

Design of Real-time Simulation Foucault Pendulum Array System: Exploring Experimental Methods for Gravitational Waves

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Abstract:

Foucault pendulums are traditionally limited by environmental damping, with motion typically ceasing within several hours. This study presents an autonomous resonance energizing control system that achieves sustained, “long-life” oscillation by converting internal potential energy into system kinetic energy. We develop a mathematical-physical model to simulate motion and energy profiles, validated through a real-time, IoT-integrated experimental array. By synchronizing physical pendulum data with a cloud-based simulation platform, we establish a distributed sensing framework. Finally, we demonstrate the utility of this system as a novel experimental proxy for exploring gravitational wave characteristics, utilizing the energy dynamics of the Qiantang River bore as a conceptual model for gravitational field fluctuations. This research bridges classical mechanical observation with modern gravitational wave exploration through real-time distributed simulation.

Keywords:

Foucault Pendulum, Energy Compensation, Internet of Things

1. Introduction

The Foucault pendulum, first demonstrated by Léon Foucault in 1851 at the Paris Panthéon, remains a cornerstone of classical mechanics [1]. By utilizing a 67-meter wire to suspend a 28-kilogram bob, Foucault provided the first direct dynamical evidence of the Earth’s rotation. The experiment demonstrated that while the pendulum’s oscillation plane appears to rotate to an observer on the ground, it is actually the Earth—a non-inertial reference frame—rotating beneath the pendulum. This phenomenon illustrates the effects of the Coriolis force, proving that any moving object on Earth is influenced by the planet’s rotation unless its plane of movement is parallel to the Earth’s axis [2].

Despite its foundational significance, the Foucault pendulum is subject to inherent physical limitations, primarily amplitude attenuation. In its natural state, the system’s kinetic energy is continuously dissipated by air resistance and friction at the suspension point, causing the oscillation to decay and eventually cease [2,3]. Historically, even the most robust pendulums have a maximum duration of

approximately four hours before the motion stops. To counteract this, modern installations, such as the pendulum at the United Nations Headquarters, employ external electromagnetic coils at the base. However, these solutions are often criticized because the application of an external force compromises the “free-swinging” nature of the pendulum, which is essential to the purity of Foucault’s original theoretical concept.

This research addresses these challenges through the design of an autonomous resonance-enabling control system. Unlike traditional electromagnetic drives, this system is integrated within the pendulum bob itself. It functions by converting internal potential energy changes—facilitated by the controlled movement of a weight inside the bob—into kinetic energy for the overall system. This internal compensation mechanism effectively overcomes environmental damping without introducing external field interference, thereby achieving a “long-life” pendulum capable of sustained, equal-amplitude oscillation over extended periods.

Building upon this mechanical stability, the primary objective of this work is the development of a distributed Foucault pendulum array. By establishing a network of “long-life” pendulums situated at identical longitudes but varying latitudes, we can analyze energy fluctuations on a global scale. This system is synchronized with real-time simulations through an Internet of Things (IoT) platform, allowing for precise data analysis of the actual movement.

We propose that such an array serves as a novel experimental proxy for exploring gravitational waves. By using the energy dynamics of the Qiantang River tide—a phenomenon driven by gravitational field perturbations—as a conceptual model, we demonstrate how synchronized pendulum energy increments can visualize the characteristics of fluctuation signals generated by the gravitational field. This integrated approach of mechanical innovation, real-time simulation, and IoT networking bridges classical mechanical observations with modern gravitational wave exploration.

2. Background and Theoretical Framework

This section introduces the background and the theoretical framework for the Foucault pendulum, encompassing its historical context, the mathematical derivation of its motion through hierarchical coordinate transformations, and the analysis of energy dissipation factors in non-ideal environments.

2.2. Historical Origins and Physical Significance

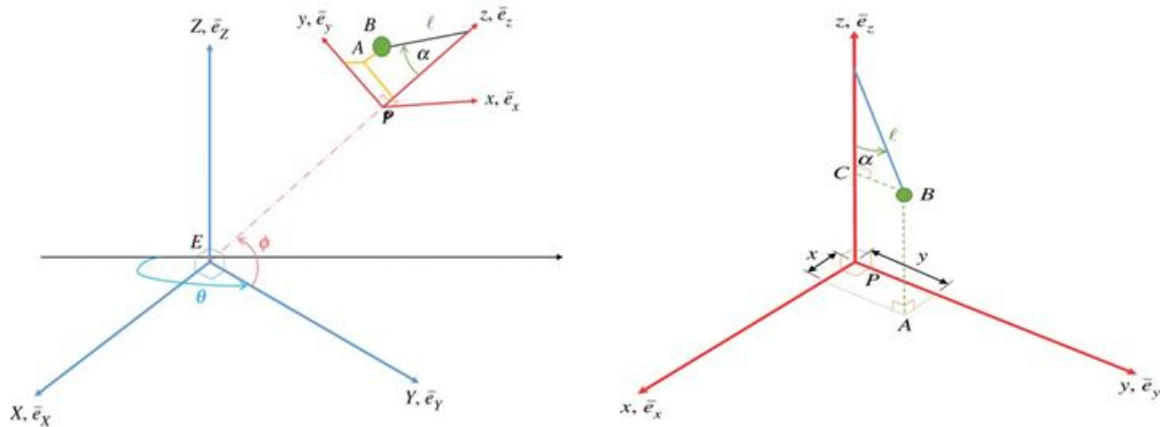
The Foucault pendulum was first conceptualized in 1851 by the French physicist Léon Foucault to demonstrate the Earth’s rotation through mechanical dynamics. His initial experiments used a 2-meter steel wire and a 5-kilogram bob, where he observed that the plane of oscillation rotated over time despite no external torque being applied to the system. By 1851, he had scaled this to the Panthéon in Paris, using a 67-meter wire and a 28-kilogram bob.

