General Physics I Lab

M4 Work, Energy and Friction

Purpose

In this experiment, you will study the relationship between work and energy and measure the coefficients of kinetic and static friction.

Equipment and Components

Inclined plane with attached pulley and mounting base, spirit level, car, measuring tape, protractor, mass and hanger set, electronic balance, and string.

Background

Energy as applied to a mechanical device may be defined as the capacity the device has for doing work. Various types of machines have been used to convert energy from one form into another. The very simple device to be used in this experiment is an inclined plane, which is shown in Figure 1 below.

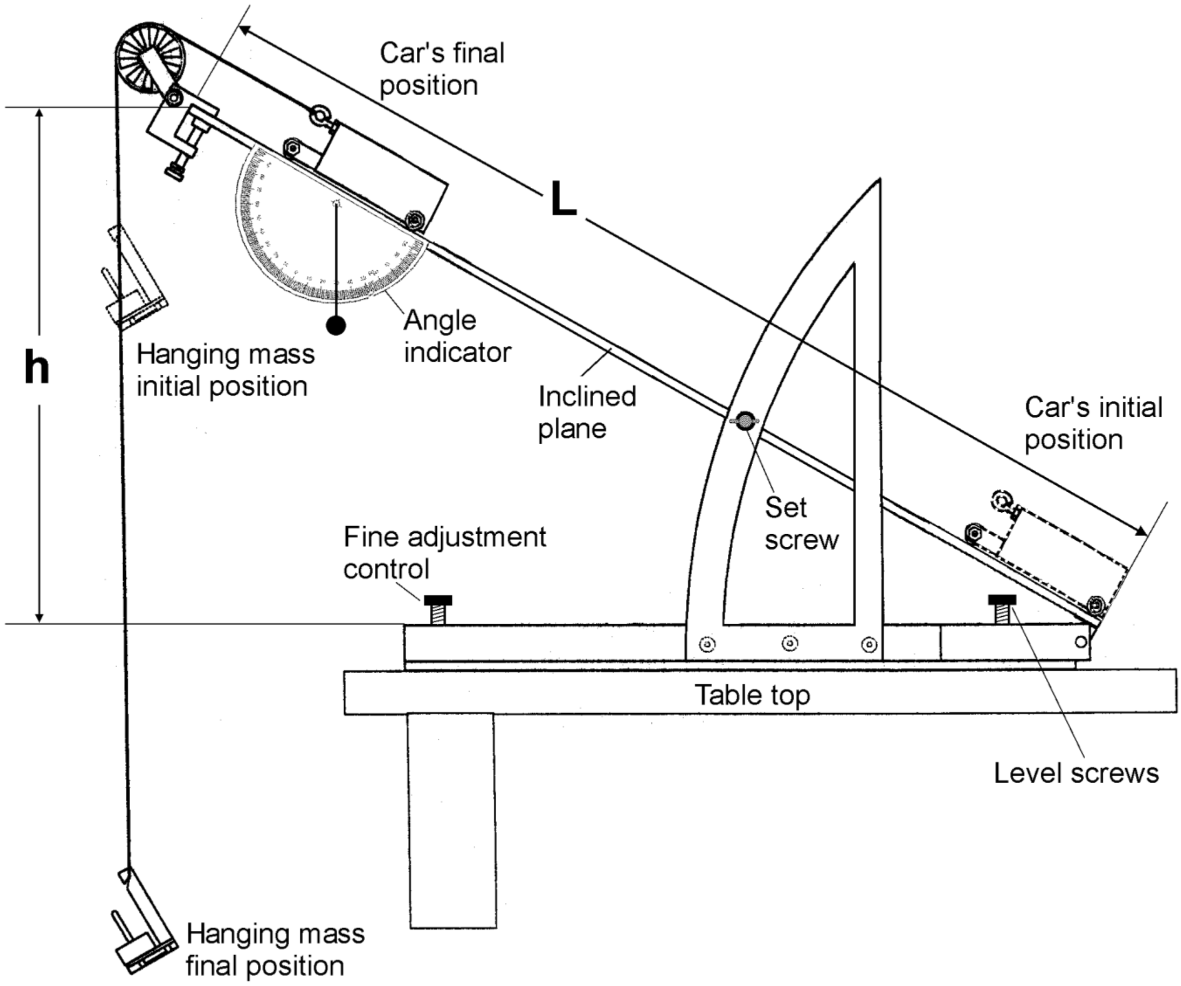

Figure 1 Experimental setup for the inclined plane

When a constant force $\boldsymbol{F}$ acts on an object and results in a displacement $\boldsymbol{S}$ of the object, the amount of work W done is given by $W = \boldsymbol{F}\cdot\boldsymbol{S} = (F\cos\theta)\,S$, where $F\cos\theta$ is the component of the force in the direction of the displacement. The units of work in the SI system are Newton·meters = Joules.

