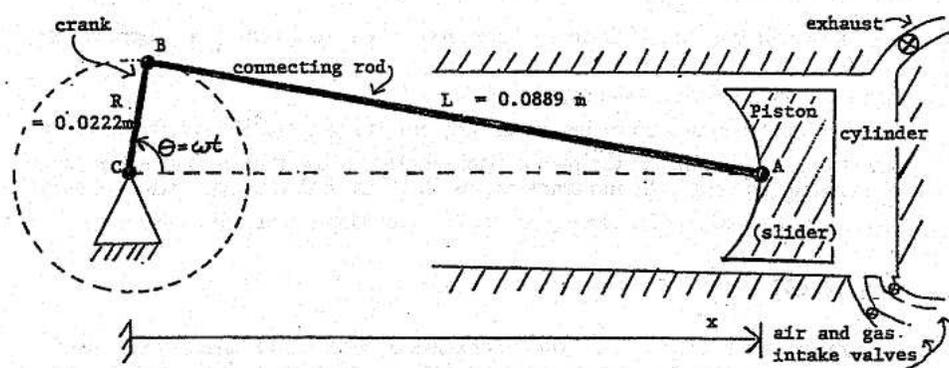

Figure 3.1: A diagram of the slider-crank system.

LABORATORY SET-UP
A stripped-down lawn mower engine is driven by a variable-speed electric motor. Sensors are installed on the engine's piston to measure displacement and velocity. A data acquisition program is used to measure, analyze, and record the piston data. Look at the engine and see how its various parts fit together. It may help to look at Figure 3.1 and at the various demonstration slider-cranks present in the dynamics laboratory. Identify the piston, connecting rod, and crankshaft (the connecting rod won't be visible at your lab set-up, but you can see it in the demonstration slider-cranks). The cylinder head has been removed, exposing the top of the piston and allowing sensors to be attached.

The speed and direction of the electric motor are controlled by a knob and switch on the motor controller. The numbers on the speed controller are arbitrary; do not write them down as r.p.m. or radians per second (instead obtain angular velocity information from the data acquisition program). *Does the direction of motor rotation affect the slider-crank kinematics?*

The displacement and velocity data are measured using a LVDT and velocity transducer. Acceleration is calculated by the computer through numerical differentiation of the velocity data. This process magnifies any noise in the data. The computer also measures and displays

the angular frequency by timing successive crossings of the zero line and converting to radians per second. The displacement, velocity, and acceleration are all plotted in *LabView* along with their minimum and maximum values (see Figure 3.2). A simple simulation program lets you compare your data to theoretical values and look at the effects of different slider-crank geometries.

Please follow safety precautions. The electric motor driving the lawn mower engine is powerful enough to cause serious injury if you get in its way. Keep long hair and loose clothing well away from the belt and pulleys at the back of the engine. If you need to touch the pulley, piston, or LVDT for some reason, check first that the electric motor power is off and that the speed control is set to zero. Make sure your lab partner knows what you are doing.

Using the LabView software

1. To run the software, open up the *Engrd203Lab* account and then open the folder *Crank* on the desktop. Open the program *Crank*. As soon as the program is running, it will ask you to move the piston to the top of its travel. Press `Ready` after you have done this and wait until the next pop-up comes before moving the piston again. Then once prompted move the piston to the bottom of its travel and press `Ready` again and allow the computer a few seconds to calibrate. This calibration procedure allows the computer to convert the output of the LVDT (in volts) into displacement (in meters). Do this carefully. It may help to rock the pulley back and forth slightly as you try to home in on the highest (or lowest) piston position. If you make a mistake, you can redo the procedure by clicking on the `SET-UP` button. The *Crank* program has a box for the initials of your lab group. Click on the box with the mouse, type your initials, and then press the `Enter` key, not the `Return` key. Your initials will then appear on your plots, making it easier to identify them as they emerge from the laser printer.

