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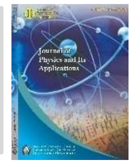

Numerical Analysis of the Doppler Effect in Circular Motion with Modulated Angular Velocity Using Python

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ABSTRACT

This study presents a numerical simulation of the Doppler effect for an object in circular motion with time-modulated angular velocity, developed using the Python programming language. The model computes angular velocity, angular position, and observed frequency as functions of time based on a modified Doppler formulation. Two simulation models were implemented: an interactive mode using an IPython widget slider to vary the modulation constant ($0 \le b \le 1$), and a comparative mode evaluating three representative modulation strengths ($b = 0.15, 0.20, 0.25$). The results demonstrate that the modulation of angular velocity produces periodic fluctuations in the observed frequency, consistent with theoretical predictions. Sensitivity testing confirmed numerical stability ($\Delta f < 0.01$ Hz) with smaller time steps ($\Delta t = 0.01$ s), validating the robustness of the computational model. These findings quantitatively reveal the relationship between modulation parameters and Doppler frequency shifts, providing a reproducible and pedagogically effective framework for studying non-uniform circular motion and its physical implications in astrophysical and acoustic systems.

1. Introduction

The Doppler effect is a cornerstone of modern physics and astrophysics, providing a fundamental means to measure motion through wave frequency shifts. It describes the change in frequency of waves perceived by an observer moving relative to the source. For instance, the shift in pitch of a siren from an approaching or receding emergency vehicle vividly illustrates this phenomenon [1]. Beyond daily experience, the Doppler effect underpins numerous scientific and technological applications, from observing blood flow in arteries and cooling atoms in laser traps to tracking the Earth's motion through space and detecting distant exoplanets orbiting other stars [2].

Although the Doppler effect is typically introduced through linear motion, the movement of celestial bodies (such as planets and stars) generally follows elliptical orbits, as governed by Kepler's Laws [3,4]. Understanding frequency variations in such systems is essential, particularly since more than 5,300 exoplanets have now been confirmed by NASA using diverse detection methods [5]. The first exoplanet, 51 Pegasi b, was discovered in 1995 by Michel Mayor and Didier Queloz using the radial velocity method, which directly applies the Doppler effect principle [6,7]. In this method, a star's radial velocity oscillates periodically due to the gravitational interaction with its orbiting planet [8,9]. The resulting red and blue shifts in spectral lines reveal orbital motion and enable estimation of planetary mass and distance [10].

In realistic exoplanet systems, the angular velocity of the star-planet pair does not remain constant. Because planetary orbits are often elliptical, the star's angular speed varies cyclically as the planet moves closer or farther in its orbit. These periodic changes produce modulated Doppler frequency shifts, a crucial factor in achieving precise radial-velocity measurements. However, many existing analyses simplify these orbits to circular motion for practical and pedagogical purposes. Laboratory experiments typically employ sound waves as analogs for starlight, exploiting their measurability and demonstrating that the mathematical form of the Doppler effect is equivalent for both acoustic and electromagnetic waves [11].

Previous studies formulated modified Doppler effect equations for circular motion and validated them through theoretical and experimental investigations [12]. Most of these works assumed constant tangential and angular velocity, often using a rotating buzzer to mimic a star's uniform motion. The resulting equations were shown to agree with Christian Doppler's original theory [13]. Subsequent experiments highlighted the influence of emitted frequency on the observed shift [7] and examined how variation in the radius of rotation affects frequency change [14].

While these studies significantly advanced Doppler effect analysis in circular motion, no research has yet examined systems with time-varying or modulated angular velocity. This gap limits the applicability of existing models to real astronomical and laboratory conditions, where angular velocity oscillates periodically.

Accordingly, this study addresses the following research question: How does modulated angular velocity affect the observed frequency in circular motion, and what parameters influence these frequency variations?

To answer this question, a Python-based numerical simulation was developed by applying the modified Doppler effect equation from previous studies [15,16]. Python was selected because of its powerful numerical and visualization libraries (NumPy, Matplotlib, and IPython widgets), which allow for both interactive and quantitative analysis. The simulation calculates angular velocity, angular position, and observed frequency as functions of time, and enables users to adjust the modulation constant (b) interactively to observe its effect on frequency variation.

The Python-based simulation was developed using the Waterfall model, ensuring a systematic workflow from requirements analysis through implementation, testing, and maintenance. This structured approach guarantees reproducibility and clear documentation throughout the simulation process.

