Dynamic Modeling and Analysis of a Single-Cylinder Engine

1 Introduction

1.1 Overview

In this assignment you will do the following:

- Consider a single-cylinder engine, and examine the piston motion analytically
- Develop an ADAMS model of the single-cylinder engine
- Find the engine shaking force and moment from the ADAMS model
- Explore the use of counterweights to reduce the shaking force and moment

1.2 ADAMS Model Advice

Creation of the ADAMS model will likely take the longest amount of time here. Therefore you should get started as soon as possible. In this document I will give you enough information to construct your ADAMS model. Note that I won’t give you all dimensions, just the ones that are critical. Some choices will be up to you.

An “exploded” view of the components appears in Figure 1.

Figure 1: The components of the single-cylinder engine
2 List of Tasks in this Exercise

I don’t know how much we’ll be able to accomplish with the time remaining, but I’d like you to do the following:

2.1 Piston Displacement, Velocity, and Acceleration

Examine the behavior of these quantities during one cycle of the engine, with the crankshaft rotating at a constant 6,000 rpm. Use the dimensions of Section 4.

2.1.1 Piston Displacement

Using the simplified expression for piston displacement (with angle $\omega t = \theta$)

$$x \approx l - \frac{r^2}{4l} + r \left( \cos \theta + \frac{r}{4l} \cos 2\theta \right),$$

plot $x$ (in) versus angle $\theta$ (DEG) from 0° to 360°. This motion is NOT QUITE a sinusoid—can you “overlay” a sinusoid on the same plot to illustrate that? (not required, but interesting if you can do it).

2.1.2 Piston Speed

Given the approximate expression for piston speed

$$\dot{x} \approx -r \omega \left( \sin \theta + \frac{r}{2l} \sin 2\theta \right),$$

find the MAXIMUM piston speed in fpm (feet per minute) at our crankspeed of 6,000 rpm. How does it compare with the “50’s hot-rodder maximum of 2500 fpm?”

- EXTRA CREDIT: At what crank angle $\theta$ does $\dot{x}_{max}$ occur? Find this analytically, and find the first value for $\theta$ after 0° (TDC). Hint: It occurs before 90°. You may want to use MATLAB function fzero to solve the resulting nonlinear equation...

2.1.3 Piston Acceleration

Using the approximate expression for piston acceleration

$$\ddot{x} \approx -r \omega^2 \left( \cos \theta + \frac{r}{l} \cos 2\theta \right),$$

find the maximum piston acceleration in units of “g’s.”

- What is the effect of the quantity $\frac{r}{l}$ on maximum acceleration (i.e. is it “better” to have a SHORT connecting rod or a LONG one)?

2.2 Crankshaft Design & Balancing

Design the crankshaft in ADAMS as I’ve presented it in Section 4.3, and save your model in ADAMS as crankshaft.bin. Place a “hinge” joint between the ground and crankshaft; call this joint “mainbearing.”

2.2.1 Main Bearing Force due to Crankshaft Unbalance

Using your ADAMS model, give the unbalanced crankshaft from Section 2.2 a constant angular speed of 6,000 rpm (remember to convert to rad/s) and find the magnitude of the force on the main bearing in pounds.

Using the mass of the crankshaft, and the location of the c.m. of the crankshaft, analytically calculate the magnitude of the main bearing force in pounds. The results from your ADAMS model and the analytical calculation should agree.
2.2.2 Crankshaft Balancing

Use identical rectangular steel balancing weights attached to crank webs opposite the crankpin to dynamically balance the crankshaft. Like in Figure 2 below:

![Figure 2: Shape and location of counterweights](image)

Each weight is a rectangular solid of dimensions $a$, $b$, and “depth” $d$ as shown. I would recommend the following design procedure:

1. Select nominal dimensions for $a$ and $b$.
2. Given $a$ and $b$ you know the location of the c.m. of the weights.
3. You know the degree of unbalance of the crankshaft, so you can calculate the necessary mass of the counterweight.
4. Given the mass of each counterweight, and the density of steel, calculate the depth dimension $d$.
5. Attach the counterweights to the crankshaft and use ADAMS to verify that the main bearing force is now very small when the crank is spinning at 6,000 rpm. **NOTE:** Before you MERGE the counterweights to the crankshaft you might attach them using a “LOCK” joint for testing purposes. The LOCK joint is easy to remove if you made a mistake and need to resize the counterweights.