This rotation occurs because the pendulum maintains its oscillation plane in an inertial frame of reference, while the Earth rotates beneath it. In the Northern Hemisphere, an observer on Earth sees the pendulum’s plane rotate clockwise; at the equator, the rotation rate is zero, while at the poles, it completes a full rotation every 24 hours. Beyond proving rotation, the system is a physical manifestation of the

Coriolis force, where any moving object in a rotating reference frame experiences a deflection proportional to its velocity and the Earth's angular velocity.

2.2. Coordinate System Transformations

To model the pendulum's motion accurately for simulation, we must transform coordinates between the global Earth frame and the local experimental platform. As shown in Figure 1, we establish four hierarchical coordinate systems: the Earth system (Earth{ E_x, E_y, E_z }), the platform system (Plate{ P_x, P_y, P_z }), the Foucault system (Foucault Pendulum{ FP_x, FP_y, FP_z }), and the pendulum bob system (Pendulum{ PD_x, PD_y, PD_z }) [4].



(a) Relationship between Earth and platform coordinate systems

(b) Detail of the local platform coordinate system

Figure 1. Reference frames and coordinate transformations for Foucault pendulum motion analysis.

The transformation from the global Earth frame to the local platform frame (where β represents the latitude-dependent angle between the respective z-axes) is given by:

$$\begin{aligned} P_x^- &= \cos \cos \beta E_x^- - \sin \sin \beta E_x^- \\ P_y^- &= E_y^- \\ P_z^- &= \sin \sin \beta E_x^- + \cos \cos \beta E_x^- \end{aligned} \quad (1)$$

Subsequent transformations define the Foucault system relative to the platform, using angle θ between the y-axes, and the bob system relative to the pendulum frame, using angle φ relative to the z-axis:

$$\begin{aligned} FP_x^- &= \cos \cos \theta P_x^- - \sin \sin \theta P_y^- \\ FP_y^- &= \sin \sin \theta P_x^- + \cos \cos \theta P_y^- \\ FP_z^- &= P_z^- \\ PD_x^- &= \cos \cos \varphi FP_x^- - \sin \sin \varphi FP_z^- \\ PD_y^- &= FP_y^- \\ PD_z^- &= \sin \sin \varphi FP_x^- + \cos \cos \varphi FP_z^- \end{aligned} \quad (2)$$

2.3. Equations of Motion

As the Earth is a non-uniformly rotating reference frame, any object in motion is subjected to inertial forces, including the Coriolis force, the Euler force, and the centrifugal force. The general dynamical equation for motion in this frame is expressed as:

$$F - m \frac{d\omega^-}{dt} \times r^- - 2m\omega^- \times \frac{dr^-}{dt} - m\omega^- (\omega^- \times r^-) = m \frac{d^2 r^-}{dt^2} \quad (3)$$

By integrating the hierarchical transformations and forces acting on the bob, the coupled second-order differential equations governing the motion are derived as [5]:

$$\begin{aligned} \frac{d^2 x}{dt^2} &= -\frac{g}{l}x + 2\Omega \sin\lambda \frac{dy}{dt} + \Omega^2 \sin^2\lambda x + \Omega^2 \sin\lambda \cos\lambda z \\ \frac{d^2 y}{dt^2} &= -\frac{g}{l}y - 2\Omega \sin\lambda \frac{dx}{dt} - 2\Omega \cos\lambda \frac{dz}{dt} + \Omega^2 y \\ \frac{d^2 z}{dt^2} &= -\frac{g}{l}z + 2\Omega \cos\lambda \frac{dy}{dt} + \Omega^2 \sin\lambda \cos\lambda x + \Omega^2 \cos^2\lambda z \end{aligned} \quad (4)$$

In these expressions, x , y , z represent the displacement along the respective horizontal and vertical axes; Ω is the Earth's angular rotation velocity; λ is the geographical latitude; g is the gravitational acceleration; l is the suspension wire length; and m is the mass of the bob. The terms involving $\Omega \sin\lambda$ represent the Coriolis acceleration, which induces the precession of the oscillation plane, while terms proportional to Ω^2 account for centrifugal effects.

2.4. Energy Attenuation and the Lagrangian

In an ideal frictionless environment, the system's total energy is represented by the Lagrangian (L), defining the difference between kinetic and potential energy in a non-inertial frame [6]:

$$L = \frac{1}{2}mv^2 + m\mathbf{v}^- \cdot (\boldsymbol{\Omega}^- \times \mathbf{r}^-) + \frac{1}{2}m(\boldsymbol{\Omega}^- \times \mathbf{r}^-)^2 - m(\mathbf{a}_0^- \cdot \mathbf{r}^-) - U \quad (5)$$

In practice, the Foucault pendulum is subject to constant energy decay due to local air density, bob windward area, and atmospheric conditions. As illustrated in Figure 2, without energy compensation, the motion trajectory follows a decaying inner cycloid, and the amplitude eventually reaches zero. The autonomous resonance energizing control system proposed in Section 3 targets these dissipation terms by introducing potential energy increments to maintain the system in its ideal Lagrangian state.

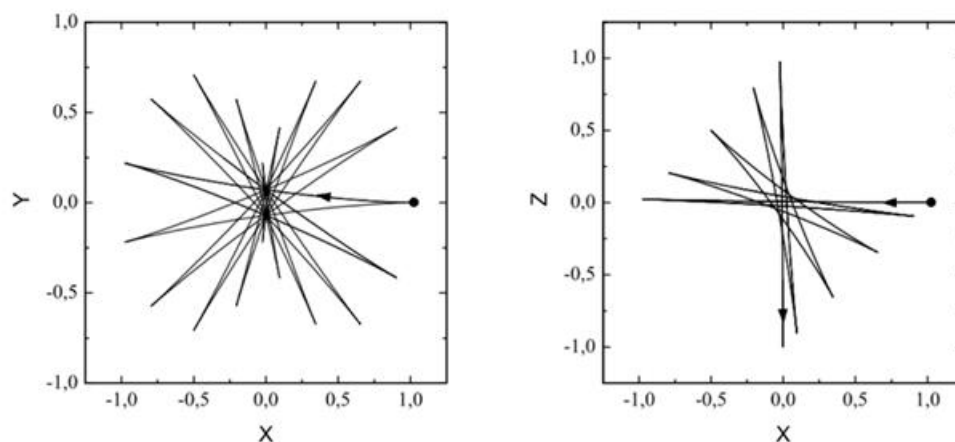


Figure 2. Draw the trajectory of Foucault's pendulum without energy compensation using a rectangular coordinate system.

