MODULE 12

ROLLING MOTION ON AN INCLINED PLANE

1. EXPERIMENT AIM

1.1. To determine constants of moment of inertia experimentally,

1.2. To determine the ratio of translational kinetic energy to rotational kinetic energy of a rolling object.

2. EXPERIMENT APPARATUS

2.1. One set of sliding board equipped with IR sensor and interface box,

2.2. Some cylindrical objects,

2.3. Power supply and serial connection cable,

2.4. PC to control and display data from the interface,

2.5. Protractor to measure distance and determine inclination of the sliding board.

3. BASIC THEORY

A point-particle object sliding down along an inclined plane with an angle of θ will experience an acceleration $a = g \sin\theta$. If the object is a rigid body which is able to rotate, then the motion is not as simple as the point particle. Figure 12.1 shows a uniform object with mass M and radius R rolling without slipping down along an inclined plane with an angle of θ, along the direction of x axis. Acceleration of the object $a_{tpm,x}$ while climbing down the incline could be derived using Newton's second law of translational motion $\left(F_{net} = M.a\right)$ and rotational motion $\left(\tau_{net} = I.\alpha\right)$. The first step is to draw the free body diagram of the object as in Figure 12.1, with

1. Gravitational force: downward,
2. Normal force: perpendicular to the inclined plane,
3. Static friction force: working on the touching point, parallel to the plane, upward.

Newton's second law in *x* direction as in Figure 12.1 is written as

$$f_s - Mg \sin\theta = Ma_{tpm,x} . \qquad (12.1)$$

This equation consists two variables which are unknown, i.e. f_s and $a_{tpm,x}$. In this case, f_s should not be assumed to be maximum ($f_{s,\mathbf{max}}$) because f_s is determined from the equilibrium of forces occurred when the object is on motion.

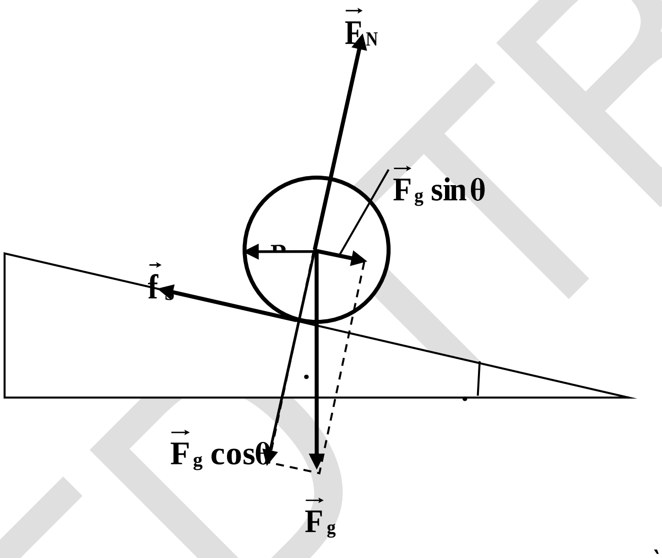

Figure 12.1. Rolling motion on an inclined plane.

Afterward, the Newton's second law of rotational motion respect to the center of mass is considered. Use equation $\tau = rF$ to determine torque on the respective point. Friction force f_s is at a distance of *R* from the rotation axis (center of mass) resulting a torque of Rf_s which has negative value as it causes the object to rotate clockwise. Force $\vec{F}_g$ and $\vec{F}_N$ each has zero moment arm, thus resulting no torque. Therefore, the Newton's second law of rotational body ($\tau_{net} = I\alpha$) respect to its center of mass is

$$Rf_s = -I_{tpm}\alpha . \qquad (12.2)$$

This equation also has two variables which are still unknown, i.e. f_s and α. Because the object is assumed to roll without slipping, then equation $a_{tpm} = \alpha R$ is useful to relate $a_{tpm,x}$ with α. Note that $a_{tpm,x}$ has positive value (object moves to *x* positive) and α has negative value (object rotates clockwise). As a result, α should be substituted with $-a_{tpm,x} / R$. Take this relation into Eq. (12.2) and simplify the equation to obtain f_s.

$$f_s = I_{tpm} \frac{a_{tpm,x}}{R^2} \tag{12.3}$$

By substituting f_s in Eq. (12.1), it could be shown that

$$a_{tpm,x} = \frac{g \sin\theta}{1 + I_{tpm} / MR^2}. \tag{12.4}$$

This equation will come in handy to determine the translational acceleration of the object ($a_{tpm,x}$) on an inclined plane with an angle of θ.

