DOI: 10.14421/impulse.2023.31-05

IMPULSE: Journal of Research and Innovation in Physics Education
Volume 3, Issue 1, 39 – 52

http://ejournal.uin-suka.ac.id/tarbiyah/impulse

Computational Analysis for Free Fall Cases with Air Friction

Iqlides Ahmad Miyaqi[1*], Supardi[2], Najilul Barokah[3]

[1]Madrasah Aliyah Ali Maksum, Yogyakarta, Indonesia
[2]Postgraduate Physics Education, Yogyakarta State University, Indonesia
[3]Huazhong University of Science and Technology, China
*Corresponding author: iqlidesahmad.2022@student.uny.ac.id

ABSTRACT

Free fall motion without initial velocity is a mechanical concept that can be analyzed using analytical, experimental, and computational methods. Free fall motion is difficult to analyze analytically if air friction is not neglected. The aim of this research is to explain computational free fall motion analysis procedures with air friction. Air friction disturbance in free fall motion is represented by the coefficient *C* which states the drag coefficient is time dependent. In this scientific study, the application used for computational analysis is *IDE Spyder* with various library support. With the help of this application, a significant difference in the output v_{max} and t_{max} is obtained between the two cases of free fall based on the interpretation of the graph that appears.

INTISARI

Gerak jatuh bebas tanpa kecepatan awal merupakan konsep mekanika yang dapat dianalisis menggunakan metode analitik, eksperimen, maupun komputasi. Gerak jatuh bebas sulit untuk dianalisis secara analitik apabila gesekan udara tidak diabaikan. Tujuan dari penelitian ini adalah menjelaskan prosedur analisis gerak jatuh bebas dengan gesekan udara secara komputasi. Gangguan gesekan udara pada gerak jatuh bebas diwakili oleh koefisien *C* yang menyatakan koefisien drag bergantung pada waktu. Dalam kajian ilmiah ini, aplikasi yang digunakan untuk analisis secara komputasi adalah *IDE Spyder* dengan berbagai dukungan *library*. Dengan bantuan aplikasi ini, didapatkan perbedaan output v_{max} dan t_{max} yang berbeda secara signifikan antara kedua kasus gerak jatuh bebas berdasarkan interpretasi grafik yang muncul.

ARTICLE HISTORY
Received: November 20, 2023
Accepted: February 16, 2024

KEYWORDS:

Free Fall Motion, Air Friction, *IDE Spyder*

KATA KUNCI:

Gerak Jatuh Bebas, Gesekan Udara, *IDE Spyder*

* Corresponding author:
IqlidesAhmad Miyaqi, Madrasah Aliyah Ali Maksum, Yogyakarta, Indonesia
✉ iqlidesahmad.2022@student.uny.ac.id

A. Introduction

Free fall is the movement of a particle caused by disturbances in the Earth's gravitational force which is considered constant. This condition causes particles moving in a straight line to experience a uniform change in the vertical y coordinate. This motion occurs assuming the distance traveled is not too far, external forces are ignored, and the initial speed is zero. The free fall motion variable is denoted by h as the distance traveled, g is the gravity acceleration, v indicates the speed of the object after traveling a distance of h, and t is the travel time, so the following equation applies:

$$v = \sqrt{2gh} \quad (1)$$

$$h = \frac{1}{2}gt^2 \quad (2)$$

The geometric shape of the earth occupied by humans is not perfectly round, and there is a large difference in the earth's radius at the equator and the radius at the poles of $\pm$ 21.10^3 meters [1]. This difference makes variations in the height of places on the face of the earth affect the value of gravitational acceleration inversely[2]. Several theories state that the value of the constant $\boldsymbol{g}$ is influenced by the height of the object [3], where this is caused by the influence of the centrifugal force at the equator which is greater, thus influencing the value of the speed of the free-falling object.

The increasing development of science has an impact on the development of technology which produces various kinds of devices that help in carrying out analysis [4], including numerical and computational analysis for physical phenomena [5]. Several devices have been developed, such as using free fall motion video-based trackers and obtaining an average value of gravitational acceleration of (9.63 ± 0.33) m/s^2 [6], [7]. To make it easier to understand the subject of free fall motion, a set of experimental tools was created with two different cases with the help of Audacity as a time sensor. The processing results obtained provide a value of 9.78 m/s^2 with an accuracy of observation and numerical results of 92% [8], [9].

In accordance with increasing precision and measuring tools, demands for the correctness of physical concepts and analysis are increasingly receiving attention and are urgent to be achieved. Including the analysis of free fall motion which previously ignored some forces and is now considered [10]. Analysis of free-fall motion by considering external forces that might influence the state of motion is rarely carried out because the concept of free-fall motion that is taught uses the assumption that free-fall motion occurs in a vacuum [11], [12]. This review eliminates the influence of external forces in the form of air friction which occurs due to friction between falling objects and small air particles [13], [14].