3. Methodology: Design of the Resonance Empowered Control System

This study designs a resonant empowerment control system located inside a single pendulum bob, primarily utilizing the JY901 nine-axis acceleration sensor as the central intelligent control component. The system is structured as a closed-loop fully negative feedback control system with a correction element, designed to convert the rotation angle of the pendulum motion into the vertical height value of the internal weight motion.

3.1. System Architecture and Feedback Control Logic

As shown in Figure 3, the input of the system is the rotation angle value around the x-axis and the rotation angle value around the y-axis output by the attitude sensor JY901. The correction element is the synthesis of rotation angle vectors for the x-axis and y-axis. The angle value after vector synthesis is the swing angle value of a single pendulum motion. The attenuation of the system is determined by the curve formed by the swing angle value and time. The controller consists of four potentiometers, which control the speed, lower limit, upper limit, and amplitude angle of three servos. The actuator consists of three servos arranged in an equidistant circular array to counteract the torque generated by each other. The circular motion of the servo arm is converted into linear motion of the rocker arm using a ball head and pin. The feedback correction element is the motion threshold of the rocker arm, which adjusts the resistance values of the four potentiometers by judging the threshold, and then adjusts the motion of the servo. The controlled object is a heavy object, and three servos pull the heavy object up and down, while the center of gravity of the overall pendulum remains vertically downward. The sensor measures the rotation angle output by attitude sensor JY901, which is placed at the center of the pendulum to more accurately measure the rotation angle of the pendulum. Disturbance is caused by environmental factors, namely the Coriolis force and air resistance of pendulum motion. The output of the system is the distance (height) of the weight moving up and down.

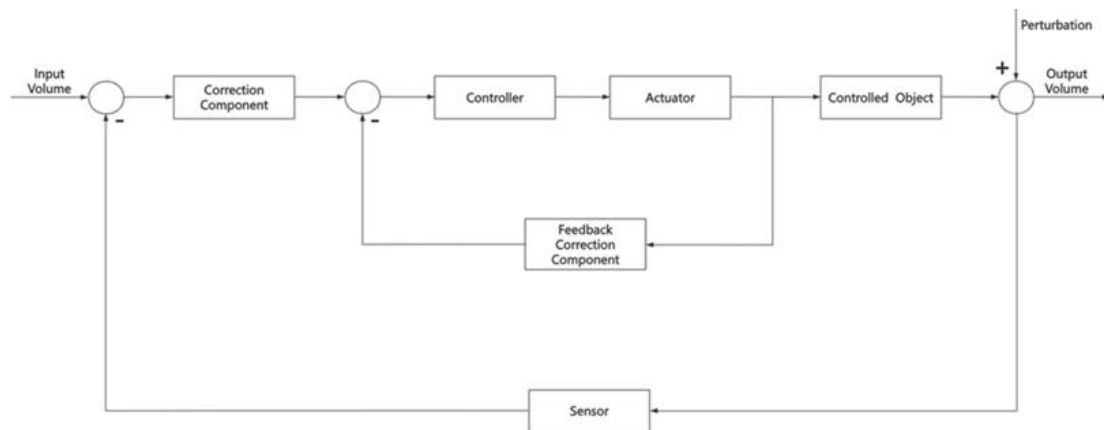


Figure 3. System Block Diagram of Resonance Empowered Control System.

3.2. Signal Flow and Energy Compensation Analysis

In order to further qualitatively analyze the control process of the resonant empowerment control system, the signal flow diagram of the resonant empowerment control system is abstracted through the constructed system diagram, as shown in the

figure. Using mathematical and physical equations to describe the kinetic and potential energy of a pendulum during its motion, analyzing the changes in motion energy to determine energy compensation, and finally obtaining the relationship between the height value of the heavy object's motion and the rotation angle value of the pendulum's motion.

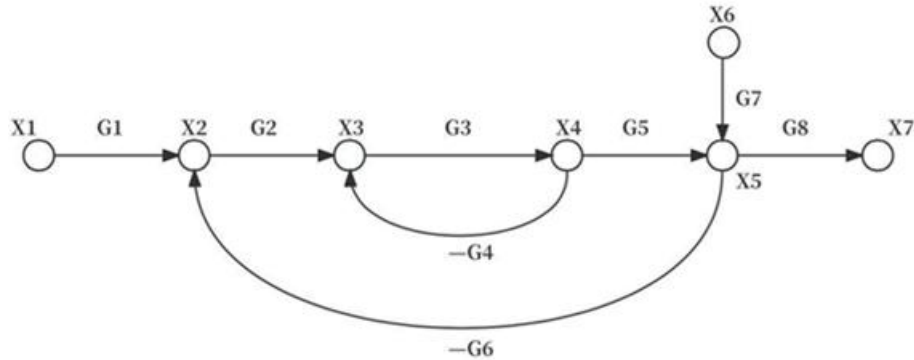


Figure 4. Signal Flow Diagram of Resonance Empowered Control System.