4. EXPERIMENT METHODS

Experiment is performed by letting a rigid body rolls along an inclined plane with an adjustable angle. The sliding board is equipped with 9 pairs of infrared sensors (IR, *infra red*) connected to interface box. Electronic circuitry inside the interface box is to measure time interval every time the object passing each pair of IR sensors. This time interval data is then displayed on the PC to be processed further.

4.1. Start with recognizing the program to control the interface from the PC,

a. The "*Open*" button is to activate communication channel between the PC and the interface,

b. The "*Reset*" button is to return the interface condition to its initial condition,

c. The "*Activate*" button is to active the sensor circuitry. Measurement will start (*t = 0*) as soon as the object passes the first pair of IR sensor. After successfully activating the sensor system, this button changes its function to "*Turn Off*" that will return the interface to non-active condition,

d. The "*Check Sensors*" button is to check that all sensors are functioning normally,

e. The ”*Read Data*” button is to display the latest set of data which is successfully measured,

f. The ”*Set Timeout*” button is to adjust the maximum time interval allowed for the object to pass the first sensor to the last sensor. This kind of function is needed to end the measurement in case of the rolling object fails to reach the last sensor (e.g. the object deviates from the trajectory),

g. The ”*Clear Screen*” button is to clear the display on response screen.

4.2. Decide a position as the START line on the upper part of the sliding board. Maintain this position as the starting point of each measurements during the experiment,

4.3. Measure carefully the distance of the first sensor, second sensor, and so on from the zeroth sensor as position data x_0, x_1, x_2, ... ,

4.4. Adjust inclination angle of the sliding board by putting something beneath to sustain it,

4.5. Adjust position of the object so that it can move as parallel as possible with the left and right edges of the sliding board,

4.6. From the *START* position, release the object and let it rolls down along the incline. Time measurement will start as soon as the object passes the first sensor and will end after the object passes the last sensor (*FINISH* position). If the experiment goes well, all measurement results will be displayed on response screen. Else, message ”Time Out” will appear. Write all of time measurement data as t_0, t_1, t_2, ... ,

4.7. Using a certain spreadsheet program (such as MS Excel), make a graph of x as a function of t and determine the parameters,

4.8. Repeat the experiment for various cylindrical objects and several inclination angle of the sliding board according to the task given by the assistant.

5. REPORT

5.1. Using the parameters obtained from the experiment (time, angle, and positions of sensors) and translational acceleration of center of mass equation, find the constant of moment of inertia of the objects!

5.2. Make a plot that compares translational kinetic energy to rotational kinetic energy in the end of the rolling motion by assuming that the object rolls without slipping during the process!

5.3. Compare the constants of moment of inertia obtained from the experiment to the existing theory. Explain why there are differences!

5.4. Why is the curve of distance (x) against time (t) not passing (0,0)? What would you conclude from the graph?

5.5. In your opinion, how can this experiment be used to detect at what angle the rolling object starts to slip?

6. REFERENCES

Resnick, Robert., Halliday, David, Krane, Kenneth S. (1992). *Physics 4th Edition Vol. 1*. John Wiley & Sons, 418 – 419.

Tyler, F. (1970) : *A Laboratory Manual of Physics*, Edward Arnold, 19.

MODULE 13

MOMENTUM AND COLLISIONS

1. EXPERIMENT AIM

1.1 To comprehend the principle of conservation of momentum,

1.2 To calculate velocities of the system at various states of collision,

1.3 To compare the momentum before and after a collision,

1.4 To compare the kinetic energy before and after a collision,

1.5 To observe various events of collision possible of two objects.

2. EXPERIMENT APPARATUS

2.1. Air Track set*,*

2.2. Photogate sensor,

2.3. Mini LabQuest,

2.4. Lattices,

2.5. Gliders,

2.6. Weights,

2.7. Weighing scale.

3. BASIC THEORY

In this module, phenomena common to our daily life will be studied, that is the phenomena of impulse and momentum.