The main contributions of this research are as follows: (1) development of a Python-based simulation framework for modeling the Doppler effect in circular motion with modulated angular velocity; (2) identification of key parameters, the modulation constant (b) and modulation frequency (ωm), that govern the observed Doppler frequency fluctuations; and (3) provision of a quantitative and interactive educational tool that enhances conceptual understanding of dynamic Doppler phenomena and supports experimental design in both physics education and astrophysics research.

This simulation bridges the gap between simplified theoretical models and real-world dynamical systems, offering a realistic and flexible approach for analyzing Doppler frequency variations in time-modulated rotational motion.

2. Literature Review

On May 25, 1842, Christian Doppler (1803–1853) introduced the Doppler principle, which explains the change in the frequency of waves perceived by an observer when the source and receiver move relative to each other. The Doppler effect applies not only to sound waves but also to electromagnetic waves, including microwaves, radio waves, and visible light [1,2].

When the source and observer are in linear motion relative to each other, the direction of approach or recession remains constant, so the observed wavelength does not change. However, when a wave source moves in a circular path with continuously changing velocity, its direction of motion constantly changes, resulting in a varying observed wavelength [14]. Therefore, an investigation is needed into how modulated velocity changes of a wave source moving in a circular path affect the observed frequency.

To model the rate of these changes, the geometric scheme in Fig. 1 below illustrates the parameters that must be considered.

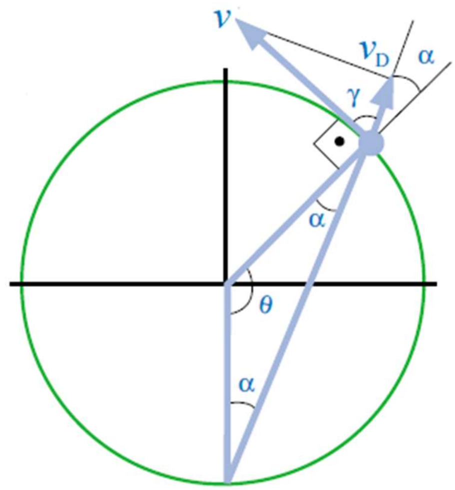

Fig. 1: Geometric scheme for calculating the velocity of a circular moving wave source [12]

Note that v_D is the relative velocity between the source and observer, with its positive value if the source is moving away and negative if approaching the observer. If the observer is stationary (v_0 = 0), then the Doppler effect equation can be written as:

$$f = f_0\left(\frac{c}{c \pm v_D}\right) \tag{1}$$

To determine v_D as a function of time, Fig. 1 provide the following information:

$$v_D = v\ \cos\gamma \tag{2}$$

where v is the tangential velocity and γ is the angle between v and v_D. For uniform circular motion, $v = \omega R$ with $\omega = \frac{2\pi}{T}$, giving

$$v = \frac{2\pi R}{T} \tag{3}$$

Thus,

$$v_D = \frac{2\pi R\cos\gamma}{T} \tag{4}$$

Based on Fig. 1, it can be seen that $\theta + 2\alpha = \pi$ dan $\alpha + \gamma = \frac{\pi}{2}$, then $\gamma = \frac{\theta}{2}$. For constant v, $\theta = \frac{2\pi t}{T}$, so $\gamma = \frac{\pi t}{T}$. Substituting γ into Equation (4) results in:

$$v_D = \frac{2\pi R}{T}\cos\left(\frac{\pi t}{T}\right) \tag{5}$$

When Equation (5) is substituted into Equation (1), the Doppler effect equation for an object moving in a circular path with constant angular velocity is obtained as follows:

$$f = f_0\left[\frac{c}{c + \frac{2\pi R}{T}\cos\left(\frac{\pi t}{T}\right)}\right] \tag{6}$$

Equation (6), as presented by Saba & Rosa (2003), forms the basis for analyzing the Doppler effect in objects moving in circular paths with constant angular velocity [12]. However, for more realistic scenarios, such as the case of exoplanets, a model that accounts for variations in angular velocity over time is required. This is especially important because planetary orbits, which affect the motion of stars, tend to follow elliptical paths governed by Kepler's laws. This concept serves as the foundation for developing a model that considers cyclical modulation of angular velocity to more accurately reflect dynamic conditions, such as those encountered in exoplanet detection.