2.2.3 Saving the Model

After balancing the crankshaft, save the model as “crankbal.bin” (or something similar). The next step will be adding the connecting rod, and each time you add a new part you should save the model with a new descriptive name.

2.3 Connecting Rod Design

Create either an aluminum or steel (I-beam) rod in accordance with the dimensions given in Section 4.4. Make sure to specify the material properly.

Place the rod in the proper position relative to the crankshaft, and put a hinge joint between the two. Name this hinge joint “rodbearing.”

Save this model (Save Database As...) with a unique name. You can run a gravity-induced simulation (with no crankshaft speed) to see it swing...
2.4 Piston and Wristpin Design

Create the aluminum piston and steel wristpin in accordance with Sections 4.5 and 4.6. Move them into the proper places.

Place a hinge joint between rod and wristpin, and another between wristpin and piston. Name them something appropriate.

Finally, place a translational joint between the piston and the cylinder wall (ground). Save the model again with a unique name. If you run a gravity-induced simulation the crank, rod, and piston will oscillate back and forth.

2.5 Shaking Force using ADAMS

From now on, apply the 6,000 rpm crank speed to the main bearing joint. The shaking force is simply “main bearing force” $F_{21}$. You can plot both the $X$ and $Y$ components of this force in ADAMS by selecting “constraints” then the “main bearing.” It should be displayed in pound force vs time (sec).

If you remember how, change the horizontal axis from “time” to “crank angle” in DEG. Use the “Math” tab in the plot window.

2.6 Shaking Moment using ADAMS

The shaking moment is give by cylinder wall force $F_{41}$ multiplied by the distance from wristpin to main bearing (this is simply $x$ from the slider-crank).

Here’s how to “compute” the quantity $F_{41}x$ in ADAMS:

1. Create a “point-to-point measure” from the crankshaft axis to the wristpin ais. This will be distance $x$. Rename it “x_piston” (use Tools/Database Navigator/Rename to rename it)

2. You may wish to plot “x_piston” to verify that it oscillates between 4.5 and 7.5 in (this plot should be identical with the one from Section 2.1.1)

3. Plot the $Y$ component of the cylinder wall force $F_{41}$

4. Select the “Math” tab in the plot window, the click on the curve in the plot

5. In the “Y Expression” field, there will be a string describing the Force MEASURE and its component, etc. To multiply this by $x$ simply type “*x_piston” after it, and click “Apply.” The plot will change slightly.

6. You may want to change the units to “ft-lb” in same way.

7. Finally, modify the axis labels to be consistent with the units you’re using

2.7 Reducing Shaking Force & Moment

In text Section 19.9 there is a discussion of reducing the shaking force and moment. A single-cylinder engine CANNOT be perfectly balanced with only crankshaft-mounted counterweights (the secondary shaking force & moment would be unaffected).

2.7.1 Apportioning Connecting Rod Mass

One end of the connecting rod goes “round-and-round,” the other end goes “side-to-side.” Everything in between describes a curve of some shape. Text Section 18.5 discusses the apportioning of the rod mass into two equivalent masses:

1. Mass $m_{3A}$ at the crankpin (describes circular motion)

2. Mass $m_{3B}$ at the wristpin (describes translational motion)

The values of $m_{3A}$ and $m_{3B}$ are given in text equation (18.18). Use the dimensions from your ADAMS model.
2.7.2 Balancing the Rotational Mass $m_{3A}$

The added rotational mass can be balanced by simply increasing the counterweight size. I would advise you to design two counterweights that can be added to the existing ones. When you are satisfied, then “Merge” the bodies together. You may wish to perform a simulation to examine the effect of the modified crankshaft counterweights. Are the shaking force/moment lower? Higher?

2.7.3 Balancing the Translating Mass $m_{3B}$

It is possible to modify the shaking forces by UNBALANCING the rotating masses. In text Section 19.9 the author proposes “…adding a counterweight opposite (i.e. at the same radius as) the crankpin whose mass exceeds the rotating mass by one-half of the reciprocating mass.”

