Lab 4. Friction

Goals

- To determine whether the simple model for the frictional force presented in the text, where friction is proportional to the product of a constant coefficient of friction, μ_K, and the magnitude of the normal force between the surfaces, n, applies to the cases of sliding aluminum-wood and aluminum-felt surfaces.
- If appropriate, to determine the kinetic coefficients of friction between wood and aluminum and between felt and aluminum.
- To determine whether the "constant" coefficients of friction are independent of the speed that one surface slides over the other for the two cases previously characterized. This is accomplished by letting the wooden block accelerate on the surface of the aluminum track.

Introduction

From a fundamental point of view one can say that all friction is due in one way or another to electromagnetic forces. Inter-atomic forces (also known as chemical bonds) are electromagnetic forces that act through distances that are on the order of the spacing between atoms, that is 10^{-10}–10^{-9} m. Most surfaces that appear smooth are rough when viewed microscopically. When viewed using visible light (with wavelengths between 400 and 700 nm), the surface will appear smooth and shiny if the roughness is smaller than the wavelengths of the light. Consequently the actual surface roughness can be as large as 10^{-7} m, equivalent to a hundred or more atomic spacings, before the roughness becomes apparent to the eye.

What we call friction arises from adhesion (atomic attraction) between the atoms of two surfaces in close proximity, even when roughness limits physical contact to the "peaks" on each surface. In some instances pieces of material can be torn off in the process of sliding across another surface, thus breaking some of the chemical bonds. For example, material is removed from a skidding rubber tire or a piece of wood as it is smoothed with sandpaper. Because chemical forces are ultimately electromagnetic in nature, friction can be attributed to electromagnetic forces.

The details are not yet well enough understood to make meaningful calculations and predictions. This is unfortunate, since about one-third of the world's energy resources are ultimately consumed by friction in one form or another.[1] The alternative is to characterize friction empirically, in other

[1] Bharat Bhushan, *Principles and Applications of Tribology* (John Wiley, New York, 1999).

words by experiment. Since static friction (the friction between two surfaces which do not move with respect to one another) is even more difficult to reproduce consistently, we will limit our study to kinetic friction, when two surfaces slide with respect to each other. Your textbook has made some simple claims for kinetic friction, namely that (1) the frictional force for a particular interface is directly proportional to the normal force exerted by one surface on the other, and (2) the frictional force is independent of the speed with which the surfaces are sliding with respect to each other.

Both of these claims are tested in this experiment, so you can begin to "get a feel" for the concept of friction. We will be studying the friction of a wooden block on a smooth aluminum surface and the friction of a felt covering on the block relative to the same aluminum surface.

Equipment set up

A 1.2 m long aluminum track acts as the supporting surface as a wooden block is dragged over it. To supply a constant force to the system in the direction of motion, a hanging mass is suspended by a string passing over a pulley at the end of the track and attached to the wooden block. By equipping the pulley with a photogate, the rotation rate of the pulley can measured. From this, Capstone computes the speed of the sliding block. This will allow you to keep the speed relatively constant as we do the measurements. Naturally, it will be impossible to keep the speed exactly constant.

Friction between wood and aluminum

Constant velocity measurements

If the wooden block and the hanging mass are moving at constant velocity, then we know that the net force acting on the system of the block and the mass must be zero (since the acceleration of the system is zero). Draw a free-body diagram of this system and clearly indicate which force(s) cancels the frictional force if the acceleration is zero. Your task is to test the hypothesis that $f_K = \mu_K n$, where f_K is the frictional force between the wooden block and the aluminum track, n is the normal force at the block-track interface, and μ_K is the constant coefficient of kinetic friction between the block and the aluminum track. Remember that μ_K is a dimensionless quantity; it has no units.

It is easier to achieve constant velocity at higher normal forces (meaning a level track and the heaviest block mass). Starting with the highest normal force and working down is less frustrating than starting with a low normal force and working up. Start with all four 100 g masses on top of the block for a total of 400 g of added mass. Then remove one 100 g mass at a time. For each value of normal force, find the weight of the hanging mass which will keep the velocity of the system reasonably constant at a value between 0.2 and 0.3 m/s. You must give the system an initial push at the desired final velocity, since the acceleration after you quit pushing should be essentially zero when the weight of the hanging mass and the friction force are equal. From your text, you know that the force of friction on objects at rest can exceed that for objects in motion. Therefore the force of friction must change at some low velocity. It is important to make sure that the velocity is approximately constant and within the correct range. Keeping the variation in speed small between runs is better, but don't spend too much time on it.

Make an appropriate graph to determine whether the frictional force is directly proportional to the normal force in this case. (How do you know if the forces are directly proportional via graph? What should be on each axis, and what are you looking for in trend analysis?) If it is directly proportional, then determine the value for the coefficient of kinetic friction from your graph.