In this study, the modulated angular velocity $\omega(t)$ is defined as a combination of the initial constant angular velocity ω_0 and a periodically varying component:

$$\omega(t) = \omega_0 + b\,\omega_0 \cos(\omega_m t) \quad (7)$$

where ω_0 is the initial angular velocity, b is the modulation constant determining the amplitude of the modulation, and ω_m represents the modulation frequency, which indicates how frequently the angular velocity changes.

In this model, the angular position $\theta(t)$ is obtained by integrating $\omega(t)$ over time:

$$\theta(t) = \int \omega_0 \, dt + \int b\,\omega_0 \cos(\omega_m t)\ dt$$

$$\theta(t) = \omega_0\, t + \frac{b\,\omega_0}{\omega_m} \sin(\omega_m t) \quad (8)$$

This integration results in Equation (8), which accounts for the cyclical modulation effect on angular motion.

For the modification of the relative velocity v_D, the factor γ is calculated as half of the angular position $\gamma = \frac{\theta(t)}{2}$. This adjustment considers the modulation of angular velocity. The tangential velocity is formulated as $v = \omega(t)R$. Hence, Equation (2) is modified as follows:

$$V_D = \omega(t)R\ \cos\frac{\theta(t)}{2} \quad (9)$$

Finally, the modified Doppler effect equation to accommodate changes in angular velocity and relative velocity is simplified as:

$$f = f_0 \left[\frac{c}{c + \omega(t)R\ \cos\frac{\theta(t)}{2}}\right] \quad (10)$$

The values of $\omega(t)$ and $\theta(t)$ must be substituted from Equation (7) and (8) respectively.

Solving Equations (7), (8), and (10) require accurate and efficient numerical analysis methods. In this context, Python emerges as a highly useful tool, facilitating complex calculations with high precision. Python not only enhances the efficiency of numerical computation but also provides ease of use, making it ideal for scientific research [17]. Python is also recognized for its data visualization capabilities, with libraries such as NumPy, Math, and Matplotlib being highly effective for data analysis and presentation [12,14]. Python's ability to combine accurate computation with informative and appealing visualizations makes it an excellent choice for this study, where developing simulations with visual elements is key to understanding and communicating the analytical results. Thus, the use of Python not only simplifies the analytical process but also aids in conveying a deeper understanding of the dynamics being studied, in line with the objectives of this research.

3. Method

This study employed a numerical simulation approach using the Python programming language to model the Doppler effect for an object in circular motion with time-modulated angular velocity. The simulation was developed following the Waterfall model, which ensured a systematic workflow through five distinct stages: Analysis, Design, Implementation, Testing, and Maintenance (Fig. 2) [18–20]. The primary objective was to visualize the relationship between angular velocity modulation and the resulting variation in observed frequency, based on Equations (7), (8), and (10).

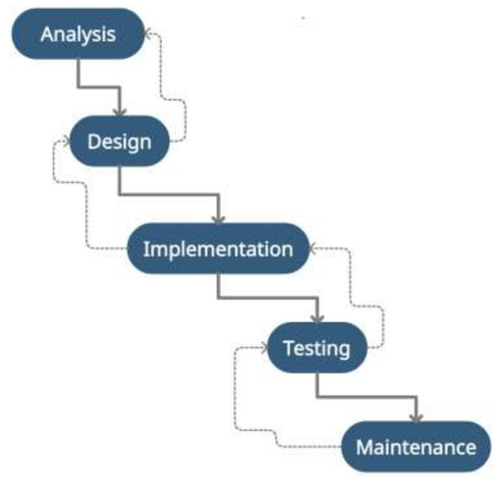

Fig. 2: Waterfall model phases [18]

In this phase, the computational requirements for simulating the Doppler effect were identified. The simulation was designed to compute three primary quantities: angular velocity $\omega(t)$, angular position $\theta(t)$, and observed frequency $f(t)$. These quantities were computed according to the following governing equations:

$$\omega(t) = \omega_0 + b\,\omega_0 \cos(\omega_m t)$$

$$\theta(t) = \omega_0\, t + \frac{b\,\omega_0}{\omega_m} \sin(\omega_m t)$$

$$f = f_0 \left[\frac{c}{c + \omega(t)R\ \cos\frac{\theta(t)}{2}}\right]$$

Python was selected for its versatility in numerical computation and visualization. The libraries used include NumPy (v1.25) for trigonometric and array operations, Math (built-in) for mathematical constants, Matplotlib (v3.8) for time-series visualization, and Ipywidgets (v8.1) for the interactive control of parameters during runtime.