3.1. Momentum

Momentum of an object is defined as multiplication of its mass with its velocity. Momentum represents a measure of how difficult to alter the tendency of an object's motion. Mathematically, linear momentum is formulated as follows.

$$p = m.v \tag{13.1}$$

where *m* is the object's mass and *v* is its velocity. The total force applied to the object causes change in the momentum over time as formulated in the following equation.

$$\sum F = \frac{dp}{dt} \tag{13.2}$$

$$= \frac{d\,(mv)}{dt}$$

$$= m\frac{dv}{dt}$$

$$\sum F = m\,a \tag{13.3}$$

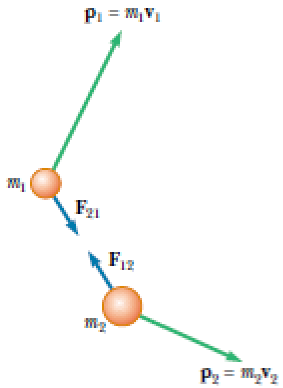

Figure 13.1. Interaction of 2 particles with momentum p_1 of particle 1 and p_2 of particle 2

Suppose two particles interacting one each other without being disturbed by the environment (external forces) and satisfying **the law of action-reaction (Newton's third law)**. Then, the law of conservation of momentum is able to be written mathematically as

$$F_{12} + F_{21} = 0$$

$$\frac{dp_1}{dt} + \frac{dp_2}{dt} = 0$$

$$\frac{d(p_1+p_2)}{dt} = 0$$

$$p_1 + p_2 = \text{constant} \tag{13.4}$$

3.2. Impulse

Impulse could be derived from the integral of force (F) with respect to time (t). Mathematically, impulse is written as

$$F = \frac{dp}{dt}$$

$$dp = F\ dt$$

$$I = \int_{t1}^{t2} F\ dt\ = \int_{p1}^{p2} dp = p_2 - p_1 = \Delta p \qquad (13.5)$$

3.3. Collision

Collision is an example of situation with conserved momentum. There are three kinds of collision, i.e. perfectly elastic collision, inelastic collision, and perfectly inelastic collision. In perfectly elastic collision case, there is no energy kinetic loss during the process so that conservation of kinetic energy applies. In inelastic collision case, some kinetic energy is lost, thus causing the final kinetic energy not same as the initial one. In perfectly inelastic collision, the two colliding objects stick together after the impact and move with the same velocity.

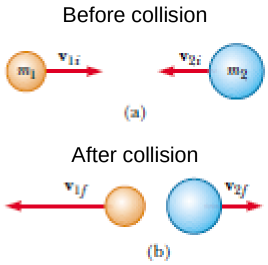

Figure 13.2. **Elastic collision of two particles: (a) before collision and (b) after collision**

Figure 13.2 (a) shows particle 1 with mass m_1 moving right toward to particle 2 with a speed v_1 while particle 2 with mass m_2 moving left toward to particle 1 with a speed v_2. The total kinetic energy before the collision is

$$K_i = \frac{1}{2} m_1 v_{1i}^2 + \frac{1}{2} m_2 v_{2i}^2 \qquad (13.6)$$

and after the collision is

$$K_i = \frac{1}{2} m_1 v_{1f}^2 + \frac{1}{2} m_2 v_{2f}^2. \qquad (13.7)$$

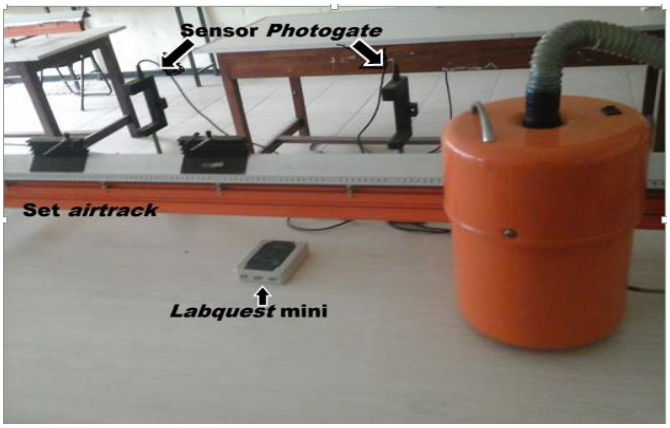

Figure 13.3. Komponen-komponen eksperimen momentum dan tumbukan

4. EXPERIMENT METHODS

4.1 Experiment instrument settings

a. Prepare two photogate sensors and connect them to LabQuest,
b. Change setting in mini LabQuest setting on computer to photogate sensor,
c. Place the first photogate sensor at a distance of 50 cm and the second photogate sensor at a distance of 150 cm,
d. Prepare the glider by attaching some additional weights and lattices,
e. Put the glider on the air track,
f. Turn the air track on and adjust the air track holders to align the air track horizontally (not tilted). Horizontally aligned air track causes no slope, thus the glider put on it will stand still when the air track is on.