Checking for velocity effects

If we make the wooden block accelerate from rest rather than moving at a constant velocity, we can check whether the frictional force is really constant over a range of velocities from zero to the final velocity of the block at the end of the track. In the first portion of this lab we were measuring the force of friction by finding a hanging mass to balance the friction drag with an equal magnitude pull. But that is not the only method available to measure friction force. So we will now approach the measurement with a second method, which allows us to lend greater credibility to the claim we are hoping to support through experimentation.

This is achieved by adding mass to the hanger such that the pull force is now known to absolutely be greater than the frictional drag force. To evaluate the results, you will need to derive a relation between the acceleration of the wooden block, the hanging mass, and the frictional force. Include the details of this derivation in your report. If you are uncertain on how to find this relationship, start by figuring out what you expect to happen if friction is zero, and compare that with what you measured.

Draw free body force diagrams for both the hanging mass and the wooden block. For each of these objects the net force is calculated as the mass times the measured acceleration, as stated in Newton's second law of motion. (Assume that the pulley has no mass and has frictionless bearings. This spinning of the pulley does use some energy, and that concept will be covered later in the semester) The tension of the string connecting the two objects together should appear in the equations for both objects.

These two force diagrams can be used to establish equations for the net force along the direction of travel.

$$Net\ Force = Force\ to\ the\ left - Force\ to\ the\ right \tag{4.1}$$

You should have two equations with two unknowns, namely, the string tension, T, and the acceleration, a. Both equations are equal to the net force, and so can be set equal to one another. This allows you to eliminate T and arrange the remaining equation to state a in terms of various known quantities, including the μ_K value you found above. If the frictional force is indeed a constant, you should observe that the acceleration depends only on quantities with constant values. (The mass values can be varied, of course, but they are constant during a given run; in the equation, therefore, they are constants.) The acceleration during a given run should be constant if the frictional force is constant for a given combination of mass values.

Place 300 g of mass on top of the block and add enough mass to the hanger (start with 120 g) so that the final velocity of the block when the hanger hits the floor is 1.0–1.2 m/s. A significant range of velocities is necessary if we are to test the hypothesis that the frictional coefficient is a constant, independent of velocity. Release the block from rest and let it accelerate down the track. Avoid looking at an acceleration graph directly because it is quite noisy; averages of noisy data are not so precise. If the acceleration is constant, the velocity-time graph should be linear. If so, use the curve-fitting capability of the Capstone software to get the numerical values for the slope and its standard deviation. (If you need help from your TA to do this, ask.) Taking three or more runs with same mass values gives a more reliable average acceleration value than simply a single run. You can also see how consistent the acceleration values are from run to run.

Using the equation that you derived earlier for acceleration versus mass, predict the magnitude of the acceleration for the block using the numerical value of μ_K determined from your constant velocity measurements. Compare this prediction with the actual acceleration obtained from the slope of the velocity plot in this exercise. (If the velocity-time graph is significantly curved, compare your predicted acceleration with the slope of the graph over the velocity range employed for the constant velocity measurements.) Use the standard error of the slope in this region as the uncertainty estimate for acceleration.

Based on your data, does the frictional force between the wood and aluminum surfaces depend on the relative velocity of the two surfaces? If so, does the frictional force increase or decrease as the relative velocity at the interface increases?

Friction between felt and aluminum

Constant velocity measurements

Turn the wooden block over so the larger felt side slides along the aluminum track. Use the same procedure you used for constant velocity measurements of μ_K on the wood-aluminum interface, keeping the velocity in the range 0.2–0.3 m/s. Make an appropriate graph to determine whether the frictional force is directly proportional to the normal force in this case. If it is directly proportional, then determine the value for the coefficient of kinetic friction from your graph.

Checking for velocity effects

Examine the effect of velocity on friction at the felt-aluminum interface using the same procedure you used to study the wood-aluminum interface. Place 200 g on top of the wooden block and about 100 grams on the mass hanger. Use enough mass to achieve a maximum velocity of 1.0–1.2 m/s. Do several runs, checking for consistency and for constancy of the acceleration. Predict the acceleration, using your value of μ_K from the constant velocity measurements (valid for velocities in the 0.2–0.3 m/s range, at least) and the equation you derived above. Compare this predicted value with the average acceleration over the same velocity range you used to determine μ_K. Again take three or more runs with the computer to get a better average and a meaningful uncertainty.

Based on your data, is the frictional force between the felt and aluminum surfaces independent of the relative velocity of the two surfaces? Does the frictional force increase, decrease, or remain constant as the relative velocity at the interface increases?

Summary

Summarize your findings clearly and concisely. Do your results support the hypothesis that friction can always be described by the simple equation given in your textbook? Cite numerical values from elsewhere in your report as you address this question.