In Figure 4, G1 represents θ_x, θ_y , The rotation angle value output by attitude sensor JY901. G2 represents the synthesis of rotation angle vectors, which is the swing angle value of a single pendulum motion, as shown in the equation:

$$\theta = \sqrt{\theta_x^2 + \theta_y^2} \quad (6)$$

G3 represents the control mechanism of the control system, which uses potentiometers and servos to describe the control variables. Energy compensation is constructed through the relationship between the potential energy generated by the up and down movement of the heavy object and the rotational kinetic energy of the pendulum movement, expressing the relationship between the height value of the heavy object movement and the rotational angle value of the pendulum movement, as shown in the equation:

$$\begin{aligned} mgh &\leftrightarrow \frac{1}{2}I \left(\frac{d\theta}{dt}\right)^2 \\ h &\leftrightarrow \left(\frac{d\theta}{dt}\right)^2 \end{aligned} \quad (7)$$

G4 represents the negative feedback quantity, which determines the maximum and minimum values that the weight can achieve in its up and down motion to adjust the control quantity of the controller, as shown in the equation:

$$\Delta (h_{max} - h_{min}) \quad (8)$$

G5 represents that after the controlled object's heavy object and pendulum reach energy compensation, there is no energy loss in the motion of the pendulum. The curve formed by the swing angle value and time is a standard sine curve, as shown in the equation:

$$\begin{aligned} \frac{d^2\theta_x}{dt^2} &= -\frac{g}{l}\theta_x \\ \frac{d^2\theta_y}{dt^2} &= -\frac{g}{l}\theta_y \end{aligned} \quad (9)$$

G6 represents $\Delta\theta_x$, $\Delta\theta_y$, it is a negative feedback quantity that adjusts and judges the controller based on the real-time output of the rotation angle value from the attitude sensor JY901.

G7 represents the interference caused by the motion of the pendulum, namely Coriolis force and air resistance.

$$\begin{aligned} & 2\Omega \sin\lambda \frac{d\theta}{dt} \\ & - \frac{k}{m} \frac{d\theta}{dt} \end{aligned} \quad (10)$$

Under external disturbances to the motion of a pendulum without energy compensation, the curve formed by the angle value of the pendulum and time is a decaying positive line curve. After a period of time, the pendulum will stop moving, as shown in the equation:

$$\begin{aligned} \frac{d^2\theta_x}{dt^2} &= 2\Omega \sin\lambda \frac{d\theta_y}{dt} - \frac{g}{l} \theta_x - \frac{k}{m} \frac{d\theta_x}{dt} \\ \frac{d^2\theta_y}{dt^2} &= -2\Omega \sin\lambda \frac{d\theta_x}{dt} - \frac{g}{l} \theta_y - \frac{k}{m} \frac{d\theta_y}{dt} \end{aligned} \quad (11)$$

G8 represents the relationship between the output value of the resonant empowerment control system, the height value of the weight movement, and the input value of the system, the rotation angle value of the pendulum movement, as shown in the equation:

$$\Delta h \longleftrightarrow \Delta \left(\frac{d\theta}{dt} \right)^2 \quad (12)$$

3.3. Circuit Design and Microcontroller Integration

This study uses the system diagram of the resonant empowerment control system to draw the circuit structure diagram of the resonant empowerment controller based on the system's input, output, control period, and execution mechanism, as shown in Figure 5. The core of this circuit diagram is the Nano microcontroller platform. The JY901 sensor receives various motion data and sends it to Nano for analysis and processing. The Nano microcontroller mobilizes various components for adjustment feedback, and sends the final processed data to Bluetooth or WiFi. Bluetooth or WiFi receives the various motion data adjusted by the Nano microcontroller and sends it to a remote computer or uploads it to the cloud platform.

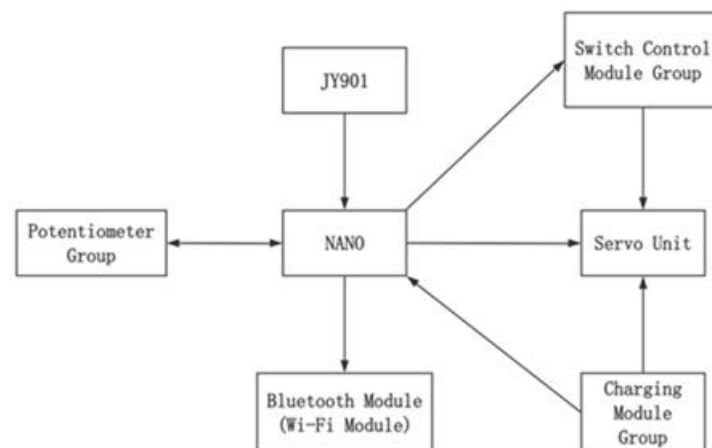


Figure 5. Circuit structure diagram of resonant power controller.

Each component consists of a potentiometer group, a rudder unit, a switch control module group, and a charging module group. The potentiometer group consists of four potentiometers, the servo unit consists of three servos, the switch control module group consists of three isolated MOS transistors, and the charging module group consists of four independent charging modules.

4. Simulation Analysis of the Foucault Pendulum Under External Forces

In Earth's natural environment, moving objects are subject to a variety of subtle influences, among which the fluctuations caused by the gravitational field are particularly significant for long-duration experiments. These gravitational fields generate low-frequency, long-period, and low-amplitude fluctuation signals that inevitably impact the motion of any object, including the Foucault pendulum. To explore these effects, this study simulates the influence of such fields by applying a constant external force to the pendulum system.

4.1. Motion Simulation in Fluctuating Environments

To analyze the motion under environmental waves, we establish a simulation model in Simulink. The fundamental behavior of the pendulum in a natural state (including air resistance and Earth's rotation) is governed by the following second-order differential equations:

$$\begin{aligned}\frac{d^2x}{dt^2} &= 2\Omega \sin\lambda \frac{dy}{dt} - \frac{g}{l}x - \frac{k}{m} \frac{dx}{dt} \\ \frac{d^2y}{dt^2} &= -2\Omega \sin\lambda \frac{dx}{dt} - \frac{g}{l}y - \frac{k}{m} \frac{dy}{dt}\end{aligned}\quad (13)$$

In these expressions:

x and y represent the displacement along the respective horizontal axes. Ω is the Earth's angular rotation velocity. λ denotes the geographical latitude of the pendulum's location. g is the local gravitational acceleration. l is the suspension wire length. m is the mass of the pendulum bob. k represents the air resistance constant.