The simulation parameters were selected based on prior experimental studies and physical plausibility. The reference configuration follows Khose (2022), who analyzed Doppler frequency shifts for a 1000 Hz sound source rotating at a radius of 0.2–0.6 m with a period of 2 s in air, assuming a sound speed of 340 m/s [14]. The complete set of parameters adopted in this study is listed in Table 1.

Table 1: Simulation parameters for circular motion with modulated angular

Sym.	Description	Value	Unit
f_0	Emitted frequency	1000	Hz
c	Speed of sound	340	m/s
R	Radius of circular path	0.20	m
T	Period	2.0	s
ω_0	Base angular velocity ($2\pi/T$)	3.14	rad/s
ω_m	Modulation frequency ($0.25\omega_0$)	0.785	rad/s
Δt	Time step	0.1	s

The modulation constant b was treated as a free variable explored interactively in the range 0 ≤ b ≤ 1 during the preliminary simulation phase. The Python initialization block is shown below.

```
# Physical constants and initial setup
c = 340     # Speed of sound (m/s)
T = 2       # Period (s)
R = 0.2     # Radius of rotation (m)
omega_0 = 2 * math.pi / T      # Base angular velocity (rad/s)
omega_m = 0.25 * omega_0       # Modulation frequency (rad/s)
f0 = 1000   # Emitted frequency (Hz)
```

This configuration ensures both physical realism and computational efficiency, providing stable results for interactive visualization and educational experimentation.

The design phase focused on translating the modified Doppler equations into a modular Python simulation capable of computing and visualizing angular motion and frequency variation. The program was implemented in Google Colab using Python 3, with Numpy for numerical computation, Matplotlib for data visualization, and Ipywidgets for creating interactive controls.

```
import matplotlib.pyplot as plt
import numpy as np
import math
import ipywidgets as widgets
from IPython.display import display, clear_output
```

Three core functions were defined to represent the mathematical relationships of angular velocity $\omega(t)$, angular position $\theta(t)$, and observed frequency $f(t)$ according to equations (7), (8), and (10).

```
def calculate_omega(t, omega_0, b, omega_m):
    return omega_0 + b * omega_0 * np.cos(omega_m * t)

def calculate_theta(t, omega_0, b, omega_m):
    return omega_0 * t + (b * omega_0 / omega_m) * np.sin(omega_m * t)

def calculate_frequency(t, f0, c, R, omega_0, b, omega_m):
    omega_t = calculate_omega(t, omega_0, b, omega_m)
    theta_t = calculate_theta(t, omega_0, b, omega_m)
    return f0 * (c / (c + (omega_t * R * np.cos(theta_t / 2))))
```

The functions were designed for modularity and verification, ensuring that each quantity could be computed and visualized independently or in combination. Two visualization modes were developed. The interactive mode (File 1) allows users to manipulate the modulation constant b in real time via an Ipywidgets slider, providing immediate feedback on its influence over the angular velocity and observed frequency plots.

```
slider_b = widgets.FloatSlider(value=0.2, min=0, max=1,
step=0.01, description='b:')
interact_plot = widgets.interactive_output(plot_doppler,
{'b': slider_b})
widgets_layout = widgets.VBox([slider_b])
display(widgets_layout, interact_plot)
```

The comparative mode (File 2) presents the output for multiple fixed b values simultaneously, allowing users to observe proportional variations in the Doppler shift and angular velocity trends.

```
plot_doppler_multiple(b_values=[0.15, 0.20, 0.25])
```

The complete simulation workflow, including data input, computation, visualization, and parameter interaction, is summarized in Fig. 3, which depicts the algorithmic flow of the numerical analysis. This design emphasizes clarity, modularity, and interactivity, enabling the simulation to serve both analytical and educational functions by connecting theoretical principles with dynamic computational modeling.

