Comparing methods of measurement of friction with simple equipment and with data-loggers

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Abstract

The Physics of friction is an important topic in the teaching of Physics at schools of all types and also of our everyday interest. Students, however, are often unable to imagine the applicability of what they learn to real-life situations, therefore, experiments should be an integral part of the teaching and learning of Physics. The main objective of these experiments is to demonstrate dynamic friction on either a horizontal or inclined plane with commonly used surfaces. All experiments have been designed as such that they are not difficult for students and teachers and, at the same time, they use the basic concepts of friction to measure the coefficient of dynamic friction.

The article presents a newly constructed school tribometer, which is accessorized with Vernier sensors in the Physics classroom to demonstrate problems in the mechanics curriculum for middle schools, high schools and universities. The inclining tribometer enables taking measurements for the following types of problems:

• Finding the coefficient of static and dynamic friction for motion
• Finding the coefficient of rolling friction
• Measuring the kinematic quantities of a body moving on horizontal and inclined planes
• A tribometer construction may also be used to demonstrate fibre friction.

Another significant advantage of this inclining tribometer is its angle, which lies in the range between −90° and 90°. This enables measurements of surfaces with very high dynamic friction coefficients. An extensive literature search did not show the same tribometer construction and its use.

The methods of finding the dynamic friction coefficient described in the text are:

• Determination of coefficient of sliding friction by measuring the tensile force on the horizontal school tribometer (inclination angle 0°)
• Determination the coefficient of sliding friction through with the aid of changing the inclination of the tribometer

Both methods were developed with simple equipment and data-logging software. This article compares the advantages and disadvantages of school experiments with and without data-logging software. Both methods described above make use of data-logging sensors by Vernier which, when connected to a PC, make tutorials more effective and also enable more exact measurements and data analysis, show graphs and make it possible to determine the uncertainty of measurements. The uncertainty of the coefficient of sliding friction is lower when using the Vernier system than with the methods of ordinary school equipment.

Vernier data-loggers enable us to measure several quantities simultaneously and display the relationship between them. Data can be transferred to other programs and can be saved for later data analysis. Using Vernier data-loggers also helps students be more competent in the use of ICT.

Keywords

Secondary education: lower (ages about 11-15), Secondary education: upper (ages about 15-19), University education, friction, coefficient of friction, tribometer, ICT

Introduction

The theory of friction was developed by Charles-Augustin de Coulomb (1785). Coulomb investigated the influence of four main factors on friction: the nature of the materials in contact and their surface coatings; the extent of the surface area; the normal pressure; and the length of time that the surfaces remained in contact. The distinction between static and dynamic friction is made in Coulomb's friction law, although this distinction was already drawn by Johann Andreas von Segner in 1758. The new discipline called tribology raised from the need of linking science with technology in the areas of friction. Any product where one material slides over another is affected by complex tribological interactions. The study of tribology plays an important role in manufacturing and modern technology. In technology operations, friction increases wear machine and the power required to work. This results in increased costs [Wahl, Nature materials, 2012]. The use of lubricants
minimize direct surface contact reduces wear machine and power requirements [Braun, Surface Science Reports, 2006, Harnoy, IEEE control systems magazine, 2008]. Since the 1990s, new areas of tribology have emerged, including the nanotribology. These interdisciplinary areas study the friction, wear and lubrication at the nanoscale, for example: materials in biomedical applications [Rubin, Wear, 2013].

Technical description of the newly designed school inclining tribometer

The tribometer consists of a steel base plate with the dimensions of 300x200x25 mm, which gives us stability. The axis of the top of the base plate is fixed with a screw connection supporting a steel rod with a length of 520 mm, at the end of which a movable joint is mounted via a hinge and locking hex bolt (locking the set angle of incline) and the test surface with a length of 1000 mm and a width of 100 mm. The test area, made of waterproof plywood, is fitted with plastic strips on the sides to prevent buckling of the testing body while moving along the test area. The test area allows you to change the type of pairs of friction materials. A metal workshop protractor with the possibility of adjusting the angle in the range from -90 ° to 90 ° with a resolution of 1 ° is fixed in the joint axis on the test area. The design of the tribometer enables measuring frictional force, using adjustable rollers and fibres, during the movement of the testing body along a horizontal plane as well as along inclined plane. The metal tribometer construction is equipped with a protective coating against corrosion [Hrabovská, Bachelor thesis, 2013].

Test friction the body

Material of the removable tribometer test pad: Spruce wood, shaped by grinding
Materials friction body: Spruce wood shaped by grinding, Perspex, Sand paper P180
Surface roughness

Measurement of surface roughness of test bodies and removable pads was performed using a Mitutoyo Surftest – 301. The profile of the surface material was obtained by using a touch sensor. The room temperature and air-movement in the lab were controlled.