Observations from the simulation curves for a system without energy compensation (Figure 6 and Figure 7) show that the oscillation amplitude decays exponentially due to the external wave environment, eventually stabilizing at an equilibrium position of approximately 2.75 radians.

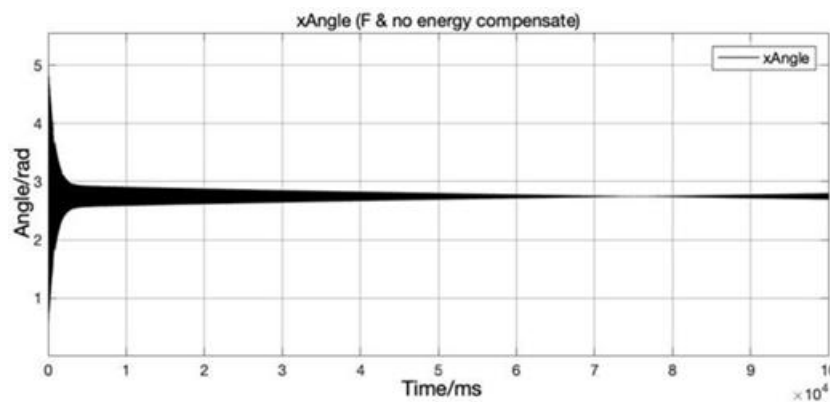


Figure 6. The x-axis angle curve of Foucault pendulum.

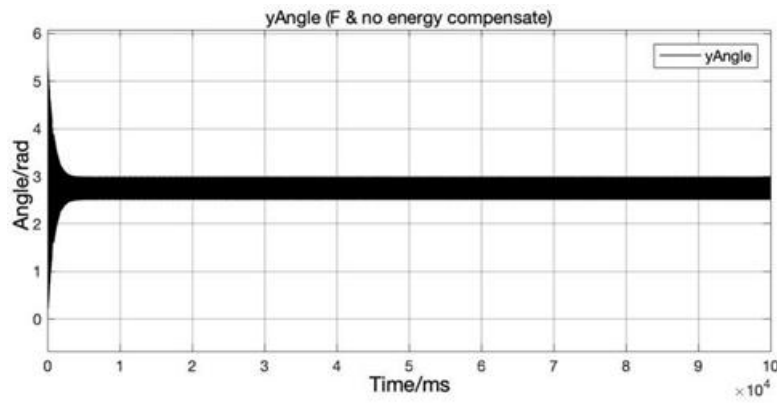


Figure 7. The y-axis angle curve of Foucault pendulum.

However, when the energy compensation system is activated to counteract air resistance, the motion profile changes significantly. As illustrated in Figure 8, the decay of the x-axis angle becomes much more gradual, resulting in a sinusoidal oscillation between 2.5 and 3.0 radians. Similarly, the y-axis angle shown in Figure 9 demonstrates high stability with no observable attenuation, maintaining a steady oscillation between 1 and 5 radians. These results confirm that internal potential-to-kinetic energy conversion can effectively sustain stable harmonic motion even under external stressors.

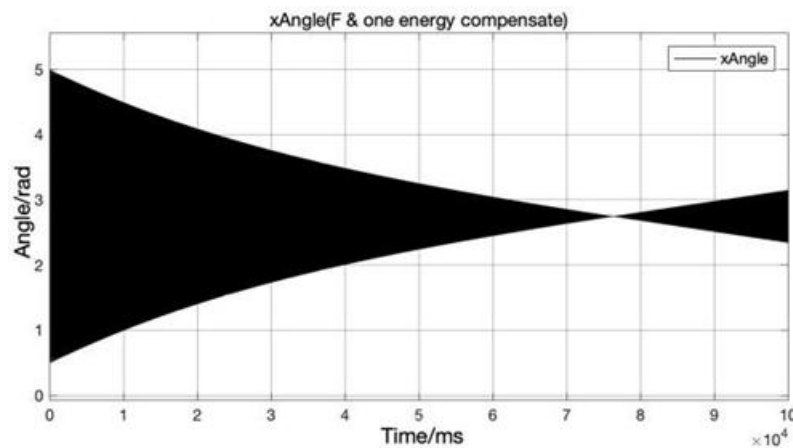


Figure 8. The x-axis angle curve of Foucault pendulum.

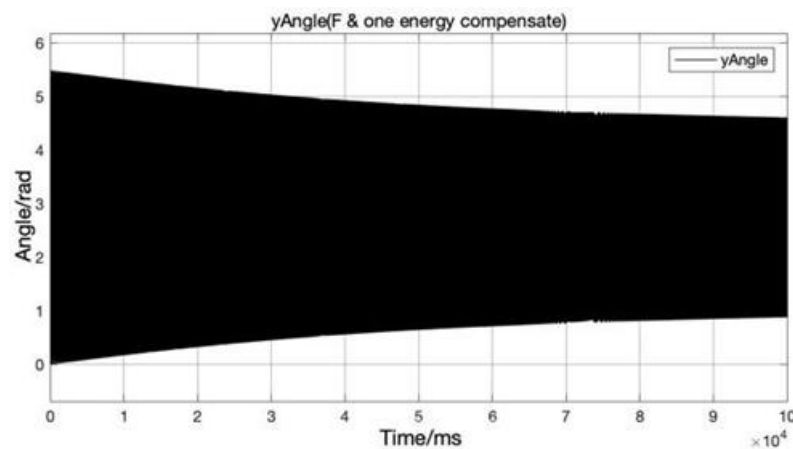


Figure 9. The y-axis angle curve of Foucault pendulum.

4.2. Energy Dynamics and Compensation Results

The presence of a fluctuation signal fundamentally alters the energy distribution of the Foucault pendulum. As shown in Figure 10, Figure 11, and Figure 12, analyzing the pendulum's energy in a fluctuating environment without energy compensation reveals that the kinetic energy decays exponentially toward zero, whereas the potential energy and total energy stabilize into harmonic oscillations between 12 J and 15 J due to the persistent influence of external fluctuations.