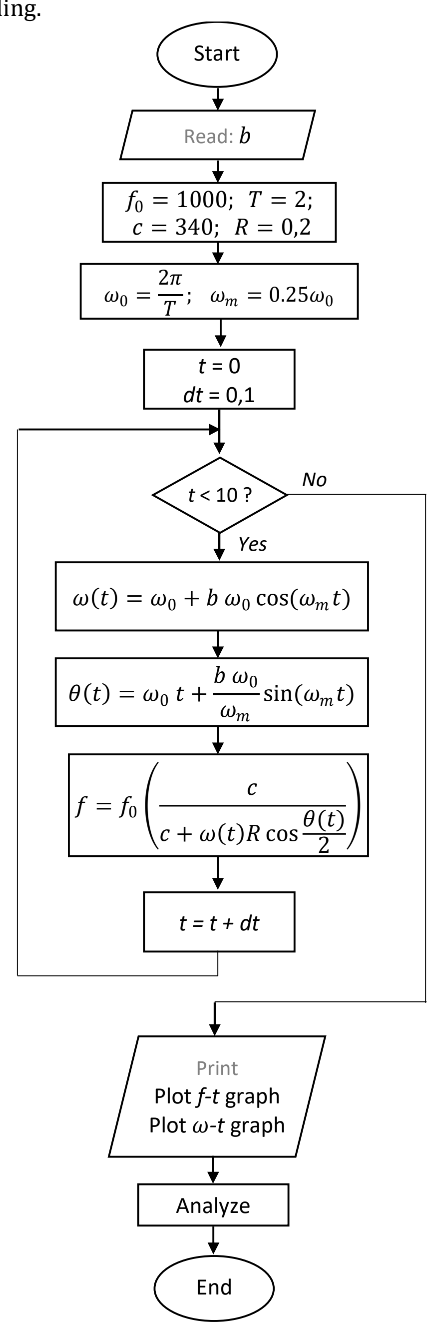

Fig. 3: Flowchart of numerical analysis of the Doppler effect for a circular moving object with modulated angular velocity

The flowchart in Fig. 3 summarizes the iterative computation of angular velocity, angular position, and observed frequency. This algorithm serves as the core simulation routine applied in both interactive and comparative visualization modes.

3.1 Implementation Phase

The implementation was carried out in Google Colab using Python 3. The first implementation (File 1) employed an interactive slider to vary b from 0 to 1 in steps of 0.01, producing dynamic real–time plots of $\omega(t)$ and $f(t)$. Preliminary observations indicated that large modulation constants (b>0.3) tend to increase waveform irregularity, suggesting potential nonlinear effects beyond the current model's scope.

The main program computes the time-dependent quantities for $t \in [0, 20]$ s with Δt = 0.1 s. Two subplots were created:

a. Angular velocity vs. time, showing the modulation pattern according to Equation (7).
b. Observed frequency vs. time, demonstrating the periodic frequency fluctuation caused by modulated angular velocity.

The Matplotlib library generated line plots and included gridlines, labels, and legends for each value of b. The Ipywidgets interface enabled smooth real-time user interaction, allowing for immediate visual updates when adjusting b.

3.2 Testing and Validation Phase

Testing and validation were conducted to ensure the numerical stability and physical consistency of the simulation results. A sensitivity test was first performed by comparing simulations with two time–step sizes ($\Delta t = 0.1$ s and $\Delta t = 0.01$ s). The deviation in the observed frequency was found to be negligible ($\Delta f < 0.01$ Hz), confirming numerical stability under time refinement.

To verify physical accuracy, a baseline case of b=0 was executed, representing uniform circular motion. The resulting frequency–time relationship was consistent with the analytical solution of Saba & Rosa (2003), validating the physical correctness of the algorithm [12]. Additional sensitivity testing was carried out for the modulation frequency ω_m. Doubling ω_m led to an increase in oscillation rate without affecting the amplitude ratio, confirming the model's robustness against parameter scaling.

Following the sensitivity and stability assessments, three representative modulation constants (b = 0.15, 0.20, and 0.25) were selected as benchmark values for subsequent comparative simulations. These values were determined to be sufficiently distinct to capture the effect of modulation strength on the Doppler frequency variation while maintaining numerical stability and physical plausibility.

3.3 Maintenance and Refinement

During the maintenance phase, the simulation code was refined to enhance its readability, modularity, and long-term adaptability. Core computational functions were reorganized into separate modules, which improved clarity and reduced redundancy across the two simulation files. Minor inconsistencies in time-step indexing were corrected to maintain synchronization between ω(t) and θ(t), ensuring consistent data alignment during computation and visualization.