Reviewing vertical free fall motion with air friction disturbances is a complex series of analyses because it involves variables of size and mass of objects. In addition, the parameters used empirically do not necessarily show real results because they depend on the surrounding conditions [15], [16]. Air friction is modeled using a linear velocity variable and calculated assuming the object moves without initial speed, is influenced by the force of gravity, and the magnitude of the friction is proportional to the square of the velocity (v^2) in the opposite direction [17], [18].

Oxygen (O_2) is categorized as a fluid so that it influences the form of friction or air resistance, so the empirical properties of the fluid need to be considered. The magnitude of the air friction force is different from the standard friction model for solid objects because it depends on the relative speed experienced by the object due to its movement in the liquid [19], [20]. The speed aspect has high complexity and only certain cases can be explained analytically [16], [21]. Very low velocities occur in small-sized particles where the air resistance is proportional to the speed expressed in the following equation:

$$f = -bv \tag{3}$$

where the negative sign of the above equation implies that the friction force always has the opposite direction to the object's speed. For cases with larger objects and higher speeds, the force exerted on the air is proportional to the square of the relative speed of the object and the air [16], [22].

$$f = -\frac{1}{2}\rho A C v^2 \tag{4}$$

where ρ is the density of the object, A is the cross-sectional area of the object, and C is the numerical drag coefficient. Meanwhile, for spherical objects, the empirical coefficient C value is 0.47 [23].

Analysis with equations 3 and 4 can of course be carried out simply if the value of the dependent variable is known. Assume that friction occurs for a falling object with no initial speed, with the value of the friction force being proportional to the square of the acceleration (v^2) which has the opposite direction. So, the total vertical force acting is:

$$F = mg - kv^2 \tag{5}$$

$$F = m.a = m.\frac{dv}{dt} \text{ dan } v = \frac{dh}{dt}$$

where h is the vertical distance of the object from the falling position to the earth's surface, so we get:

$$\frac{dv}{dt} + \frac{k}{m}v^2 = g \tag{6}$$

However, sometimes this mathematical expression is only described numerically, giving the impression that there is no other method for analyzing free fall motion [24], [25].

Analysis in physics is generally divided into two, namely numerical and computational analysis. Physics analysis using computational methods using computer assistance with programming language input, such as *Java*, *Matlab* [26], *Phyton*, and etc [27], [28]. The use of this analysis is seen to facilitate mathematical calculations for cases with complicated variables where the user is only required to define the desired quantities and operations [29], [30]. This research aims to explain how to analyze the free fall motion of objects with air friction constraints using the *IDE Spyder*.

B. Method

The research method used is computational free fall motion analysis carried out using *IDE Spyder* software with a *Python*-based programming language. Use this software as a tool in carrying out computational-based analysis with *Numpy*, *Matplotlib*, and *Matplotlib.pyplot* libraries.

C. Result and Discussion

Computational physics case analysis this time uses *IDE Spyder* software in free fall cases by installing the application first on the computer. This application can be downloaded for free on several internet sites. *Spyder* is a *Python* language-based *interactive development environment* (*IDE*) that has a variety of advanced editing features, interactive testing, debugging analysis, evaluation, and numerical application space. *Spyder* can also be used as a library feature that provides widgets related to console settings support from *IPyton*, *NumPy*, *SciPy*, or *matplotlib* [27], [28]. This support allows users to integrate the debugging console into program designs directly. *Spyder's* capabilities can be expanded by integrating with a variety of plug-ins and instruments, such as *Pyflakes*, *Pylint*, and *Rope*.

The first step that needs to be taken is to download and install the *IDE Spyder* software. This is because this application is not the default software for Windows OS or Mac OS. Once installed, the user will enter the *Spyder* display as shown in the following figure:

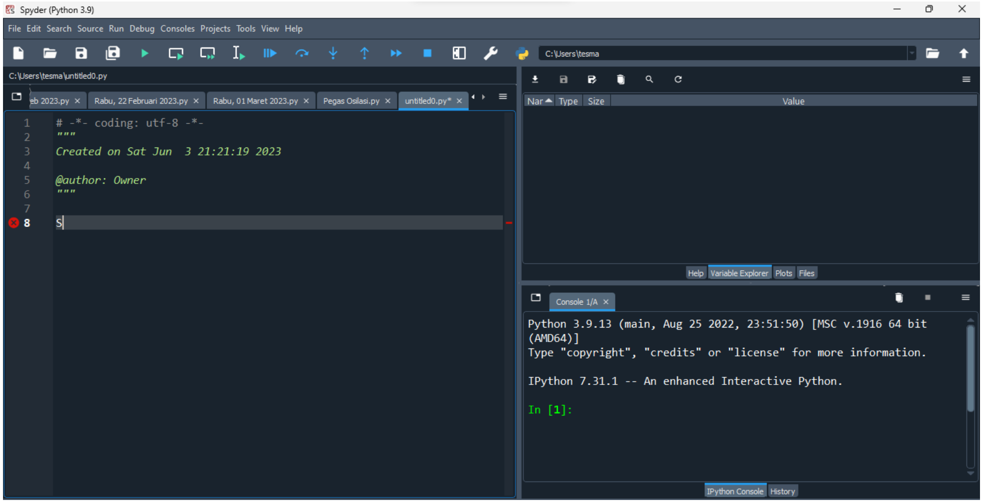

Figure 1. Interface of Spyder application

The initial appearance of Spyder is divided into 3 bars. The left bar is a worksheet for users where in this section the user can compile programming, analysis, or coding. The top right bar is a part of the library that displays the processes carried out, definitions of variables, or other important information. The bottom right bar is the view of an application of the program created [26].

The next step is to prepare the work environment on the worksheet by inserting a *library* as a program library so that the programming that has been created can be function as intended [30], [31], [32]. The *library* input is as follows:

```
@author: User
SS"""

#Persiapan Lingkungan Kerja
import numpy as np
import matplotlib as mpl
import matplotlib.pyplot as plt
from pylab import*
```

Figure 2. Work Environment Preparation

Input the *library* using the "*import*" command. Then continue with the command "*as*" to provide initials to make it easier to use later. *Numpy* contains a package of commands related to numbers to operate *scientific computing*, *matplotlib* contains visualizations related to mathematical operations and *matplotlib.pyplot* contains commands to provide additional information on visualizations from previous *library* [32]. This work environment preparation needs to be done before the coding is input so that it is a reference for the coding language in carrying out operations at the next stage.

The next step is to create parameters for the case to be resolved. This process is like the steps in mathematical representation, namely finding the value of the variable quantity contained in the problem [32], [33]. The specified parameters then become a reference in the operations carried out by *NumPy*. As for this physics case, the parameters are determined as follows:

```
#Menentukan Parameter
g=9.81
y0=9
v0=0
t0=0
dt=0.1
Cd=0.47
```

Figure 3. Phenomenon Parameter Determination

Referring to Equations 1 and 2, it is explained that the free fall motion of an object is influenced by several variables, namely *g* (gravitational acceleration), h/y_0 (height), v_0 (initial speed), and *t* (time). Meanwhile, for cases with air friction, according to Equation 4, there is an entity *C* (drag coefficient) which is a factor inhibiting movement [34]. Figure 3 shows the influencing variables along with the desired values. This value can be varied according to needs

Then, define the previously created parameters into the programming language by formulating *numpy library* (represented by *np*) with a data structure (*array*) for each parameter. This is necessary so that the previous parameters can be formulated using *scientific computing*.

```
#Membuat Variabel
v=np.array([v0])
y=np.array([y0])
t=np.array([t0])

#Inisiasi Gerak Mula mula
ketinggian=y0
waktu=t0
kecepatan=v0
```

Figure 4. Creating Variables on the Worksheet

It should be noted that the variables operated must match the parameters in Figure 4 because they are interconnected. Apart from that, variables are also created specifically for the parameters that change, in this case speed (v_0), height (y_0), and time (t_0). Then in the "*Inisiasi Gerak Mula mula*" section, there is a variable input bar for the initial state of motion with a value that can be changed according to the desired initial condition. Free fall motion is motion without initial velocity vertically so that the initial input is the same as the parameters that have been created as in Figure 3.

The next process is to carry out mathematical operations using computational analysis. This stage is carried out to find the numerical integral of the free-fall motion.

```
#Loop untuk mencari integral numerik dari gerak jatuh bebas
while ketinggian >=0:
    kecepatan = kecepatan - ((g-Cd*kecepatan**2)*dt)
    v = np.append(v, kecepatan)
    ketinggian = ketinggian + kecepatan*dt
    y = np.append(y, ketinggian)
    waktu = waktu + dt
    t = np.append(t, waktu)
```

Figure 5. Finding the Numerical Integral of Free-Falling Motion

Figure 5 shows the numerical analysis by finding the integral of the free fall motion case. The operation uses *Numpy* formulation with *append* function so that variable values can be added to the final array. The operation of the variable v is influenced by the value of the time-dependent friction force, the operation of the variable y depends on the time-dependent fall speed at the current height, and the operation of the variable t changes by dt.

```
#Mencari perhitungan v max dan t max
print(v[-1])
print(t[1])
```