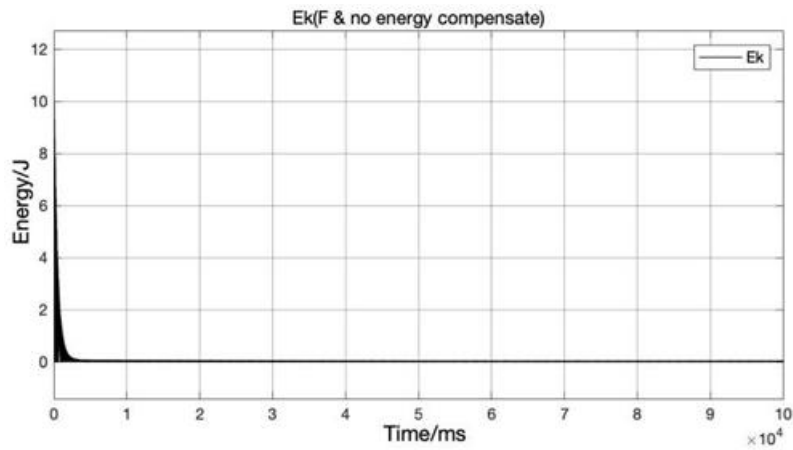


Figure 10. Kinetic energy curve of Foucault pendulum.

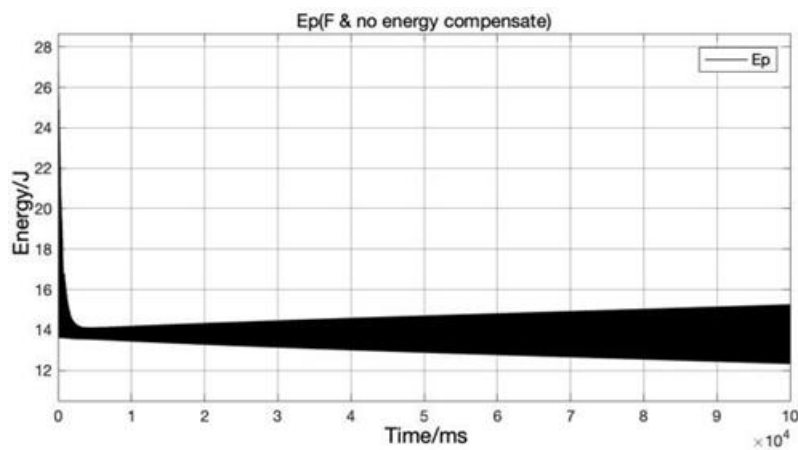


Figure 11. Potential energy curve of Foucault's pendulum.

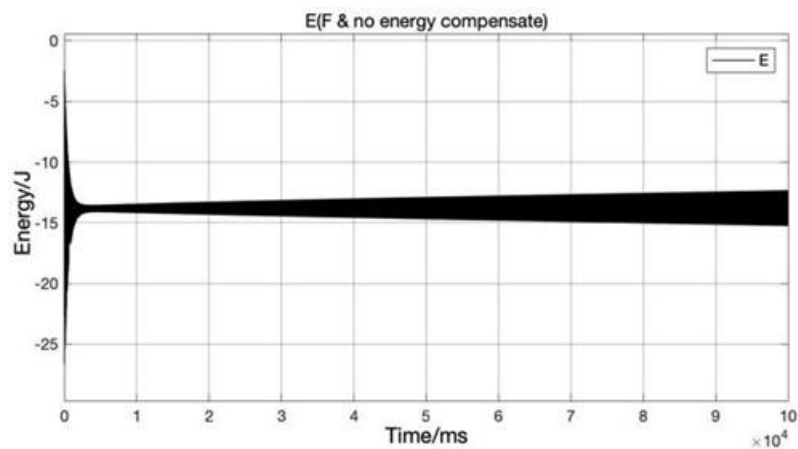


Figure 12. The total energy curve of the Foucault pendulum.

The energy profiles of the pendulum in a fluctuating environment with air resistance compensation are illustrated in Figure 13, Figure 14, and Figure 15. The

kinetic energy curve indicates a relatively slow decay, ultimately stabilizing into a sinusoidal oscillation between 0 J and 3 J, while the potential energy curve and total energy curve exhibit virtually no long-term attenuation, maintaining oscillations between approximately 6 J and 28 J for potential energy, and 3 J and 28 J for total energy.

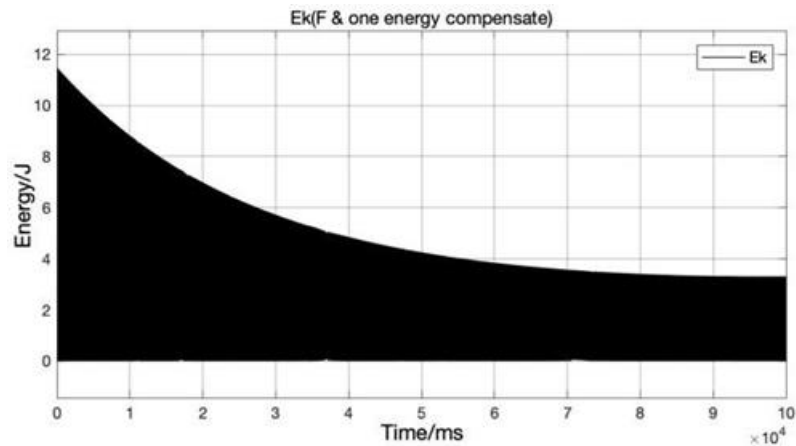


Figure 13. Kinetic energy curve of Foucault pendulum.