<table>
<thead>
<tr>
<th>Surface roughness</th>
<th>Material (removable pad - Spruce wood)</th>
<th>Material (test body - Spruce wood)</th>
<th>Material (test body - Perspex)</th>
<th>Material (test body - Sand paper P180)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Ra$ ($\mu m$)</td>
<td>8,88</td>
<td>6,68</td>
<td>0,02</td>
<td>23,92</td>
</tr>
<tr>
<td>$Rz$ ($\mu m$)</td>
<td>54,47</td>
<td>38,93</td>
<td>0,17</td>
<td>171,60</td>
</tr>
</tbody>
</table>

$Ra$ – arithmetical mean deviation of the assessed profile
$Rz$ – the highest elevation of the profile

Parameters $Ra$, $Rz$ used for the basic evaluation of surface roughness of the material.

Measuring the weight of friction test bodies was performed using OHAUS EXPLORER PRO accurate analytical balance to 620g. The room temperature and air-movement were controlled in the lab.

Methods of measurement

Two bodies of different masses were used to find the coefficient of static and dynamic friction for each pair of surfaces. Each measurement was repeated 10 times and the average value of the friction coefficient was calculated.

Determination of coefficient of sliding friction by measuring the tensile force on the horizontal tribometer (inclination angle 0 °)

The tribometer unit was set in a horizontal position using a spirit level and metal workshop protractor. The tribometer test area was equipped with a removable wooden surface.

The body was pulled along the tribometer sliding test area using spun bond fibre routed through a pulley, which is attached to the tribometer frame. At the other end of the fibre a hanging bowl was attached to hooks. The bowl was gradually loaded with weights until the body started to move. The tensile force caused by the gravitational force of weights and bowls on the test body is transmitted by the fibre. In this case, the ratio of tensile force to the force of gravity on the test body gives the static coefficient of friction.

When measuring the dynamic coefficient of friction, the mentioned test body was set in motion by a slight impact on the bowl. The weights were set in constant motion. The type of movement was estimated. The ratio of tensile force which corresponds to the constant motion of the test body and the force of gravity, gives the dynamic coefficient of friction [Mechlová, 1999].

Let us consider the cuboid body mass $m$, which moves along the horizontal surface and which is constantly force $\vec{F}_N$ in the direction of its movement.

If $\vec{F}_N = \vec{F}_N$, the body is still or movement takes place at a constant speed. The static coefficient of friction will apply:

$$f_{st} = \frac{\vec{F}_t}{\vec{F}_N} = \frac{m_{st}}{m_{st}} = \frac{g m_{st}}{m_{st} + m} = m_{st}/m$$

$m_{st}$ - Amount of weight for static friction, $m$- the weight of the test body, $\vec{F}_{st}$ - frictional force for static friction, $\vec{F}_N$- normal force, $g$ - acceleration of gravity.
Dynamic coefficient of friction:

\[ F_t = F_N f, \quad f = \frac{F_t}{F_N} = (g \cdot m_z) / (g \cdot m) = m_z / m \]

\( m_z \) - Amount of weight for dynamic friction, \( F_t \) - frictional force for dynamic friction

### Table 2. Average Values of the coefficients of friction, inclination angle 0 °, [Hrabovská, Bachelor thesis 2013]

<table>
<thead>
<tr>
<th>Friction materials</th>
<th>( m ) (g)</th>
<th>( m_{ex} ) (g)</th>
<th>( m_z ) (g)</th>
<th>( f_0 ) (1)</th>
<th>( f ) (1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spruce wood- Spruce wood</td>
<td>138,507</td>
<td>93,862</td>
<td>91,691</td>
<td>0.678</td>
<td>0.664</td>
</tr>
<tr>
<td>Spruce wood- Perspex</td>
<td>138,507</td>
<td>45,692</td>
<td>38,632</td>
<td>0.330</td>
<td>0.279</td>
</tr>
<tr>
<td>Spruce wood- Sand paper P180</td>
<td>102,014</td>
<td>90,541</td>
<td>84,349</td>
<td>0.888</td>
<td>0.827</td>
</tr>
</tbody>
</table>

Determination of the coefficient of sliding friction by measuring the tensile force of the horizontal tribometer (inclination angle 0 °, Vernier system)

The body was pulled along the tribometer sliding test area using spun bond fibre routed through a pulley, which is attached to the tribometer frame. A Vernier force sensor was mounted at the other end of the fibre using hooks. The load cell was gradually loaded manually until the body was set in motion. The tensile force is transmitted by the fibre. The intensity of the gravitational force exerted on the body on the sliding test pad was measured by the Vernier load cell. The ratio of tensile force to the force of gravity on the sliding test body gives the static coefficient of sliding friction.