Visualization parameters were also optimized to achieve smoother real-time performance in the interactive mode and to maintain graphical consistency in the comparative mode. This refinement finalized the Waterfall development process by consolidating all functional components into a stable and reproducible simulation framework.

Future developments may include exporting simulated data for integration with machine learning algorithms, particularly for automated pattern recognition and feature extraction in Doppler frequency shifts.

3.4 Limitations

While the simulation effectively models frequency variations under modulated angular velocity, several limitations remain. The model assumes a perfectly circular trajectory and neglects relativistic effects, which could become significant at higher velocities. Environmental influences, such as signal attenuation in the propagation medium, were also excluded from the current framework. Furthermore, the model was not validated against empirical data, although the numerical results showed strong agreement with established theoretical predictions. These limitations will be addressed in future work through experimental validation and by extending the model to elliptical orbits.

4. Results and Discussion

The simulation successfully visualized the relationship between modulated angular velocity and the resulting Doppler frequency in circular motion. Two computational modes were implemented: an interactive single mode, which allows users to adjust the modulation constant b in real-time using a slider interface, and a comparative multi-mode, which plots several curves for different b values on the same axis. Both simulation modes confirm that the modulation of angular velocity produces periodic variations in the observed frequency, consistent with the theoretical model defined in Equations (7), (8), and (10).

To verify the consistency of the numerical implementation with the analytical model, the variation of angular velocity with time was first analyzed.

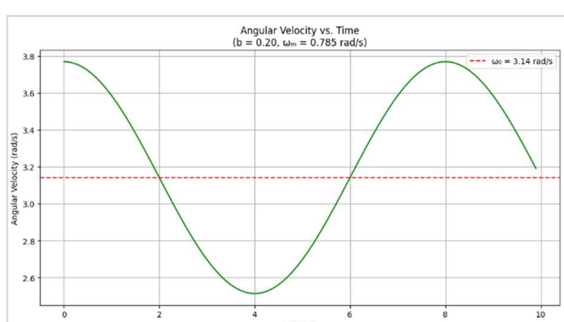

Fig. 4: Angular velocity vs. time for modulation constant b =0.20; with ω_0 = 3.14 rad/s, ω_m = 0.785 rad/s, R= 0.20 m

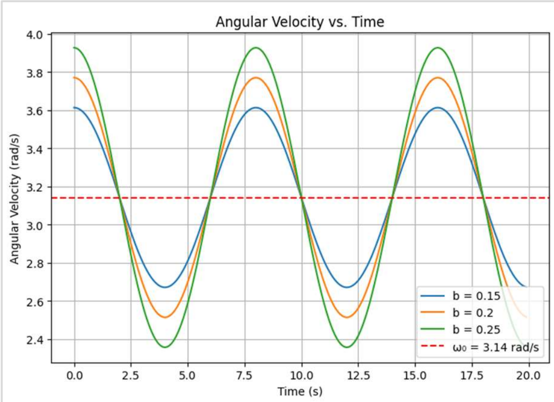

Fig. 5: Angular velocity as a function of time for three modulation constants *b.* The curves illustrate the periodic modulation of angular speed around the base value ω_0 = 3.14 rad/s under ω_m= 0.785 rad/s and *R* = 0.20 m

As shown in Fig. 4, the angular velocity $\omega(t)$ follows a cosine shaped waveform centered around the base value $\omega_0 = 3.14$ rad/s with a modulation frequency $\omega_m = 0.25\omega_0$. The single mode case with b = 0.20 demonstrates how the instantaneous angular velocity oscillates around the mean, representing alternating acceleration and deceleration in circular motion.

To examine the influence of different modulation strengths, the comparative simulation was used to plot angular velocity for three modulation constants b (0.15, 0.20, 0.25). The resulting curves, shown in Fig. 5, display a proportional increase in oscillation amplitude with increasing *b,* indicating a linear relationship between modulation constant and angular velocity variation. For b = 0.15, the angular velocity ranges from 2.67 to 3.61 rad/s, whereas for b = 0.25, it spans from 2.35 to 3.93 rad/s. These results demonstrate quantitatively that modulation determines the degree of variation in rotational speed.