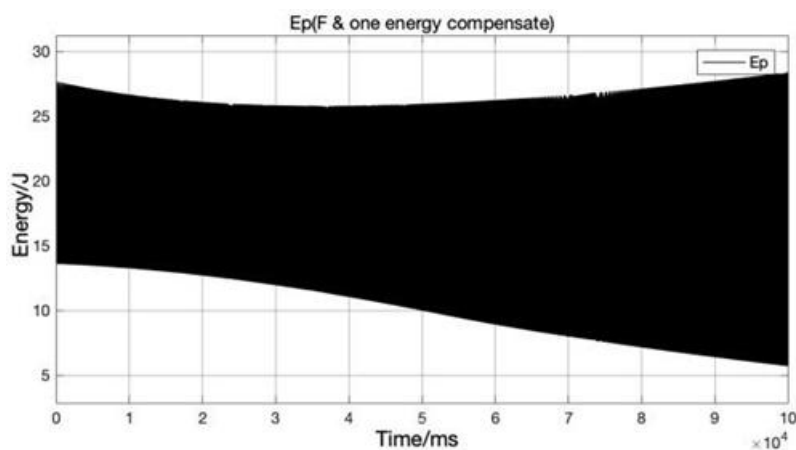


Figure 14. Potential energy curve of Foucault's pendulum.

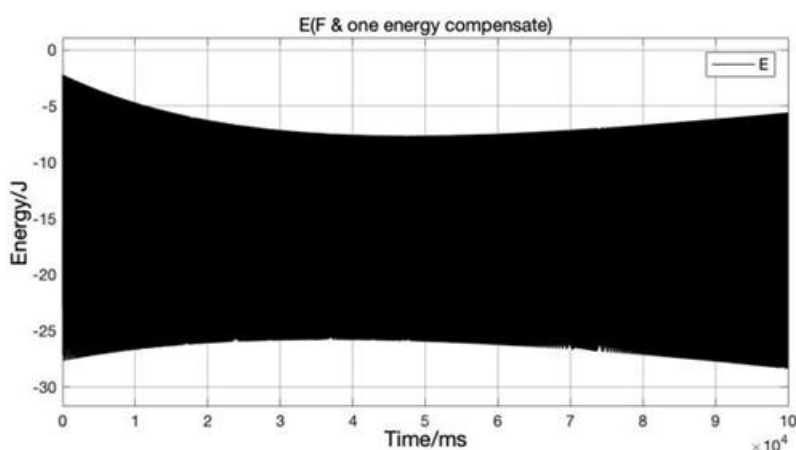


Figure 15. The total energy curve of the Foucault pendulum.

4.3. Comparative Signal Extraction

To identify the specific characteristics of these fluctuation signals, we developed a comparison model to calculate the differential values between a system subject to simulated external forces and one in a force-free state. The differential curves for various system variables, reveal that external fluctuations have a significant impact on the pendulum's x-axis angle, potential energy, and total energy, while exerting a negligible influence on the y-axis angle and kinetic energy. These results suggest that monitoring the total energy variance of a compensated Foucault pendulum array is a viable method for exploring the characteristics of gravitational waves.

5. Integrated Network Observation: Digital Twin and Distributed Array Design

To transition from a single-point experiment to a global detection system, this research integrates real-time simulation with an Internet of Things (IoT) framework to manage a distributed array of Foucault pendulums. This architecture ensures that theoretical models and physical reality remain synchronized [7], allowing for the isolation of subtle gravitational signals across varying geographic coordinates.

5.1. Real-Time Synchronization and Digital Twin Framework

Standard simulations typically operate based on machine-time units, which are detached from Earth's natural oscillation cycles. To create a functional “Digital Twin,” we utilize a real-time synchronization methodology that aligns simulation time steps and positional units with physical reality.

- **Time Synchronization:** The Real-Time-Sync module ensures simulation steps correspond to actual wall-clock time.
- **Spatial Alignment:** The VR-Sink module matches simulated positional units with physical displacement, as seen in the real-time model (Figure 16).
- **System Reliability:** This synchronization follows the “Lunar Rover” operational logic: if the network connection to a physical pendulum is interrupted, the real-time simulation continues to predict the trajectory based on established physical laws. When the connection is restored, the physical position resynchronizes with the simulation, preventing data loss.

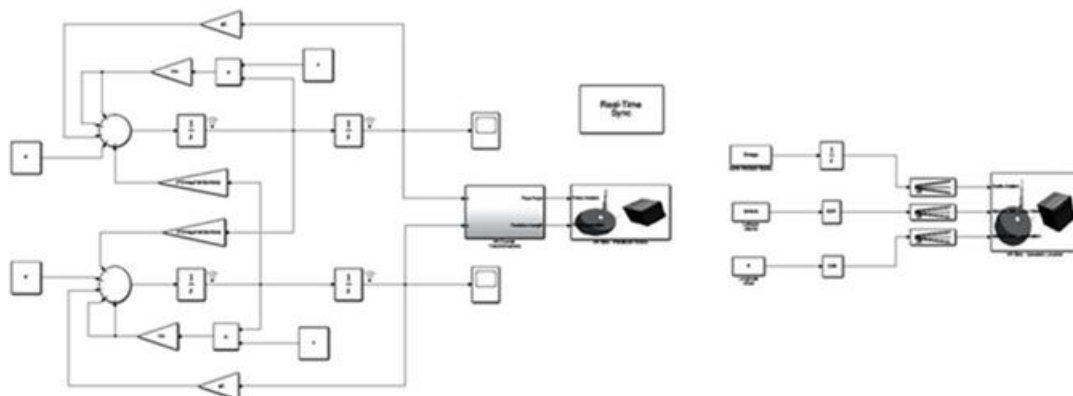


Figure 16. Real-time Foucault pendulum simulation model.

5.2. IoT Network and MQTT Implementation

The sensor data from the pendulum bob is managed through an IoT framework designed for high-frequency data streaming.