Figure 6. Calculations to Find the Maximum Value

The next stage is to find the maximum v and t values. The values of these two variables indicate the speed immediately before hitting the ground (y_0 = 0) and the duration of the object until it hits the ground [3]. Values in the form of numbers are displayed using the print function, a function to display the investigated output from the coding that has been created. This function is applied to the variables v and t.

```
#Menampilkan hasil perhitungan gerak jatuh bebas
fig, ax = plt.subplots(2,1,sharex = True)
fig.subplots_adjust(hspace=0.6)
```

Figure 7. Programming coding to display calculation results

To display the results graph, a previously imported *library* is used, namely *plt (matplotlib.pyplot)*. Before you can display the results as required, it is necessary to first create a graphic framework that will be used to display the output of the previous operation. Two graphic frames have been created with a vertical downward arrangement with 2 (vertical) × 1 (horizontal) configuration with coding *`fig, ax = plt.subplots(2,1,sharex = True)`*. Then create a separation distance with the coding *`fig.subplots_adjust(hspace=0.6)`*. The *hspace* value states the desired distance between two graph frames, the smaller the value entered, the closer the graph frames will be.

```
ax[0].plot(t,y)
ax[0].set_xlabel("Waktu, t(s)")
ax[0].set_ylabel("Ketinggian, y(m)")
ax[0].set_title("Ketinggian")
ax[0].set_ylim(0.0,11.0)

ax[1].plot(t,v)
ax[1].set_xlabel("Waktu, t(s)")
ax[1].set_ylabel("Kecepatan, v(m/s)")
ax[1].set_title("Kecepatan Jatuh Bebas")
show()
plt.savefig(r'D:\User')
```

Figure 8. Determination of the Coordinate Axis on the Output Graph

After the graphic framework is created, the next step is to create an identity for each framework. The first graph is symbolized by ***ax[0]*** with an explanation regarding the coding entered as follows:

```
ax[0].plot(t,y)                          → Create an axis plot
ax[0].set_xlabel("Waktu, t(s)")          → X axis identity
ax[0].set_ylabel("Ketinggian, y(m)")           → Y axis identity
ax[0].set_title("Ketinggian")                  → Graphic Title
ax[0].set_ylim(0.0,11.0)                 → Create a length limit for the
y-axis
```

The second graph is symbolized by ***ax[1]*** with the following coding input

```
ax[1].plot(t,v)                          → Create an axis plot
ax[1].set_xlabel("Waktu, t(s)")          → x axis identity
ax[1].set_ylabel("Kecepatan, v(m/s)")          → y axis identity
ax[1].set_title("Kecepatan Jatuh Bebas") → Graphic Title
ax[1].set_ylim(0.0,11.0)                 → Create a length limit for the
y-axis
```

Then, issue a graphical output command with the following coding

```
show()                                → Output functions
plt.savefig(r'D:\User')                  → Output storage directory
```

The thing to note is that the *User* name must match *@author* in Figure 2. The next step is to run the coding program by selecting the *Run* option (▶) or pressing F5 (*for Windows devices*) until the numerical analysis output appears on application display bar as in Figure 9