The time dependent behavior of the observed frequency $f(t)$ was also analyzed to evaluate how angular modulation affects the detected Doppler shift. In the single mode simulation, as illustrated in Fig. 6, the observed frequency oscillates periodically around the emitted frequency $f_0 = 1000$ Hz. The waveform reflects alterning phases of approach and recession between the source and the observer. When $cos\frac{\theta(t)}{2} > 0$, the source moves toward the observer, resulting in frequency maxima, whereas minima appear when $cos\frac{\theta(t)}{2} < 0$.

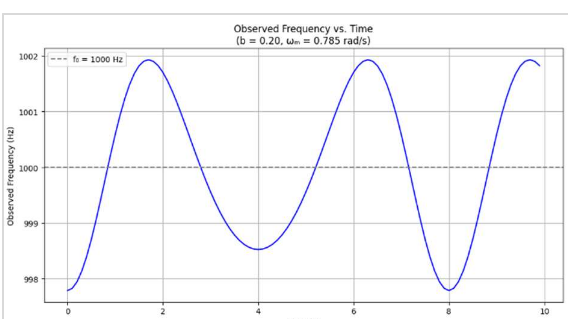

Fig. 6: Observed frequency vs. time for modulation constant b = 0.20; with f_o = 1000 Hz and c = 340 m/s

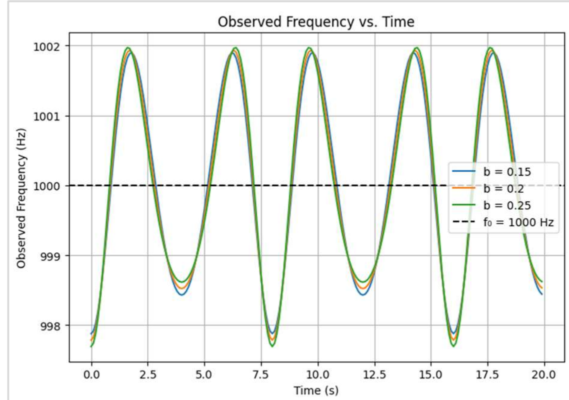

Fig. 7: Observed frequency as a function of time for three different values of the modulation constant b. Increasing b produces larger oscillation amplitudes in the Doppler-shifted frequency, with f_0 = 1000 Hz, c = 340 m/s, T = 2 s

A comparison of the observed frequency for the three modulation constants is presented in Fig. 7. Increasing the modulation constant b widens the frequency fluctuation range, while the mean frequency remains close to f_0 . The results summarized in Table 2 show that the amplitude and standard deviation of frequency fluctuations increase monotonically with b. This measurable trend indicates that modulation strength directly influences the magnitude of observed frequency variations without altering the mean position of the signal.

Table 2: Quantitative summary of observed frequency fluctuations for different modulation constants (b)

b	Frequency Range (Hz)	Amplitude (±Hz)	Std. Dev (Hz)
0.15	999.6 – 1000.6	± 0.50	0.29
0.20	999.4 – 1001.1	± 0.85	0.47
0.25	999.0 – 1001.9	± 1.45	0.63

The simulation outcomes align with the classical Doppler principle, whereby the observed frequency depends on the relative radial velocity between the source and the observer. The periodic modulation of angular velocity introduces cyclic Doppler frequency variations, with frequency maxima corresponding to approaching motion and minimum to receding motion. At higher modulation strengths, a slight asymmetry appears in the waveform envelope, caused by the nonlinear coupling between angular position θ(t) and angular velocity ω(t) in Equation (10). This behavior accurately reproduces the dynamic characteristics of circular motion with non-uniform angular velocity.

These results are consistent with the theoretical framework of Saba & Rosa (2003), who modeled the Doppler effect in circular motion assuming a constant angular velocity [12]. The present study extends that framework by incorporating time-modulated angular velocity, yielding periodic variations consistent with the expected Doppler behavior. Compared with the work of Khose (2022), which focused on linear motion under variable velocity, the present model introduces cyclic modulation and thereby captures a frequency periodicity absent in linear systems [14]. Thus, the proposed simulation bridges the conceptual gap between linear and circular motion within Doppler analysis.

The numerical findings hold potential implications for astrophysical observations, particularly in the detection of exoplanets via radial-velocity methods. In such systems, a star's angular velocity varies cyclically as it responds to the gravitational influence of orbiting planets, leading to measurable oscillations in the observed frequency. The simulation demonstrates that even small modulations, such as b = 0.15, can produce detectable frequency variations of approximately ±0.5 Hz for an emitted 1000 Hz signal. This result emphasizes the necessity of precisely modeling angular velocity modulation to improve the accuracy of Doppler-based measurements.