In other words, take the crankshaft as modified in Section 2.6.2, and add additional counterweights such that

$$W_{cw} \times r_{cw} = \frac{W_{recip}}{2} \times r$$

where $r$ is the crankpin offset (1.5 in), and $r_{cw}$ is the c.m. of the added counterweight (likely the same counterweight c.m. as in Figure 2, since you’ll probably just increase the “depth” of these in this step).

Simulate the engine and plot the shaking force and moment. Any better?

2.8 Analytical Treatment

Based on what I did in class on Monday, perform any analytical modeling you wish here. I’m not expecting much, because of the lack of time and classroom coverage. Still, if you can confirm any of the ADAMS results analytically it would be nice.

3 Engine Problem Submission

Complete as much of this engine problem as you wish. Write it up in and submit it on the assigned date.

Please label & number each section of your writeup EXACTLY as I have labeled and numbered it!! That is, your “piston displacement” work should be labeled 2.1.1 Piston Displacement, and your “shaking moment using ADAMS” should be labeled 2.6 Shaking Moment using ADAMS. Thank you.
4 ADAMS Model of Single-Cylinder Engine

The single cylinder engine will consist of the following separate bodies:

1. crankshaft
2. connecting rod (conrod or just rod)
3. wristpin (sometimes called piston pin)
4. piston

These four bodies will be modeled as simple geometric structures, with a few key dimensions.

4.1 Nature of Mechanism

When we begin modeling in ADAMS using objects with “depth,” it’s easy to lose sight of the nature of the mechanism. This engine is a basic slider-crank: exactly the same as shown in text Figure P14.2, which is reproduced in Figure 3.

![Figure 3: Slider-crank mechanism: same as this engine](image)

The dimensions of Figure 3 are—of course—different than the engine in this assignment, but the parts are all there (the wristpin is not explicitly shown, but it must actually be there to connect bodies 3 and 4).

Specifically, the bodies and features shown in Figure 3 are:

- Body 1 = engine block (fixed)
- Body 2 = crankshaft
- Body 3 = rod
- Body 4 = piston
- Distance $O_2A = 1/2$ of the engine stroke; the stroke will be 3 in
- Distance $AB =$ rod length; this will be 6 in
- Point $O_2$ is the crankshaft axis and main bearing
- Point $A$ is the crankpin and rod bearing
- Point $B$ is the wristpin and wristpin bearing
4.2 Engine Bore and Stroke

The bore (cylinder diameter; same as piston diameter) and stroke (total length of piston sweep) will be:

- Bore = 3.000 in
- Stroke = 3.000 in

An engine with equal bore and stroke is termed “square.” If bore > stroke this is “oversquare,” while bore < stroke is “undersquare.”

4.2.1 Engine Displacement

Engine displacement is the volume swept by the piston from top (Top Dead Center, or TDC) to bottom (Bottom Dead Center, or BDC). It is simply piston area times stroke,

\[ V = \frac{\pi (bore)^2}{4} \times \text{stroke} = 21.2 \text{ in}^3 = 347.5 \text{ cm}^3 \]  

(1)

So this is a 350cc engine; according to some, 350cc is the optimal cylinder size.

4.3 Crankshaft

The crankshaft is a single piece, and can be constructed of ADAMS Cylinders and Boxes. A screenshot of what I mean is shown in Figure 4, with a “top” view and an “near-isometric” view.

![Crankshaft](image)

(a) Top view. (b) Near-isometric view.

Figure 4: Crankshaft.

4.3.1 Crankshaft Dimensions and Material

- Material: steel (density 7801.0(kg/meter**3)
- Stub shaft length: not important
- Stub shaft O.D.: 1.000 in
- Main bearing O.D.: 2.000 in
- Main bearing width: 0.500 in
- Rod bearing O.D.: 1.750 in
- Rod bearing width: 0.500 in
- Web width: 0.5 in
- Distance from main bearing axis to rod bearing axis = 1.5 in (distance $O_2A$ in Figure 3; half the stroke)

The shafts and bearings are ADAMS Cylinders, while the webs are Boxes. I used the ADAMS filletting tool to radius some edges of the webs, but this is not necessary (or even desirable when you add the counterweights).