Let us consider the cuboid body mass \( m \), which moves along the horizontal surface and which is constantly force \( F_t \) in the direction of its movement. If \( F_{t0} = F_t \), the body is standing still or movement takes place at a constant speed. The static coefficient of friction will apply:

\[ F_{t0} = F_N f_0, \quad f_0 = F_{t0} / F_N \]

Dynamic coefficient of friction:

\[ F_t = F_{t0} f, \quad f = F_t / F_N \]

\( F_N \) - Normal force (Vernier force sensor)

During measurement of the dynamic coefficient of sliding friction, the mentioned test body was placed into an evenly linear motion. Determining the type of movement was controlled by measuring the position and by Vernier motion sensors [Vernier 2014]. The ratio of tensile force and gravitational force on the sliding test body gives the dynamic coefficient of friction.

Vernier sensors used: LabQuest mini sensor, position and motion sensor, force sensor

### Table 3. Average values of the coefficients of friction, inclination angle 0 °, Vernier system, [Hrabovská, Bachelor thesis, 2013]

<table>
<thead>
<tr>
<th>Friction materials</th>
<th>( m ) (g)</th>
<th>( F_N ) (N)</th>
<th>( F_{t0} ) (N)</th>
<th>( F_t ) (N)</th>
<th>( f_0 ) (1)</th>
<th>( f ) (1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spruce wood- Spruce wood</td>
<td>138,507</td>
<td>1,483</td>
<td>0,544</td>
<td>0,403</td>
<td>0,367</td>
<td>0,272</td>
</tr>
<tr>
<td>Spruce wood- Perspex</td>
<td>138,507</td>
<td>1,483</td>
<td>0,370</td>
<td>0,301</td>
<td>0,249</td>
<td>0,203</td>
</tr>
<tr>
<td>Spruce wood- Sand paper P180</td>
<td>102,014</td>
<td>1,124</td>
<td>0,895</td>
<td>0,854</td>
<td>0,797</td>
<td>0,760</td>
</tr>
</tbody>
</table>

Determination the coefficient of friction through direct measurement of the angle with the school tribometer

The method is based upon moving a test body along the inclined plane of the tribometer, which allows altering the angle of inclination. The test body starts to move at the point when the angle of inclination is being increased. The angle at which this happens is called the friction angle and it allows us to determine the coefficient of friction. This method makes no use of data-loggers.

The testing surface of the tribometer was set in a horizontal position, using a spirit level and universal workshop protractor. The coefficient of static friction was determined by the school tribometer, whose angle of inclination we can alter and...
measure. The sliding test body was placed on the tribometer and the angle was increased until it begun to move. In this case, the following equality is satisfied:

\[ \vec{F}_p = \vec{F}_t \]

\[ mg \sin \alpha = f_0 mg \cos \alpha \] 

\( \vec{F}_p \) - movement force

Therefore, the coefficient of static friction is:

\[ f_0 = \tan \alpha \]

The coefficient of dynamic friction \( f \) depends on the angle \( \alpha \), which is the friction angle [Mechlová, 1999]. The friction force and the normal force are mutually perpendicular, therefore:

\[ f = \frac{\vec{F}_t}{\vec{F}_n} = \tan \alpha \]

The angle of inclination was set such that the test body followed a uniform motion. That occurs only when the angle of inclination is equal to \( \alpha \).

### Table 4. Average values of the coefficients of friction, friction angle, [Hrabovská, Bachelor thesis, 2013]

<table>
<thead>
<tr>
<th>Friction materials</th>
<th>( m ) (g)</th>
<th>Friction angle ( \alpha_f ) (°)</th>
<th>Friction angle ( \alpha ) (°)</th>
<th>( f_0 ) (1)</th>
<th>( f ) (1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spruce wood</td>
<td>138,507</td>
<td>23,3</td>
<td>17,2</td>
<td>0,431</td>
<td>0,310</td>
</tr>
<tr>
<td>Spruce wood</td>
<td>256,800</td>
<td>22,7</td>
<td>16,6</td>
<td>0,418</td>
<td>0,298</td>
</tr>
<tr>
<td>Spruce wood - Perspex</td>
<td>138,507</td>
<td>19,1</td>
<td>16,9</td>
<td>0,346</td>
<td>0,304</td>
</tr>
<tr>
<td>Spruce wood</td>
<td>256,800</td>
<td>19,1</td>
<td>16,8</td>
<td>0,346</td>
<td>0,302</td>
</tr>
<tr>
<td>Sand paper P180</td>
<td>102,014</td>
<td>37,1</td>
<td>36,1</td>
<td>0,756</td>
<td>0,729</td>
</tr>
<tr>
<td></td>
<td>216,040</td>
<td>37,4</td>
<td>35,8</td>
<td>0,765</td>
<td>0,725</td>
</tr>
</tbody>
</table>