5. Conclusions

This study investigated the Doppler effect in circular motion with time-modulated angular velocity using a Python-based numerical simulation. The primary objective, to determine how the modulation of angular velocity influences the observed frequency, was achieved by applying a modified Doppler equation and varying the modulation constant b and modulation frequency ω_m.

The results show that increasing b leads to a measurable broadening in the range of observed frequencies, while ω_m determines the rate of oscillation. The simulation confirms that even small variations in angular velocity can induce detectable frequency shifts around a source frequency of 1000 Hz, consistent with the theoretical predictions of the Doppler principle. The model thus extends classical constant-velocity formulations to accommodate periodic angular modulation.

In addition to validating the theoretical relationship between angular and frequency modulation, the developed simulation provides a flexible and reproducible tool for exploring Doppler phenomena. It allows for the visualization of frequency variation in systems where rotational velocity changes cyclically, an analogy relevant to astrophysical systems such as exoplanet-star interactions. The approach also supports instructional applications, enabling students to interactively examine how physical parameters affect the Doppler frequency.

Future work may extend this model to elliptical trajectories or incorporate experimental validation to strengthen the connection between simulation and real-world observations.

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References

[1] D. Halliday, R. Resnick, and J. Walker, Physics 7th Extended Edition 7th ed. Erlangga, (2010).
[2] D. D. Nolte, "The Fall and Rise of The Doppler Effect" Phys. Today, 73, 30–35, (2020).
[3] D. Halliday, R. Resnick, and J. Walker, Fundamentals of Physics John Wiley & Sons, (2013).
[4] B. W. Carroll and D. A. Ostlie, An Introduction to Modern Astrophysics Cambridge University Press, (2017).
[5] NASA, "NASA Exoplanet Archive".
[6] M. Mayor and D. Queloz, "A Jupiter-Mass Companion to A Solar-Type Star" Nature, 378, 355–359, (1995).
[7] K. Médjahdi, "Radial Velocity of A Sound Source in Circular Motion for Illustrating The Detection of An Exoplanet" Am. J. Phys., 88, 814–818, (2020).
[8] H. Karttunen, P. Kröger, H. Oja, M. Poutanen, and K. J. Donner, "Exoplanets" in Fundamental Astronomy Springer Berlin Heidelberg, 459–462, (2017).
[9] S. B. Howell, "The Grand Challenges of Exoplanets" Front. Astron. Space Sci., 7, (2020).
[10] G. Saleh, M. J. Faraji, and D. R. Alizadeh, "A New Explanation for Redshift/Blueshift" in APS New England Sect. Fall Meet., C01-009, (2021).
[11] S. Klinaku, "The Doppler effect is the same for both optics and acoustics" Optik, 244, 167565, (2021).
[12] M. M. F. Saba and R. A. da S. Rosa, "The Doppler Effect of a Sound Source Moving in a Circle" Phys. Teach., 41, 89–91, (2003).
[13] A. Romero and M. E. Capoulat, Análisis Del Efecto Doppler Para Una Fuente En Movimiento Circular (2005).
[14] B. Khose, "Investigating the Doppler Effect when the Wave Source Moves in a Circular Path" J. Stud. Res., 11, (2022).
[15] W. McKinney, Python for Data Analysis O'Reilly Media, Inc., (2022).
[16] W. McKinney, Python for Data Analysis: Data Wrangling with Pandas, NumPy, and IPython O'Reilly Media, Inc., (2012).
[17] R. Johansson, Numerical Python: A Practical Techniques Approach for Industry Apress, (2015).
[18] A. Saravanos and M. X. Curinga, "Simulating the Software Development Lifecycle: The Waterfall Model" Appl. Syst. Innov., 6, 108, (2023).
[19] Y. Bassil, "A Simulation Model for the Waterfall Software Development Life Cycle" Int. J. Eng. Technol., 2, (2012).
[20] M. Ahyar, Y. Pramudya, and O. Okimustava, "Implementasi Sistem Pengolahan Data Sky Quality Meter Berbasis Visual Basic Untuk Analisis Perubahan Tingkat Kecerahan Langit" J. Kumparan Fis., 3, 239–246, (2020).