4.2 Collision 1

a. Put two gliders each on the end of the air track,
b. Prepare the LabQuest to start reading the data,
c. Push the gliders carefully and make sure that they collide in the region located between the two photogate sensors,
d. Write the time readings of the sensor,

e. Calculate speeds before and after the collision of each gliders,
f. Repeat the steps for various weights attached on the gliders,
g. Tabulate the data on Table 13.1.

Table 13.1. Data of mass, initial speed, and final speed in collision 1

Variation	Glider 1			Glider 2		
	Mass (kg)	Initial Speed (m/s)	Final Speed (m/s)	Mass (kg)	Initial Speed (m/s)	Final Speed (m/s)
1						
2						
3						
4						
5						

h. From Table 13.1, calculate coefficient of restitution of each variations and tabulate the results on the following table.

Table 13.2. Data of coefficient of restitution in collision 1.

Variation	Coefficient of restitution (e)
1	
2	
3	
4	
5	

i. From Table 13.1, determine momentum of the gliders and total momentum of the system before and after the impact. Tabulate the results on the following table.

Table 13.3. Data of momentum of glider 1, glider 2, and the system before and after the impact in collision 1.

Variation	Before Collision			After Collision		
	p glider 1 (kg m/s)	*p* glider 2 (kg m/s)	*p* system (kg m/s)	*p* glider 1 (kg m/s)	*p* glider 2 (kg m/s)	*p* system (kg m/s)
1						
2						
3						
4						
5						

j. Calculate kinetic energy of the system before and after the impact. Compare and tabulate the results on the following table.

Table 13.4. Data of kinetic energy (KE) before and after the impact in collision 1.

Variation	Initial KE (J)	Final KE (J)
1		
2		
3		
4		
5		

4.3. Collision 2

a. Put the first glider on the end of the air track and the other glider between the two photogate sensors. Make sure the second glider is not moving,

b. Prepare the LabQuest to start reading the data,

c. Push the glider on the end of the air track carefully and let it collide with the second glider,

d. Write the time readings of the sensor,

e. Calculate speeds before and after the collision of each gliders,

f. Repeat the steps for various weights attached on the gliders,

g. Tabulate the data on Table 13.5.

Table 13.5. Data of mass, initial speed, and final speed in collision 2

Variation	Glider 1			Glider 2		
	Mass (kg)	Initial Speed (m/s)	Final Speed (m/s)	Mass (kg)	Initial Speed (m/s)	Final Speed (m/s)
1						
2						
3						
4						
5						

h. From Table 13.5, calculate coefficient of restitution of each variations and tabulate the results on the following table.

Table 13.6. Data of coefficient of restitution in collision 2.

Variation	Coefficient of restitution (e)
1	
2	
3	
4	
5	

i. From Table 13.5, determine momentum of the gliders and total momentum of the system before and after the impact. Tabulate the results on the following table.

Table 13.7. Data of momentum of glider 1, glider 2, and the system before and after the impact in collision 2.

Variation	Before Collision			After Collision		
	p glider 1 (kg m/s)	*p* glider 2 (kg m/s)	*p* system (kg m/s)	*p* glider 1 (kg m/s)	*p* glider 2 (kg m/s)	*p* system (kg m/s)

1						
2						
3						
4						
5						

j. Calculate kinetic energy of the system before and after the impact. Compare and tabulate the results on the following table.

Table 13.8. Data of kinetic energy (KE) before and after the impact in collision 2.

Variation	Initial KE (J)	Final KE (J)
1		
2		
3		
4		
5		

4.4. Collision 3

a. Put one glider on the end of the air track and put a rigid body between the two photogate sensors,

b. Prepare the LabQuest to start reading the data,

c. Push the glider on the end of the air track carefully and let it collide with the rigid body located between the photogate sensors,

d. Write the time readings of the sensor,

e. Calculate speeds before and after the collision of the glider,

f. Repeat the steps for various weights attached on the glider,

g. Tabulate the data on Table 13.9.

