Chapter 5: Circular Motion; Gravitation

Outline

5-1 Kinematics of Uniform Circular Motion
5-2 Dynamics of Uniform Circular Motion
5-3 Highway Curves, Banked and Unbanked
*5-4 Nonuniform Circular Motion
*5-5 Centrifugation
5-6 Newton’s Law of Universal Gravitation
5-7 Gravity Near the Earth’s Surface: Geophysical Applications
5-8 Satellites and “Weightlessness”
*5-9 Kepler’s Laws and Newton’s Synthesis
5-10 Types of Forces in Nature

Summary

Chapter 5 begins with the study of uniform circular motion. This chapter introduces Newton's law of universal gravitation and applies it to spherical objects. Kepler's laws are stated and discussed, as is the general equation for gravitational potential energy and its role in the conservation of energy. The chapter ends with an optional section on tides.

Major Concepts

By the end of the chapter, students should understand each of the following and be able to demonstrate their understanding in problem applications as well as in conceptual situations.

- Uniform circular motion
  - Centripetal acceleration
  - Centripetal force
  - Banked and unbanked highway curves
- Newton's law of universal gravitation
  - Universal gravitation constant $G$
  - Inverse square dependence on the distance
  - Point and spherical objects
  - Cavendish experiment
- Kepler's laws of orbital motion
  - Law of orbits
  - Law of areas
  - Law of periods

Teaching Suggestions and Demonstrations

Many students have difficulty with circular motion and centripetal acceleration. Carefully work out the vectors for centripetal acceleration. All students have experience with the gravitational force, but not all of them will connect the force we feel on Earth with the one that holds the solar system (and the galaxy and the universe) together. Some of their intuitive ideas about gravity will be correct; others will not be correct. You will have to make careful assessment of student progress for this chapter.
Sections 5-1 through 5-3

**Uniform circular motion** is another concept that is not intuitive for students. The discussion at the beginning of Section 5-1 is excellent. Remind the students that if an object is not moving in a straight line, it must have a force on it, and use that idea to justify the direction of the force. (See Figure 5-4.) You then can define the **centripetal acceleration**. You will need to go through the derivation of Equation 5-1 carefully. There are several steps that are tricky for the students. Point out that for uniform circular motion, the acceleration vector and the velocity vector are perpendicular to one another, as in Figure 5-3.

You will need to spend some time defining the concepts of **frequency** and **period**. These concepts are introduced here and will come up again in later chapters. Go through Example 5-1 to illustrate how the period and frequency relate to centripetal acceleration.

Emphasize that the **centripetal force** is not a mysterious force imposed on a situation from the outside. It must be provided by some force in the problem (e.g., gravity, the tension in a string, the normal force).

Any force that is serving as a centripetal force can be written in the form: \( f_{cp} = ma_{cp} = \frac{m v^2}{r} \).

There is a very good discussion of the centripetal force and the **centrifugal force** in Section 5-2, illustrated in Figures 5-5 and 5-6.

**DEMO 5-1** The traditional ball on a string swung in a horizontal circle works well for demonstrating circular motion. Variations include a (small) bucket of water or sand swung in a vertical circle (very dramatic!). See Example 5-4.

Students like to see the mechanics of amusement park rides worked out. You can do the case of the loop-the-loop roller coaster (where the cars go upside down – see Problem 5-13) and the spinning cylinder ride (see Problem 5-19). Have the students work together in pairs or groups of three to figure out why the riders don't fall out of the ride in either case!

Section 5-3 shows the forces on a car going around a flat curve and a banked curve. (See Figures 5-13 and 5-14.) Work through Examples 5-6 and 5-7 and lead students in a discussion of the advantages of banked roadways.

Sections 5-4 and 5-5

Sections 5-4 and 5-5 are optional discussions of **nonuniform circular motion** and **centrifugation**. If you have pre-health professions students in your class, it is a good idea to go over the acceleration vectors for nonuniform circular motion and the principles behind the centrifuge. (These topics may appear on the MCAT.) These two sections may be skipped without loss of continuity.