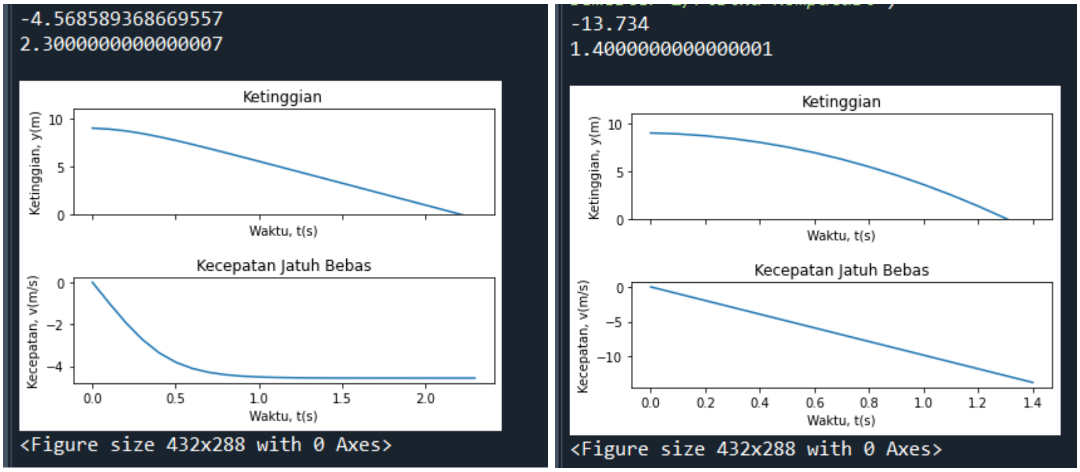

Figure 9. Numerical Output and Graph of Free Fall Motion with Air Friction

The use of the negative sign (-) in the free fall speed value is used to indicate that the direction of the object's fall is towards the center of gravity. Apart from that, a graph of the falling motion on the negative *y-axis* was also made to show that the object's motion was downward [35]. This action was carried out as a form of conformity to the interpretation of physics in this computational analysis which refers to the Cartesian coordinate system (*x*, *y*, *z*). This was created to minimize misunderstandings among the public, especially for those who are studying physics.

The results of computational analysis for numerical integrals in free fall motion with air friction produce v_{max} = -4.56858. . . m/s and t_{max}= 2.3 s and the speed graph shows a gradient with extreme slope values. This output shows that there is an influence of air friction on the speed of the free fall motion so that it does not include an *uniformly accelerated rectilinear motion* (GLBB). The image on the right side shows a computational analysis for free fall motion without the influence of air friction, resulting in v_{max} = -13.734 m/s and t_{max} = 1.4 s which is to the results of the analytical method. The gradient on the speed graph is also constant and this shows that the motion is an *uniformly accelerated rectilinear motion* (GLBB)[36], [37].

The graph and results in Figure 9 show that there are quite significant differences in the two free fall motion calculation results. The first simulation uses air resistance as a function of disturbance causing the falling speed of the object to be far apart, namely 4.5 m/s compared to 13.7 m/s from a height of 10 meters. The interpretation that can be taken is that air resistance behaves as "*something that collides and resists the departure*" of something that passes through it [38], [39]. This behavior is caused by the dense concentration of molecules that make up air (N, O, C, and so on) in the path the falling object takes. The absence of a number of these molecules smoothes the path of falling objects so that the transformation of the object's potential energy into kinetic energy can be maximized [40].

Figure 9 is the result obtained with an input value of ***h*** (height) of 10 m for objects with air friction constraints and without any constraints. Below we will also present several computational analysis results for different variations of ***h*** values:

Table 1. Comparison of the Results of Computational Analysis of Variables v and t

Height (m)	**Air friction constraints**		**Non-air friction constraints**	
	v	***t***	***v***	***t***
5	4,55	1,41	9,91	1,01
10	4,57	2,30	13,73	1,40
15	4,57	3,59	17,17	1,75
20	4,57	4,69	19,82	2,02
25	4,57	5,79	22,17	2,26
30	4,58	6,89	24,23	2,47

The differences in results for these two variables are illustrated in Figure 10.

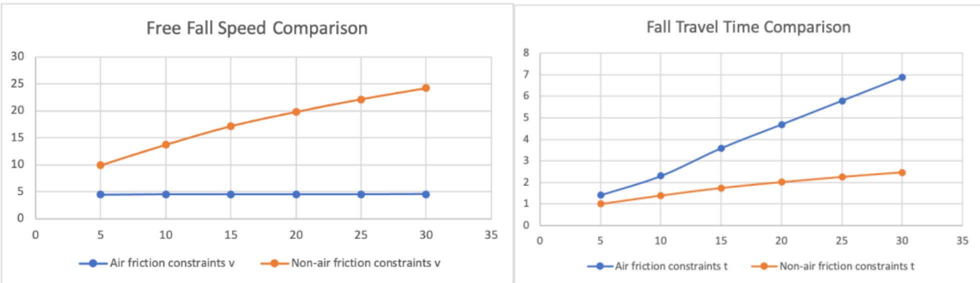

Figure 10. Comparison Graph of *v* and *t* Values

There is a significant difference in the speed graph, where the variable *v* on the blue line (with air friction) tends to be stagnant and flat, while on the orange line (without air friction) it produces a sloping line with a constant average gradient. Differences also occur in the duration of the fall to a height (*h*) = 0 m. The blue line shows the results in the form of a line with a large gradient when compared to the orange line which has a small slope. The large gradient value on the fall time graph shows that air friction ultimately also has an effect on the longer fall time based on the increased initial height value [2].

Computational calculation and analysis methods have been presented as an effort to minimize measurement errors in various cases, including cases of free fall motion. The use of this method has the effect of increasing the accuracy of the calculation results obtained [41]. Apart from that, this method also does not require a lot of resources to carry out experiments (in some cases it requires high costs to purchase an application license) because it is preloaded by the device used. The positive side of using computational methods is that they can be used to analyze cases that are difficult to realize in the real world, such as atomic collisions [42], and molecule interactions, or to model physics cases that are full of mathematical equations (such as quantum mechanics and black body radiation)[43].