Another form of energy involved when moving a car along the inclined plane is the gravitational potential energy, GPE. When the car of mass m is lifted a height h as it moves up the plane, the gravitational potential energy of the car is changed by an amount of $\Delta GPE = mgh$, where g is the acceleration due to gravity. If there were no friction between the plane and the car and it were moving at a uniform speed, the amount of work done by the hanging mass would be equal to ΔGPE for the car. Because friction opposes the motion of the body, some of the work done by the hanging mass is used to overcome the frictional forces.

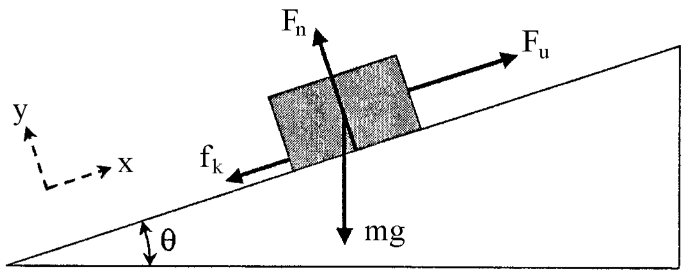

Figure 2 Force diagram for motion up the plane

As shown in Fig. 2, both the force of friction, f_k, and the parallel component due to the weight of the car, F_p ($= mg \cdot \sin\theta$), oppose the pulling force F_u. Therefore, one has $F_u = F_p + f_k$ for an uniform motion up the plane. According to the law of the conservation of energy, we have

$$F_u L = f_k L + \Delta GPE \tag{1}$$

Similarly, when the car moves down the plane with a uniform speed, the pulling force F_d and the frictional force f_k are in the same direction opposing F_p, and one has

$$F_d = F_p - f_k. \tag{2}$$

Combining the above two equations, one obtains

$$F_u - F_d = 2f_k. \tag{3}$$

Using Eq. (3) one can calculate the force of friction f_k when both F_u and F_d are measured.

The frictional force f_k is called *kinetic frictional force*. When a body slides over the surface of another object, we are concerned with the *sliding* frictional force between the two surfaces that are in contact. Experimentally, one finds that for a moving object the kinetic frictional force, f_k, is given by

$$f_k = \mu_k F_n, \tag{4}$$

where F_n is the magnitude of the normal force and μ_k is the coefficient of kinetic friction, which depends on the materials of the two surfaces that are in contact.

A simple way to determine the coefficient of sliding friction is to tilt an inclined plane (see Fig. 3 below) until the object on the plane starts to slide down at a constant speed. In this case, the parallel component F_p due to the weight of the object is just balanced by the opposing frictional force f_k, and therefore we have

$$\mu_k = f_k / F_n = F_p / F_n = \tan\theta_k, \tag{5}$$

where θ_k is the limiting angle at which uniform motion occurs.

To put an object at rest into motion, it is necessary to use a force to overcome the *static frictional force*, f_s. The static frictional force is usually larger than the kinetic frictional force. Similar to f_k, the static frictional force f_s is also found to be proportional to F_n, i.e.,

$$f_s = \mu_s F_n. \tag{6}$$

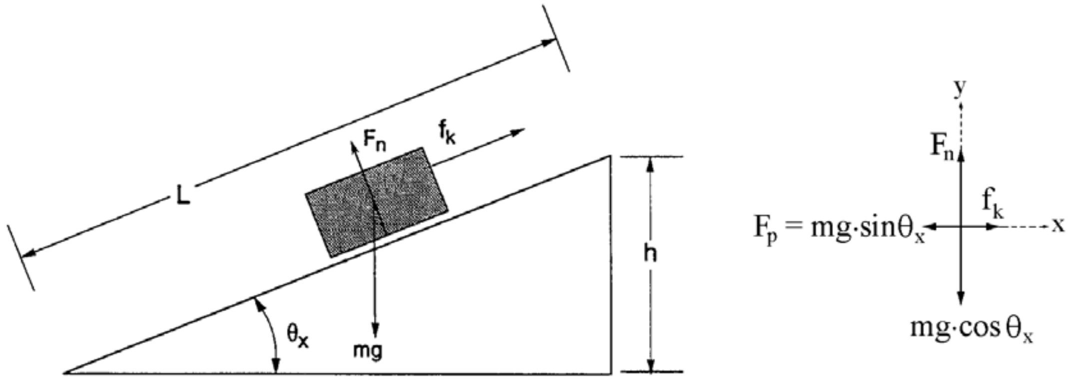

Figure 3 Limiting angle for kinetic and static friction

In the above, μ_s is the coefficient of static friction, which depends on the type of materials from which each surface is made, the condition of the surfaces, and other variables such as temperature. Typical values of μ_s range from around 0.01 for smooth surfaces to around 1.5 for rough surfaces. As shown in Fig. 3, when an object is resting on the inclined plane, the limiting angle of static friction is the angle, θ_s, of the incline required for the object to be on the verge of slipping. In this case, we have

$$\mu_s = f_s/F_n = F_p/F_n = \tan\theta_s. \qquad (7)$$

In general, $\theta_S > \theta_k$ and thus $\mu_s > \mu_k$.