2. When the data acquisition "switch" on the screen is turned on, the computer acquires and displays a new set of data every ten seconds or so. Allow ten or twenty seconds for the data plot to stabilize after changing the motor speed. If you have a plot that you want to keep, turn the data acquisition off. Also turn the motor off promptly when you are not acquiring data to save wear and tear on the lab set-ups and on the nerves of other students.

   The legend and scale factors for the plots are displayed in the top left corner. Multiply the y-axis reading (between -1 and 1) by the appropriate scale factor to obtain the actual measured value, in the units given in the legend. For example, if the velocity plot has a y-value of 0.5 at a particular time, and a scale factor of 4 m/s, the measured velocity at that time would then be 0.5*4 m/s = 2 m/s.

3. **Before printing, check that data acquisition is off. Otherwise, one plot can take 20 minutes or more.** Also, be sure your initials are on the graph so you can distinguish it from another lab group's graph. To print, pull down the `File` menu and

select `Print`. Each new graph takes a minute or two, so only print one out if you really need it. However, you can get a copy for your lab partner in just a few additional seconds by setting `Number of Copies` equal to two. You can continue working while plots are being printed.

4. The `SAVE` button stores your data on the hard disk, but the file created this way can only be used by the simulation program (*CrankSim2*).

5. To exit from the program, click the "close" box in the top right corner of the window. To leave *LabView* completely, at any time, pull down the `File` menu and select `Quit`. If the program tells you that "Quitting now will stop all active VIs" select `OK`.
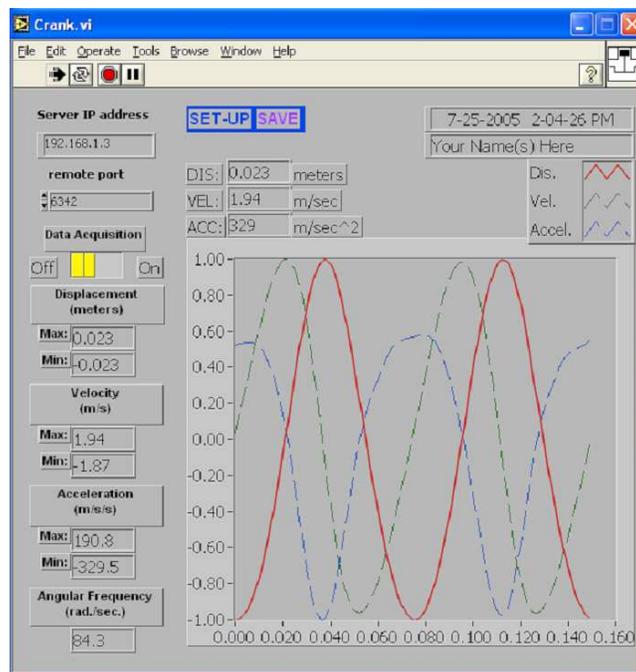

Figure 3.2: Using the *LabView Crank* program.

PROCEDURE

You will record and analyze $x(t)$, $v(t)$, and $a(t)$ while spinning the lawn mower engine at various speeds.

1. Check that the electric motor power switch is off, the speed control knob is at zero, and the data acquisition is on. Twist the pulley back and forth by hand and look at the resulting plot of piston position, velocity, and acceleration. If the piston moves upwards, in what direction does the plotted curve move? *(i.e. how is the coordinate system defined for our system?)* You will need to wait several seconds for the data to be displayed.

2. Put a penny on top of the piston, turn on the motor, and adjust the motor speed so that the penny just barely starts to bounce on top of the piston. You should be able to hear a faint clinking sound. Wait until you have a good graph of the data and then turn off first the data acquisition and then the motor. Record the angular velocity and the minimum and maximum values for the displacement, the velocity, and the acceleration. Check that the displacement plot makes sense, given that the crank length is known to be 0.0223 m. Check that the acceleration data makes sense - *what should the acceleration be when the penny begins to leave the top of the piston? Given the coordinate system for our engine should that be the maximum or minimum value of the acceleration for this data?*

3. Remove the penny and repeat the procedure above for at least four additional speeds. Try to get as wide a variety of speeds as possible. At very slow speeds the motor does not turn smoothly and the data is drowned out by noise. When using very high speeds, try to acquire data quickly, turn off the data acquisition "switch", and shut the motor off immediately. Record your data in a table (including the penny data).