D. Conclusion

The phenomenon of free fall can be analyzed using various methods, one of which is computing with the help of Spyder. Analysis with this application is used because the analytical calculations for this case are quite complex and require a lot of time so this application can be used as a solution. The analysis begins with creating a work environment and then creating mathematical operations for the case. The results obtained show that there is an influence of air friction on the speed of free fall motion which causes a significant difference in tmax compared to tmax for free fall motion without air friction.

In this analysis, objects in free fall motion are assumed to be particles so their geometric shape is not taken into account. Further research can take analysis with different geometric shapes.

Acknowledgements

Thanks are expressed to Dr. Supardi, S.Si, M.Si for his guidance and direction in preparing the article. Thanks are also expressed to colleagues in the Physics Education Masters Program at Yogyakarta State University for the opportunity to continue our studies that have been given.

References

[1] P. H. Winingsih *et al.*, “Analysis of understanding of physics concepts through problem solving units review in free fall motion materials,” *Revista Mexicana de Física E*, vol. 20, no. 2 Jul-Dec, pp. 020205 1-6-020205 1–6, Jun. 2023, doi: 10.31349/REVMEXFISE.20.020205.

[2] Muhammad Subhan, Eka Rahmawati, Lis Suswati, Y. Yus’iran, and F. Fatimah, “Variasi Ketinggian MDPL terhadap Nilai Percepatan Gravitasi Bumi pada Konsep Gerak Jatuh Bebas (GJB) untuk Pendekatan Pembelajaran,” *Jurnal Pendidikan MIPA*, vol. 12, no. 3, pp. 831–837, Sep. 2022, doi: 10.37630/jpm.v12i3.660.

[3] D. C. Giancoli, *Physics for Scientists & Engineers, Vol. 1 (Chs 1-20).* Pearson Education UK, 2013.

[4] N. Mambai, Triwiyono, and A. Lumbu, “Implementation of an Inquiry Model Assisted with PHET and Teaching Aids to Improve Vocational Students’ Learning Outcomes in The Sound Waves Concept,” *Impulse: Journal of Research and Innovation in Physics Education*, vol. 2, no. 2, pp. 97–106, Dec. 2022, doi: 10.14421/impulse.2022.22.04.

[5] M. S. Zulkarnain and J. Sabaryati, “Solusi Numerik Logika Fisika Berbasis Matlab Algoritm,” Ahlimedia Book, Medan, 2008.

[6] F. M. Bara, “Analisis Percepatan Gravitasi Menggunakan Aplikasi Phyphox Pada Gerak Jatuh Bebas,” *Jurnal Luminous: Riset Ilmiah Pendidikan Fisika*, vol. 2, no. 2, pp. 11–17, 2021.

[7] A. Ghisi, D. Faraci, S. Adorno, and A. Corigliano, “The role of anchor imposed motion in the failure of MEMS microphones under free fall tests,” *Microelectronics Reliability*, vol. 135, 2022, doi: 10.1016/j.microrel.2022.114584.

[8] T. Firdaus, E. Erwin, and R. Rosmiati, “Eksperimen Mandiri Siswa dalam Penentuan Percepatan Gravitasi Bumi pada Materi Gerak Jatuh Bebas,” *Titian Ilmu: Jurnal Ilmiah Multi Sciences*, vol. 11, no. 1, pp. 31–36, 2019.

[9] J.-T. Kim, Y. Jin, S. Shen, A. Dash, and L. P. Chamorro, “Free fall of homogeneous and heterogeneous cones,” *Phys Rev Fluids*, vol. 5, no. 9, 2020, doi: 10.1103/PhysRevFluids.5.093801.

[10] W. E. Ardhanariswari, W. N. Wulandari, H. I. Khalidah, and B. Setiaji, “Analysis of High School Students’ Learning Difficulties in Understanding the Mechanics Concept,” *Impulse: Journal of Research and Innovation in Physics Education*, vol. 1, no. 2, pp. 72–79, 2021.

[11] A. Pujianto, “Analisis konsepsi siswa pada konsep kinematika gerak lurus,” *JPFT (Jurnal Pendidikan Fisika Tadulako Online)*, vol. 1, no. 1, pp. 16–21, 2013.

[12] M. Tawil and M. Amin Said, “Understanding the Newton’sMotion Concept Through Qualitative and Quantitative Teaching,” *JPPPF*, vol. 8, no. 1, 2022, doi: 10.21009/1.