For your interest, a photograph of the crankshaft from a Ducati V-twin engine is shown in Figure 5. There are two connecting rods attached at the crankpin, whereas we have only one. The main bearing diameter is relatively small because ball bearings slide over these diameters (unusual these days) instead of journal bearings (much more common).

Note the large counterbalancing portions of the crank web. Also note the “I-beam” cross section of the (steel) connecting rods.

![Figure 5: Crankshaft from Ducati V-twin engine.](image)

### 4.4 Connecting Rod

The connecting rod connects the crankpin to the wristpin (points $A$ and $B$ in Figure 3). The connecting rod can be either aluminum or steel, and its shape will be different depending on the choice of material.

#### 4.4.1 Aluminum Rod

Forged aluminum rods have a larger cross-section, due to the lower strength of aluminum. An example of my profile for this rod is shown in Figure 6(a).

Critical dimensions of the Aluminum rod are:
Material: aluminum (density 2740.0(kg/meter**3))
Distance between bearing axes: 6.000 in
Rod depth: 0.500 in
“Big end” I.D.: same as crankpin O.D.: 1.750 in
“Small end” O.D.: 1.000 in
“Small end” I.D.: 0.750 in
“Small end” depth: 1.0 in

The general size and shape of the rod are not critical.

### 4.4.2 Steel Rod

The steel connecting rod is similar to the aluminum rod, but has an “I-beam” cross-section, as shown in Figure 6(b). Note that I Chamfered the Aluminum rod, but not the Steel rod. This is done using the ADAMS Chamfer tool, and is optional. Same critical dimensions here as for the aluminum rod; select your own I-beam cross-section. You could also use the Fillet tool to radius some of the edges on the “big end” of the steel rod to make it look pretty.

### 4.5 Wristpin

An image of the wristpin is shown in Figure 7. This is a simple cylinder with a hole through it. Critical properties are:

- Material: steel (always)
- Length: 2.75 in (is centered within piston and rod small end)
- O.D.: 0.750 in
- Wall thickness: 0.125 in
4.6 Piston

The piston is the last component of the engine model. An isometric view of the bottom side of the piston is shown in Figure 8(a), along with a view of an actual piston and rod in Figure 8(b).

![Figure 8: Underside of piston.](image)

The piston can be created by starting with a solid cylinder of diameter equal to the piston diameter. Specify a hole that leaves the skirt of desired thickness. The piston crown (the top of the piston) is another solid cylinder that is attached to the top of the skirt. The bosses are what surround the wristpin as it connects piston and connecting rod; they are simply cylinders that are attached as shown, then holes are created in them.

Critical properties:

- Material: aluminum (always), density 2740.0(kg/meter**3)
- Piston O.D.: 3.000 in (actually a little less to provide some clearance, but use 3.000)
- Skirt thickness: 0.125 in
- Crown thickness: 0.50 in
- Overall piston height: 2.0 in
- Boss O.D.: 1.000 in
- Boss I.D.: 0.750 in (accepts wristpin)
- Gap between bosses: 1.00 in (small end of rod fits in here as seen in Figure 8(b))
4.7 ADAMS Tips for Creating the Model

There are few ADAMS tool I used in creating this model that we haven’t seen before. I’ll present a brief description of these.

4.7.1 Joining Bodies Together

You will frequently have to combine two bodies to make one. There are two tools for this, with icons:

- The unite tool *MUST* be used if the two bodies overlap.
- The merge tool works if bodies don’t overlap
- If bodies are just touching, use whichever one works!

4.7.2 Extruding Solids

The Extrude tool is *VERY USEFUL* in creating solids with polygonal (including I-beam) cross sections. I used it to create the aluminum rod also.
4.7.3 Fillet, Chamfer, and Hole

The Fillet tool can round off edges, the Chamfer tool can chamfer edges, and the Hole tool can place holes in bodies.

![Fillet, Chamfer, and Hole tools]

4.7.4 Specifying the Material (aluminum, steel, etc.)

ADAMS has internal properties of many materials, but I COULD NOT find out how to change material. Every time I created a new part, it was always STEEL.

What I do is to manually specify the density using the Modify window:

![Modify Body window]

The value shown in the window is for aluminum. Steel is 7,801 kg/meter³, IIRC. Those are the only two materials we have in this exercise.