You will now simulate the slider-crank mechanism on the computer. The *CrankSim2* program (Figure 3.3) will be used to compare the theoretical values for displacement, velocity, and acceleration with the values measured above. The effects of changing the crank length R, connecting rod length L, and angular velocity ω of the crankshaft may also be observed.

1. To start up the simulation program double-click on *CrankSim2* in the *Crank Lab* folder. If you want to compare your simulation to your most recently saved data, turn the measured-data "switch" on; otherwise, turn it off to eliminate the clutter of all the extra graphs. Described below are the parameters you can change in the simulation:

    - R is the crank length in meters.
    - L is the connecting rod length in meters.
    - ω is the angular velocity of the drive shaft in radians per second.
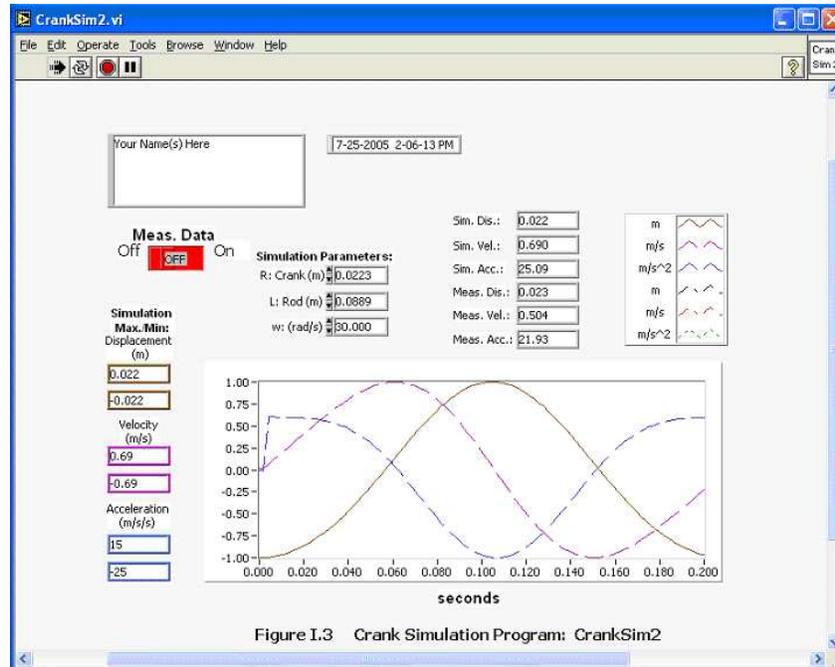
Figure 3.3: Using the *LabView CrankSim2* program.

As with the data acquisition program, the maximum and minimum values are displayed. These are the simulation maxima and minima. Note that the displacement shown is the value x in Figure 3.1 minus the connecting rod length L. This makes it more easily comparable to the measured data. The $x = 0$ point is thus defined to be halfway between the piston's top and bottom positions instead of at the center of the crankshaft.

2. Set up the simulation with the crank length and connecting rod length of the lawn mower engine. Enter the angular velocity used in the data you saved previously and turn the Measured Data switch on. Adjust the simulation curve up or down for best alignment and compare the two sets of plots. **You will need to print your data.**

3. Switch off the measured-data curve. Now simulate slider-cranks with different geometries by varying the crank length R and the connecting rod length L. Observe and record velocities and accelerations when:

   - L is much greater than R - i.e. L of 10 m, and R of 0.0223 m

   - R is increased, but still much smaller than L - i.e. L of 10 m and R of 0.223 m

   - L is decreased, but still much larger than R - i.e. L of 1 m and R of 0.0223 m

   - R and L equal the values for the lawn mower engine - i.e. L of 0.089 m and R of 0.0223