[13] D. Halliday, R. Resnick, and J. Walker, *Fundamentals of Physics*. John Wiley & Sons, 2013.

[14] J. Miljojković, V. Kočović, M. Luković, A. Živković, and K. Šimunović, “Development of a Modular Didactic Laboratory Set for the Experimental Study of Friction,” *Tehnicki Vjesnik*, vol. 29, no. 1, pp. 269–277, 2022, doi: 10.17559/TV-20210925171045.

[15] F. Lyrath, C. Stechert, and S. I. U. Ahmed, “Application of Augmented Reality (AR) in the Laboratory for Experimental Physics,” *Procedia CIRP*, vol. 119, pp. 170–175, Jan. 2023, doi: 10.1016/J.PROCIR.2023.03.089.

[16] R. Ekawati, A. Setiawan, A. R. Wulan, and D. Rusdiana, “Development of concept essential in kinematic topics,” in *Journal of Physics: Conference Series*, 2020. doi: 10.1088/1742-6596/1521/2/022019.

[17] N. Yuningsih and S. Sardjito, “Gerak Vertikal Benda Berukuran Berbeda yang Jatuh Tanpa Kecepatan Awal dan Bergesekan dengan Udara,” in *Prosiding Industrial Research Workshop and National Seminar*, 2020, pp. 710–714.

[18] S. Achouch, L. Masmoudi, M. Gharbi, and P. Nonnon, “Design and development of a sensor for distance and velocity measurement using an Infrared camera for studying kinematic movements,” in *2019 International Conference on Wireless Technologies, Embedded and Intelligent Systems, WITS 2019*, 2019. doi: 10.1109/WITS.2019.8723696.

[19] E. Pardiyanto and W. Winarti, “Generative Learning Strategy Assisted by Flash Animation to Remediate Students’ Misconceptions on Newton’s Law of Gravity,” *Jurnal Pendidikan Sains Indonesia (Indonesian Journal of Science Education)*, vol. 9, no. 2, pp. 201–216, 2021.

[20] P. Winingsih *et al.*, “Analysis of understanding of physics concepts through problem solving units review in free fall motion materials,” *Revista Mexicana de Física E*, vol. 20, no. 2 Jul-Dec, Jun. 2023, doi: 10.31349/RevMexFisE.20.020205.

[21] N. Yuningsih, S. Sardjito, and Y. C. Dewi, “Determination of earth’s gravitational acceleration and moment of inertia of rigid body using physical pendulum

experiments," in *IOP Conference Series: Materials Science and Engineering*, IOP Publishing, 2020, p. 022001.
[22] N. S. Belousova and O. G. Glotov, "Laws of motion and aerodynamic drag coefficient for large titanium particles burning in air," *Thermophysics and Aeromechanics*, vol. 29, no. 4, pp. 557–565, 2022, doi: 10.1134/S0869864322040084.
[23] P. Mohazzabi, "When does air resistance become significant in free fall?," *Phys Teach*, vol. 49, no. 2, pp. 89–90, 2011.
[24] M. Garg, K. Kalimullah, P. Arun, and F. M. S. Lima, "Accurate measurement of the position and velocity of a falling object," *Am J Phys*, vol. 75, no. 3, pp. 254–258, 2007.
[25] G. Avallone, L. Agostini, M. Conconi, V. Parenti-Castelli, R. Vertechy, and N. Sancisi, *Low-Cost Gyroscope and Accelerometer Calibration with Free Fall Pendulum Motion: Results and Sensitivity*, vol. 606. 2022. doi: 10.1007/978-3-031-06409-8_15.
[26] H. Putranta *et al.*, "Visualization of Refractive Index and Reflectance of Sodium Metal Based on Drude's Theory Using MATLAB as an Alternative for Optics and Astrophysics Lectures.," *SAR Journal (2619-9955)*, vol. 5, no. 3, 2022.
[27] A. Seto Priambodo and A. Sony, "Studi Komparasi Simulasi Sistem Kendali PID pada MATLAB, GNU Octave, Scilab, dan Spyder," *ELINVO*, vol. 4, no. 2, pp. 169–175, 2019, doi: 10.21831/elinvo.v4i2.
[28] B. Crnokić, F. Pehar, J. Spajić, and I. Bagarić, "Stem classroom: Creating a phyton application for an EV3 brick robotic system used to transport 3D printed boxes," in *Annals of DAAAM and Proceedings of the International DAAAM Symposium*, 2020, pp. 88–97. doi: 10.2507/31st.daaam.proceedings.012.
[29] E. Bufasi and K. Lakrad, "Improving Teaching Techniques Using Visual Python: A Case Study," 2019. [Online]. Available: www.ijstr.org
[30] E. Muzayyanah, A. Megananda, H. P. Darmayanti, and Z. I. Priana, "Development of digital distance measurement instrument based on Arduino Uno for physics practicum," *Impulse: Journal of Research and Innovation in Physics Education*, vol. 1, no. 2, pp. 80–88, 2021.
[31] A. Jodra, C. García-Iriepa, and L. M. Frutos, "An Algorithm Predicting the Optimal Mechanical Response of Electronic Energy Difference," *J Chem Theory Comput*, vol. 19, no. 18, pp. 6392–6401, 2023, doi: 10.1021/acs.jctc.3c00490.
[32] M. Serik, G. Yerlanova, Y. N. Karelkhan, and N. Temirbekov, "The Use of The High-Performance Computing in The Learning Process," *International Journal of Emerging Technologies in Learning*, vol. 16, no. 17, pp. 240–254, 2021, doi: 10.3991/ijet.v16i17.22889.
[33] A. Astalini, D. Darmaji, D. A. Kurniawan, and N. N. Simamora, "Comparison of Perception and Implementation of Mathematical Physics for Matrices," *Jurnal Pendidikan Fisika dan Keilmuan (JPFK)*, vol. 7, no. 1, Jul. 2021, doi: 10.25273/jpfk.v7i1.9509.
[34] H. W. Prabawa, R. Rosjanuardi, and E. Nurlaelah, "Problem Decomposition Skills, Mathematical Maturity, and Their Relation to Mathematics Problem-Solving in A Computer Science Learning Class," *Jurnal Kependidikan: Jurnal Hasil Penelitian dan Kajian Kepustakaan di Bidang Pendidikan, Pengajaran dan Pembelajaran*, vol. 9, no. 3, p. 946, Sep. 2023, doi: 10.33394/jk.v9i3.8258.
[35] A. Susac, A. Bubic, E. Kazotti, M. Planinic, and M. Palmovic, "Student understanding of graph slope and area under a graph: A comparison of physics