Procedure

In Part I of the experiment, you will measure the work done and energy change for motion up and down the plane. In Part II, you will measure the coefficients of kinetic and static friction.

Part I. Measurement of Work and Energy

1. Level the bottom plate of the inclined plane by adjusting the level screws as shown in Figure 1.
2. Set up the inclined plane as shown in Fig. 1 with the incline angle with respect to the horizontal equal to 15°. You can read the angle of inclination directly from the angle indicator on the apparatus. M*ake sure that the set screw is tightened to secure the inclined plane*. There is a fine adjustment control near the bottom plate, with which you can fine tune the incline angle to within 1°.
3. Measure the mass of the car and the length L of the inclined plane as shown in Fig. 1. Record the values in Table 1.
4. Connect the car and the mass hanger with the string provided and place the car on the inclined plane as shown in Fig. 1. Make sure that the string pulling the car goes through the groove of the pulley freely without any friction against the side walls of the groove. To calculate the work done by the hanging mass, the string should be kept *parallel* to the plane (by adjusting the angle of the pulley), so that the pulling force and the displacement are in the same direction.
5. Determine the force F_u required to pull the car up the incline at a *slow uniform speed* after the car is given *a small push to get it started*. Try to move the car with different weights so that you can determine F_u with an accuracy of a few millinewtons. Measure the total mass (up) and record it in Table 1. Note that the pulling force is just the weight of the total mass.
6. Then remove sufficient weights from the mass hanger to allow the car to roll down the plane at a constant speed after being started. This gives you F_d. Measure the total mass (down) and record it in Table 1. Record the values of F_u and F_d in Table 1. Calculate the

height h between the two ends (see Fig. 1) and the kinetic frictional force f_k using Eq. (3). Record your results in Table 1.

7. Repeat the above steps for two more incline angles, one at 30° and the other at 45°. Record your measurements in Table 1.

<u>Data recording and analysis</u>

8. Compute the work, F_uL, done to pull the car up the entire length L of the plane, the work f_kL, done by the frictional force against the motion, and the change of the gravitational potential energy ΔGPE of the car. Record your results in Table 2. **NOTE:** Although the current setup prevents you from measuring the actual travelling distance of the car, the work calculated for the entire length L is proportional to the work calculated for any smaller lengths.

9. Compare F_uL with $f_kL+\Delta$GPE. Compute the percent difference between the two quantities and record it in Table 2.

Part II. Measurement of the coefficients of kinetic and static friction

1. We now measure the coefficient of sliding friction using the same setup with the incline angle being at 0° (horizontal). Place the car on the plane with its back in contact with the surface (upside down position). **NOTE:** Adjust the angle of the pulley to keep the string parallel to the plane.
   HINT: The surface of the inclined plane may not be uniform. Therefore, when measuring the sliding friction, you can limit the movement of the cart within a small part (~20 cm) of the inclined plane to achieve consistency.

2. Add mass to the mass hanger until the car will slide at a uniform speed *after being given a small push*. Record the mass and calculate the coefficient of the sliding kinetic friction μ_k using Eq. (4). Record your results in Table 3.

3. Repeat the above steps but this time determine the force required to slide the car at rest without *giving a small push*. Record this force as the force of static friction f_s in Table 3. Compute the coefficient of static friction μ_s using Eq. (6), and record your result in Table 3. Note the difference between the force to start the motion and that needed to maintain uniform motion after the car *is given a small push*.

4. Now detach the string from the car and position the car on the plane in the normal position, so that it can roll on the plane. Set the plane at the 0° angle (horizontal). Gradually increase the incline angle, until the car at rest starts to roll down the plane. **NOTE**: *Do not allow the car to bump into any hard object at the bottom of the plane or to roll off the table.*

5. Tighten the set screw to secure the inclined plane. Use the fine adjustment control near the bottom plate to adjust the incline angle until the car will roll down the plane at a constant speed *after being given a small push.* Record this angle in Table 4 and calculate the coefficient of rolling kinetic friction $\mu_{k,\ rolling}$ using Eq. (5).

6. Set the car on the plane in an upside down position, so that it can slide on the plane. Repeat the above steps and determine the incline angle required to slide the car at a uniform speed *after being given a small push*. Compute the coefficient of sliding kinetic friction $\mu_{k,\ sliding}$ and record it in Table 4.

7. Compare your result with the value found using the flat plane and calculate the percent difference between the two values in the space provided.

8. Repeat the above steps but this time determine the incline angle required to slide the car at rest *without giving a small push*. Record this angle in Table 4. Compute the coefficient of static friction μ_s using Eq. (7), and record your result in Table 4.

9. Compare your result with the value found using the flat plane and calculate the percent difference between the two values in the space provided.