   - L is only slightly greater than R - i.e. L of 0.0224 m, and R of 0.0223 m *What happens physically when R is greater than L? Make one or two print-outs if necessary to support your observations and conclusions.*

Next you will work with the adjustable slider-crank. This device allows you to adjust the crank length to connecting rod ratio $\frac{R}{L}$ from zero to slightly more than one, using an adjustment knob which changes the effective crank length. A handle is located underneath to rotate the apparatus by hand. **Please be gentle with it!** Large forces can be generated with even a small input torque when the ratio is close to 1. If you see things bending, back off. When turning the hand crank, do it slowly. You can also push and pull on the masses at the end of the "piston" to look at the way it converts linear to rotary motion. Be sure you can identify the crank, connecting rod, and piston on the adjustable crank apparatus as first appearances may be misleading. Here is a hint: the long thin rod with a weight on each end is the piston. Compare the shapes of the curves you saw in the simulation above to what you observe and feel with the adjustable crank.

The slider-crank is just one of many devices that have been invented to convert linear to rotational motion or vice-versa. The scotch yoke, the cam, and the four-bar linkage are some others.

1. Look over the scotch yoke mechanism, which is driven by an electric motor and gearbox. Try it at different speeds and (with the motor off) push and pull on its various parts. Rotate the pulley by hand while watching the motion of the rod. Take measurements or make a drawing if you wish. Be prepared to find a kinematical equation relating disk rotation to yoke displacement and think about the advantages and disadvantages of the scotch yoke relative to the slider-crank.

2. Cam-and-follower mechanisms are a particularly versatile way to convert rotary to linear motion because you can select the type of motion you want by changing the shape of the cam. For example, cams are used in an internal combustion engine to open and close the intake and exhaust valves. Cam shapes are chosen to optimize fuel economy, power, and emission control. The cam in this lab is a simple eccentric disk - i.e. a circle rotating about a point other than its center. Try out the cam mechanism by turning it with your hand. Feel the output from the follower as the cam is rotated and then try rotating the cam by pushing and pulling on the follower.

LAB REPORT QUESTIONS

1. Plot peak piston acceleration vs. crankshaft angular velocity on linear and log-log paper. From these graphs find an appropriate equation relating the two variables. Does this equation make sense? Explain.

2. How does the peak piston velocity depend on the angular velocity of the crankshaft? Plot your experimental data and find an approximate formula relating the two variables. Does this equation make sense? Explain.

3. Examine your plot comparing the measured data and the corresponding simulation data. What explanations can you give of the similarities or differences in the graphs?

4. From your experimental data, what is the crankshaft angular velocity for which an ant standing on the top of the piston would start to need sticky feet in order to not lose contact with the piston? Explain.

5. Using your simulation data, how does the length of the connecting rod, relative to the crank length, affect the shape of the displacement, velocity, and acceleration curves?

6. The lawn mower engine piston weighs 0.175 kg. Using your simulation data, what are the maximum velocity, acceleration, and force on the piston, approximately, for a connecting rod length only slightly longer than the crank length? For a connecting rod length extremely long compared to the crank length? For the connecting rod length actually used in the engine? Use the same crank angular velocity and length in each case.

7. Argue for or against the following points. Back up your arguments with either real or simulated data and/or any other appropriate analysis and logic.

    (a) For all slider-cranks the peak velocity occurs at the midpoint of the stroke.
    (b) There is an optimum $\frac{L}{R}$ ratio for a lawn mower engine *(Clearly state what is being optimized if you support this point)*.

8. For the scotch yoke, work out the equation relating rotation of the pulley to linear motion of the rod.

9. Why is the slider-crank, and not a scotch yoke, used in an engine? Also, what special advantages does the scotch yoke have in some applications?

10. How does the cam-follower mechanism you saw in lab compare kinematically to the scotch yoke? What reasons might a designer have for choosing one over the other?

CALCULATIONS & NOTES