Sections 5-6 through 5-8

**Newton's law of universal gravitation** is elegant and simple, especially for spherical or point objects. Emphasize that the force acts between centers of the objects, is always attractive, is proportional to both masses, and is inversely proportional to the distance between the centers squared. You will need to discuss the implications of the inverse square nature of the force. The **infinite range of the gravitational force** and the fact that it is the weakest of the **four fundamental forces** are often surprising to students. It is a good idea to talk about why we don't have to worry about the gravitational force from everyday
objects. (See Example 5-10.) For most cases, the only time we have to take the gravitational force into account is when at least one of the two objects is the size of a planet.

There is a nice treatment of the Cavendish experiment in Section 5-6 and Figure 5-20. Point out that $G$ is a universal constant; it is the same for all pairs of objects. Students often find it amazing that the mass of the Earth wasn't known until 1798, long after Newton's death, since the radius of the Earth was known to the ancient world.

The students will find the discussion of satellite motion, particularly geosynchronous satellites, interesting. Be sure to go over Figures 5-24 and 5-25 and Example 5-14. The following section on apparent weightlessness will be very useful in later discussion of relativity; plan to spend a few minutes of class time on it here.

Section 5-9

This section is marked as optional and can be skipped if you are short on time however, we recommend that you include it if possible. The students find Kepler's laws interesting and understandable. Kepler's laws can be derived from Newton's laws, but Kepler deduced them from astronomical data collected by visual observation. The story of Brahe and Kepler makes interesting reading; students find it fascinating. (See Resource Information.)

Kepler's first law is also called the law of orbits. Giving up the idea of circular orbits for planets involved a major shift of worldview for Kepler. You will probably need to spend some time talking about the properties of ellipses before continuing to the second law.

DEMO 5-2 Using suction cups attached to the blackboard or whiteboard and a piece of string tied in a loop, draw an ellipse. Show the students what happens if the foci are moved farther apart or closer together. Show them how a circle is a special case of an ellipse.

Kepler's second law is called the law of areas. Point out that it is based in the conservation of angular momentum.

Kepler's third law is called the law of periods. It is important to emphasize to the students that the "constant" that appears in the third law is not the universal constant $G$. It is a "constant" that is the same for all objects orbiting the same mass. Plan to go through Example 5-16, the calculation of the Sun’s mass, in class.

Section 5-10

Section 5-10 is a concise treatment of the fundamental forces of nature. You will need to allow some time for general discussion of these force and their relative strengths.

Resource Information

Transparencies

T42. Figure 5-2 Determining the change in velocity for a particle moving in a circle.
T43. Figure 5-3 For uniform circular motion, $a$ is always perpendicular to $v$.
   Figure 5-4 A force is required to keep an object moving in a circle.
T44. Figure 5-6 If centrifugal force existed.
T45. Figure 5-9 Exercise C.
T46. Figure 5-13 Example 5-6. (Skidding on a curve.)
    Figure 5-14 Normal force on a car rounding a banked curve.
T47. Figure 5-15 The speed of an object moving in a circle changes.
T48. Figure 5-17 Two positions of a rotating test tube in a centrifuge.
T49. Figure 5-20 Schematic diagram of Cavendish’s apparatus.
T50. Figure 5-24 Artificial satellites launched at different speeds.
    Figure 5-25 A moving satellite "falls" out of a straight-line path toward the Earth.
T51. Figure 5-26 An object in an elevator.
T52. Figure 5-28 Kepler's first law.
    Figure 5-29 Kepler's second law.
T53. Table 5-2 Planetary Data Applied to Kepler's Third Law.
T54. Figure 5-30 Our solar system.

Suggested Readings


Ronhovde, P. and Sirochman, R., "Center of Mass Correction to an Error-Prone Undergraduate Centripetal Force Lab," American Journal of Physics (February 2003), pp. 185–188. Describes a simpler correction to a centripetal force laboratory experiment.


**Notes and Ideas**

*Class time spent on material: Estimated: ______  Actual: ____________*

*Related laboratory activities:*

*Demonstration materials:*

*Notes for next time:*