Grading Rubric

	No Effort	Progressing	Expectation	Exemplary
AA Is able to extract the information from representation correctly Labs: 1-12	No visible attempt is made to extract information from the experimental setup.	Information that is extracted contains errors such as labeling quantities incorrectly, mixing up initial and final states, choosing a wrong system, etc. Physical quantities have no subscripts (when those are needed).	Most of the information is extracted correctly, but not all of the information. For example physical quantities are represented with numbers and there are no units. Or directions are missing. Subscripts for physical quantities are either missing or inconsistent.	All necessary information has been extracted correctly, and written in a comprehensible way. Objects, systems, physical quantities, initial and final states, etc. are identified correctly and units are correct. Physical quantities have consistent and informative subscripts.
AB Is able to construct new representations from previous representations Labs: 1-12	No attempt is made to construct a different representation.	Representations are attempted, but omits or uses incorrect information (i.e. labels, variables) or the representation does not agree with the information used.	Representations are constructed with all given (or understood) information and contain no major flaws.	Representations are constructed with all given (or understood) information and offer deeper insight due to choices made in how to represent the information.
AC Is able to evaluate the consistency of different representations and modify them when necessary Labs: 1-11	No representation is made to evaluate the consistency.	At least one representation is made but there are major discrepancies between the constructed representation and the given experimental setup. There is no attempt to explain consistency.	Representations created agree with each other but may have slight discrepancies with the given experimental representation. Or there is inadequate explanation of the consistency.	All representations, both created and given, are in agreement with each other and the explanations of the consistency are provided.

	No Effort	Progressing	Expectation	Exemplary
AE Force Diagram Labs: 1-12	No representation is constructed.	Force Diagram is constructed but contains major errors such as mislabeled or not labeled force vectors, length of vectors, wrong direction, extra incorrect vectors are added, or vectors are missing.	Force Diagram contains no errors in vectors but lacks a key feature such as labels of forces with two subscripts vectors are not drawn from single point, or axes are missing.	The diagram contains no errors and each force is labeled so that it is clearly understood what each force represents. Vectors are scaled precisely.
AG Mathematical Labs: 1-4, 6-12	No representation is constructed.	Mathematical representation lacks the algebraic part (the student plugged the numbers right away) has the wrong concepts being applied, signs are incorrect, or progression is unclear.	No error is found in the reasoning, however they may not have fully completed steps to solve problem or one needs effort to comprehend the progression.	Mathematical representation contains no errors and it is easy to see progression of the first step to the last step in solving the equation. The solver evaluated the mathematical representation with comparison to physical reality.
AI Graph Labs: 1, 3-7, 10-12	No graph is present.	A graph is present but the axes are not labeled. There is no scale on the axes. The data points are connected.	The graph is present and axes are labeled but the axes do not correspond to the independent and dependent variable or the scale is not accurate. The data points are not connected but there is no trend-line.	The graph has correctly labeled axes, independent variable is along the horizontal axis and the scale is accurate. The trend-line is correct, with formula clearly indicated.
BA Is able to identify the phenomenon to be investigated Labs: 1, 4, 5, 10-12	No phenomenon is mentioned.	The description of the phenomenon to be investigated is confusing, or it is not the phenomena of interest.	The description of the phenomenon is vague or incomplete but can be understood in broader context.	The phenomenon to be investigated is clearly stated.
BB Is able to design a reliable experiment that investigates the phenomenon Labs: 1, 4, 5, 12	The experiment does not investigate the phenomenon.	The experiment may not yield any interesting patterns.	Some important aspects of the phenomenon will not be observable but experiment does reveal some surface level information.	The experiment might yield interesting patterns relevant to the investigation of the phenomenon.