and nonphysics students," *Phys Rev Phys Educ Res*, vol. 14, no. 2, 2018, doi: 10.1103/PhysRevPhysEducRes.14.020109.

[36] P. A. Tipler and G. P. Mosca, *Physics for Scientists and Engineers, 5th edition - Volume 1*, vol. 1. 2002. Accessed: Jun. 04, 2023. [Online]. Available: https://ui.adsabs.harvard.edu/abs/2002pse..book.....T/abstract

[37] L. K. Wee, K. K. Tan, T. K. Leong, and C. Tan, "Using Tracker to understand 'toss up' and free fall motion: A case study," *Phys Educ*, vol. 50, no. 4, pp. 436–442, 2015, doi: 10.1088/0031-9120/50/4/436.

[38] M. Garg, K. Kalimullah, P. Arun, and F. M. S. Lima, "Accurate measurement of the position and velocity of a falling object," *Am J Phys*, vol. 75, no. 3, pp. 254–258, 2007.

[39] N. Yuningsih and S. Sardjito, "Experimental study of determination of earth's gravitational acceleration using the concept of free-fall motion and conservation of mechanical energy," in *AIP Conference Proceedings*, AIP Publishing, 2021.

[40] A. Mayang Sari, "The Integrated Physics Learning E-Module with Pancasila Character Values in Work and Energy Subjects as Solution to Improve Students' Critical Thinking Ability and Independence: Is It Effective?," *Jurnal Ilmiah Pendidikan Fisika Al-BiRuNi*, vol. 10, pp. 85–100, 2021, [Online]. Available: https://ejournal.radenintan.ac.id/index.php/al-biruni/index

[41] M. S. da Silva, L. A. Heidemann, and R. R. Campomanes, "Combining computational and experimental activities: an alternative using the free fall paradox | Integração de atividades computacionais e experimentais: uma alternativa utilizando o paradoxo da queda livre," *Revista Brasileira de Ensino de Fisica*, vol. 45, 2023, doi: 10.1590/1806-9126-RBEF-2023-0082.

[42] J.-L. Gao, W.-J. Bi, J. Zhang, and J. Zang, "Numerical Investigations on Harbor Oscillations Induced by Falling Objects," *China Ocean Engineering*, vol. 37, no. 3, pp. 458–470, 2023, doi: 10.1007/s13344-023-0038-y.

[43] G. Kalies and D. D. Do, "Momentum work and the energetic foundations of physics. I. Newton's laws of motion tailored to processes," *AIP Adv*, vol. 13, no. 6, 2023, doi: 10.1063/5.0147910.