Table 13.9. Data of mass, initial speed, and final speed in collision 3

Variation	Glider 1		
	Mass (kg)	Initial Speed (m/s)	Final Speed (m/s)
1			
2			

3			
4			
5			

h. From Table 13.5, calculate coefficient of restitution of each variations and tabulate the results on the following table.

Table 13.10. Data of coefficient of restitution in collision 3.

Variation	Coefficient of restitution (e)
1	
2	
3	
4	
5	

i. From Table 13.9, determine momentum of the glider and total momentum of the system before and after the impact. Tabulate the results on the following table.

Table 13.11. Data of momentum of glider 1 and the system before and after the impact in collision 3.

Variation	Before Collision		After Collision	
	p glider 1 (kg m/s)	*p* system (kg m/s)	*p* glider 1 (kg m/s)	*p* system (kg m/s)
1				
2				
3				
4				
5				

j. Calculate kinetic energy of the system before and after the impact. Compare and tabulate the results on the following table.

Table 13.12. Data of kinetic energy (KE) before and after the impact in collision 3.

Variation	Initial KE (J)	Final KE (J)
1		
2		
3		
4		
5		

5. REPORT

5.1 Verification of law of conservation of momentum

1. Make graphs of position as a function of time (x vs t) for the three conditions!
2. Determine speeds according to the three obtained graphs!
3. According to the data of initial and final speeds, is the law of conservation of momentum confirmed?
4. Give your analysis about this experiment!

5.2 Determination of impulse of the system

1. Determine accelerations of the system from the graph obtained in section 5.1, then make the three corresponding graph of force as a function of time!
2. Determine impulse of the system according to the obtained graphs!
3. Compare the impulses calculated according to the graphs to the one obtained from the change of momentum!
4. Give your analysis about this experiment!

6. REFERENCES

Resnick, Robert., Halliday, David, Krane, Kenneth S. (1992). *Physics 4th Edition Vol. 1*. John Wiley & Sons, 209 – 210.

Amend, Bill. (2011) : *Physics 16 Laboratory Manual*, Armhest College, 24 – 26.

Physics Department. (2011) : *Introductory Physics Laboratory Manual*, The City University of New York, 60 – 62

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Revision:

This module book has been revised several times when the LFD is coordinated by Dr. Hendro, M.Si. The latest revision was made in 2016 by Dr. Hendro, M.Si. Assisted by technical assistants consisting of Valdi Rizki Yandri, Dewanto Kamas Utomo, Fandy Gustiara, Wilson Jefriyanto, and Jerfi.

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<u>REPORT FORMAT</u>

MODULE XX

Title

Day, date, time of practicum
Monday, 25 January 2010
Time 14.00 – 17.00

Assistant : *Name / NIM of the assistant*

I. LAB CONDITION

CONDITION / TIME	BEGINNING	END
Temperature	$(28 \pm 0.5)\ ^{\circ}C$	$(29 \pm 0.5)\ ^{\circ}C$
Humidity	$(80 \pm 0.5)\ \%$	$(81 \pm 0.5)\ \%$
Barometric Pressure	(695.45 ± 0.025) mmHg	(696.15 ± 0.025) mmHg

II. EXPERIMENTAL AIM

Do not copy the one written in module, please write by your own language. Make it appropriate to the purposed result of the practicum.

III. EXPERIMENTAL APPARATUS

Write it according to the tools and the materials provided during the practicum.

IV. BRIEF THEORY

Write no more than half page. This section consists of very basic theory and main equations which correspond with the practicum.

V. DATA AND PROCESSING

Write the data into the table (will be guided by assistant). Do not forget to write the corresponding unit and the uncertainty of measurement.

Data processing and calculation should be written in the form of table (will be guided by assistant). If it is necessary to draw a graph, do it directly on the journal book (do not need to use millimeter blocks papers). If it is necessary to derive any equations, please do it in data processing section.

VI. ANALYSIS / DISCUSSION

Format of writing analysis or discussion is in ***paragraph****. It is not allowed to write in points. The contents of analysis are not just to blame the equipment. Some analysis may be directed by the assistant.*

VII. CONCLUSION

This section is generally to answer the objective. It is allowed to write in points.