	No Effort	Progressing	Expectation	Exemplary
BC Is able to decide what physical quantities are to be measured and identify independent and dependent variables Labs: 1, 4, 5, 11, 12	The physical quantities are irrelevant.	Only some of physical quantities are relevant or independent and dependent variables are not identified.	The physical quantities are relevant. A small fraction of independent and dependent variables are misidentified.	The physical quantities are relevant and independent and dependent variables are identified.
BD Is able to describe how to use available equipment to make measurements Labs: 1, 4, 5, 11, 12	At least one of the chosen measurements cannot be made with the available equipment.	All chosen measurements can be made, but no details are given about how it is done.	All chosen measurements can be made, but the details of how it is done are vague or incomplete, repeating measurements would require prior knowledge.	All chosen measurements can be made and all details of how it is done are clearly provided.
BE Is able to describe what is observed concisely, both in words and by means of a picture of the experimental setup. Labs: 1, 4, 5, 11, 12	No description is mentioned.	A description is incomplete. No labeled sketch is present. Or, observations are adjusted to fit expectations.	A description is complete, but mixed up with explanations or pattern. OR The sketch is present but relies upon description to understand.	Clearly describes what happens in the experiments both verbally and with a sketch. Provides other representations when necessary (tables and graphs).
BF Is able to identify the shortcomings in an experiment and suggest improvements Labs: 1, 4, 5, 11, 12	No attempt is made to identify any shortcomings of the experimental.	The shortcomings are described vaguely and no suggestions for improvements are made.	Not all aspects of the design are considered in terms of shortcomings or improvements, but some have been identified and discussed.	All major shortcomings of the experiment are identified and reasonable suggestions for improvement are made. Justification is provided for certainty of no shortcomings in the rare case there are none.
BG Is able to identify a pattern in the data Labs: 1, 4, 5, 10-12	No attempt is made to search for a pattern	The pattern described is irrelevant or inconsistent with the data.	The pattern has minor errors or omissions. OR Terms labelled as proportional lack clarity- is the proportionality linear, quadratic, etc.	The patterns represents the relevant trend in the data. When possible, the trend is described in words.

	No Effort	Progressing	Expectation	Exemplary
BH Is able to represent a pattern mathematically Labs: 1, 4, 5, 10-12	No attempt is made to represent a pattern mathematically	The mathematical expression does not represent the trend.	No analysis of how well the expression agrees with the data is included, OR some features of the pattern are missing.	The expression represents the trend completely and an analysis of how well it agrees with the data is included.
BI Is able to devise an explanation for an observed pattern Labs: 1, 4, 5, 10-12	No attempt is made to explain the observed pattern.	An explanation is vague, not testable, or contradicts the pattern.	An explanation contradicts previous knowledge or the reasoning is flawed.	A reasonable explanation is made. It is testable and it explains the observed pattern.
GA Is able to identify sources of experimental uncertainty Labs: 2-4, 7, 9-10, 12	No attempt is made to identify experimental uncertainties.	An attempt is made to identify experimental uncertainties, but most are missing, described vaguely, or incorrect.	Most experimental uncertainties are correctly identified. But there is no distinction between random and experimental uncertainty.	All experimental uncertainties are correctly identified. There is a distinction between experimental uncertainty and random uncertainty.
GB Is able to evaluate specifically how identified experimental uncertainties may affect the data Labs: 2-4, 7, 9-10, 12	No attempt is made to evaluate experimental uncertainties.	An attempt is made to evaluate experimental uncertainties, but most are missing, described vaguely, or incorrect. Or only absolute uncertainties are mentioned. Or the final result does not take the uncertainty into account.	The final result does take the identified uncertainties into account but is not correctly evaluated. The weakest link rule is not used or is used incorrectly.	The experimental uncertainty of the final result is correctly evaluated. The weakest link rule is used appropriately and the choice of the biggest source of uncertainty is justified.
GC Is able to describe how to minimize experimental uncertainty and actually do it Labs: 2-4, 7, 9-10, 12	No attempt is made to describe how to minimize experimental uncertainty and no attempt to minimize is present.	A description of how to minimize experimental uncertainty is present, but there is no attempt to actually minimize it.	An attempt is made to minimize the uncertainty in the final result is made but the method is not the most effective.	The uncertainty is minimized in an effective way.
GD Is able to record and represent data in a meaningful way Labs: 1-12	Data are either absent or incomprehensible.	Some important data are absent or incomprehensible. They are not organized in tables or the tables are not labeled properly.	All important data are present, but recorded in a way that requires some effort to comprehend. The tables are labeled but labels are confusing.	All important data are present, organized, and recorded clearly. The tables are labeled and placed in a logical order.

	No Effort	Progressing	Expectation	Exemplary
GE Is able to analyze data appropriately Labs: 1-12	No attempt is made to analyze the data.	An attempt is made to analyze the data, but it is either seriously flawed or inappropriate.	The analysis is appropriate but it contains minor errors or omissions.	The analysis is appropriate, complete, and correct.
IA Is able to conduct a unit analysis to test the self-consistency of an equation Labs: 1-12	No meaningful attempt is made to identify the units of each quantity in an equation.	An attempt is made to identify the units of each quantity, but the student does not compare the units of each term to test for self-consistency of the equation.	An attempt is made to check the units of each term in the equation, but the student either mis-remembered a quantity's unit, and/or made an algebraic error in the analysis.	The student correctly conducts a unit analysis to test the self-consistency of the equation.

EXIT TICKET:

- ☐ Quit Capstone and any other software you have been using.
- ☐ Straighten up your lab station. Put all equipment where it was at start of lab.
- ☐ Report any problems or suggest improvements to your TA.
- ☐ Have TA validate Exit Ticket Complete.