### Determination of the coefficient of friction through finding the friction angle with the school tribometer (Vernier system)

The testing surface of the tribometer was set in a horizontal position, using a spirit level and universal workshop protractor, and a 3-D sensor for acceleration due to gravity was attached. The 3-D sensor measures the x, y and z components of acceleration due to gravity and it was used to measure the angle of the tribometer testing plane. The sensor was attached to the pivoted joint of the inclining tribometer. The x axis was chosen to be along the testing plane of the tribometer, y axis was perpendicular to it (vertical). The z component of acceleration was zero. The 3-D acceleration sensor was connected to CH 1 of the LabQuest, which was connected to a PC. The settings on the Logger Lite programme were as follows: Duration of sample 10 s, sampling frequency: 50/s [Vernier, 2014].

The sliding test body was placed on the tribometer testing plane. The angle of inclination was increased until the body began to move. Vernier data-loggers enabled us to find the x, y components of the acceleration and the friction angle was found as \( \tan \alpha = \frac{\alpha_f}{\alpha} \).

At the moment when the test body begins to move:

\[ \vec{F}_p = \vec{F}_t \]

\[ mg \sin \alpha = f_0 mg \cos \alpha \]

And therefore the coefficient of static friction is:

\[ f_0 = \tan \alpha \]

Coefficient of dynamic friction is:

\[ f = \tan \alpha \]

When the coefficient of dynamic friction was measured, the test body was moving at a constant speed down the plane, which was monitored by the Vernier position and motion sensor.

Vernier sensors used: LabQuest mini sensor, position and motion sensor, 3D gravitational acceleration sensor (up to 5 g).

### Table 5. Average values of the coefficients of friction, friction angle, Vernier system [Hrabovská, Bachelor thesis, 2013]

<table>
<thead>
<tr>
<th>Friction materials</th>
<th>( m ) (g)</th>
<th>Friction angle ( \alpha_f ) (°)</th>
<th>Friction angle ( \alpha ) (°)</th>
<th>( f_0 ) (1)</th>
<th>( f ) (1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spruce wood</td>
<td>138,507</td>
<td>27,377</td>
<td>26,428</td>
<td>0,518</td>
<td>0,497</td>
</tr>
<tr>
<td>Spruce wood</td>
<td>256,800</td>
<td>26,378</td>
<td>25,886</td>
<td>0,496</td>
<td>0,485</td>
</tr>
<tr>
<td>Spruce wood - Perspex</td>
<td>138,507</td>
<td>17,244</td>
<td>16,826</td>
<td>0,310</td>
<td>0,302</td>
</tr>
<tr>
<td>Spruce wood</td>
<td>256,800</td>
<td>17,140</td>
<td>16,921</td>
<td>0,308</td>
<td>0,304</td>
</tr>
<tr>
<td>Spruce wood</td>
<td>102,014</td>
<td>33,472</td>
<td>32,758</td>
<td>0,661</td>
<td>0,643</td>
</tr>
</tbody>
</table>
Results and discussions

The measurement results correspond to the theoretical dependencies. The measurements were validated by the relationship between the coefficient of friction, frictional force and normal force. It was confirmed by the dependence of the coefficient of friction on the angle of the inclined plane. The work verified the claim that the static coefficient of friction is greater than the dynamic coefficient of friction.

Measuring the surface roughness characteristics of the sliding bodies and removable tribometer pad was performed using the surface-sensitive method (contact profilometer). This measurement describes in detail the surface roughness. Impaired quality and higher roughness parameters effect the results of the coefficients of sliding friction, thus the coefficients acquire higher values.

The coefficients of the friction of wood are mainly influenced by uneven surface morphology. The morphology of the surface of the wood is set by its anatomical structure and the method of mechanical processing. Wood surfaces have defects (tree rings, knots, cracks and burrs).

Conclusion

Contribution of this work is the validation of the current knowledge concerning the measurement of the coefficient of friction by using commonly available tools in the student laboratory, as well as using the Vernier measurement system. The results of measurement are in accord with common theories. The validity of the relationships between the coefficient of dynamic friction, frictional force, normal reaction and the angle of inclination were confirmed. They also enhance student understanding that friction can be useful (braking, motion, rubbing and grinding) as well as a nuisance (unwanted deceleration, heating effects in machinery). The use of ICT in teaching allows publication of experiences and sharing them with the educational community.

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References


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