- **Data Transmission:** Information from the internal attitude sensors is transmitted via Wi-Fi using the MQTT (Message Queuing Telemetry Transport) protocol [8,9].
- **Connectivity Logic:** The system establishes secure communication through specific Product IDs, Device IDs, and token-based authentication (Figure 17).
- **Stability Monitoring:** The IoT platform provides a continuous data stream, visualizing the pendulum's swing angle as a non-attenuating sine wave, which confirms the long-term effectiveness of the internal energy compensation system (Figure 18).

```
#include <Arduino.h>
#include "WiFi.h"
#include "PubSubClient.h"
#include "Ticker.h"
#include "Math.h"

const char *ssid = "a610"; //wifi名
const char *password = "a610a610"; //wifi密码
const char *mqtt_server = "183.230.40.96"; //onenet 的 IP地址
const int port = 1883; //端口号
float y;
#define mqtt_devId "FK8" //设备ID
#define mqtt_pubId "407910" //产品ID
#define mqtt_password "version=2018-10-31&res=productsX2F407910X2FdevicesX2FFK8&et=2177427661&method=ndS&sign=NXSGN6nJks7WEhzhGu8PsgK3DK30" //鉴权信息
WiFiClient espClient; //创建一个WiFi连接客户端
PubSubClient client(espClient); //创建一个PubSub客户端，传入创建的WiFi客户端
char msgJson[75]; //发送信息缓冲区
char dataTemplate[] = "{\"id\":123,\"dp\":{\"x\":\"%f\",\"y\":\"%f\"}}"; //信息模板
Ticker tim1; //定时器，用来循环上传数据
void setupWifi() //连接WiFi相关函数
{
    void callback(char *topic, byte *payload, unsigned int length) //收到主题下发的回调，注意这个回调要实现三个形参 1:topic 主题, 2: payload: 传递过来的信息 3: length: 长度
    {
        void sendAngle() //向主题发送模型的角度数据
    }
    void clientReconnect() //重连函数，如果客户端断线，可以通过此函数重连
}
void setup()
{
    void loop()
}
```

Figure 17. Foucault pendulum IoT program.

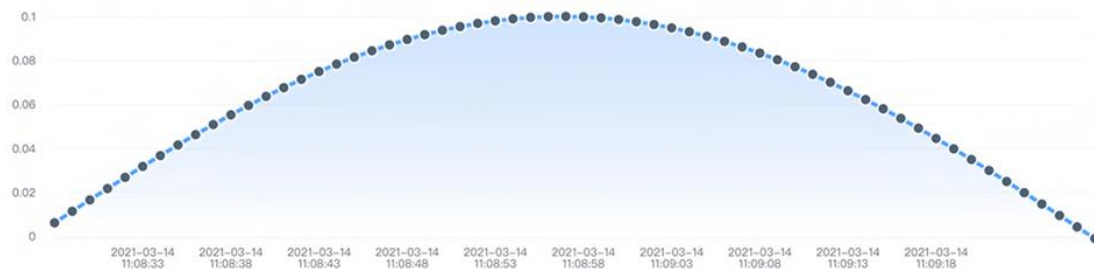


Figure 18. The swing angle curve of Foucault's pendulum IoT.

5.3. Distributed Array Configuration

The exploration of gravitational fluctuation signals requires a multi-point observation strategy. Because fluctuation signals arrive at different latitudes with varying peaks and timestamps, a single pendulum is insufficient.

- **Latitudinal Distribution:** The array consists of pendulums placed at identical longitudes but distinct latitudes—specifically at the Equator (0°), 22.5° , 66.5° , and 90° (the Poles) in both the Northern and Southern Hemispheres (Figure 19).
- **Parameter Standardization:** Every pendulum in the array utilizes the same structural parameters (27 m wire length, 5 kg bob weight) to ensure that observed energy differences are solely due to geographic and gravitational variances rather than mechanical discrepancies.
- **Signal Isolation:** By networking these pendulums, the system can compare the total energy changes of each unit in real-time. This differential analysis allows the

system to filter out local environmental noise and isolate broader gravitational field signals.

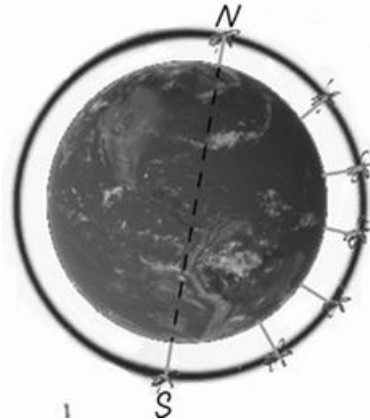


Figure 19. Foucault pendulum array system model.

6. Discussion: Gravitational Wave Exploration and Tidal Energy Analogy

The ultimate goal of the long-lasting Foucault pendulum array is to provide a novel experimental method for detecting gravitational waves. As defined by the Einstein Field Equations (EFE) [10], gravitational waves are ripples in the curvature of spacetime caused by the acceleration of massive, non-spherically symmetric objects. The fundamental equation governing this phenomenon is expressed as follows:

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu} \quad (14)$$

In this equation, $R_{\mu\nu}$ represents the Ricci curvature tensor, describing the local curvature of spacetime; $g_{\mu\nu}$ is the metric tensor, which defines the geometric properties of the spacetime. R is the Ricci scalar (the trace of the Ricci tensor). Λ denotes the cosmological constant. G is the gravitational constant, and C is the speed of light. $T_{\mu\nu}$ represents the energy-momentum tensor, which describes the distribution of matter and energy.

6.1. The Qiantang Tide Analogy

The methodology proposed in this research relies on an energy accumulation principle modeled after the Qiantang River tide. The surging tide in Hangzhou Bay is a macro-scale manifestation of gravitational field effects. Just as the tide represents an integration of energy over time as the Earth and Moon align, the energy fluctuations in a Foucault pendulum can be viewed as an accumulation process.

By analyzing the total energy increment of the pendulum system, as simulated in the cumulative energy model (Figure 20), we observe a steady increase in energy that reflects the “surge” of gravitational influence. The resulting energy accumulation curve serves as a proxy for tidal intensity, demonstrating how a stable “long-lasting” system can reveal energy shifts that would otherwise be lost to atmospheric damping.

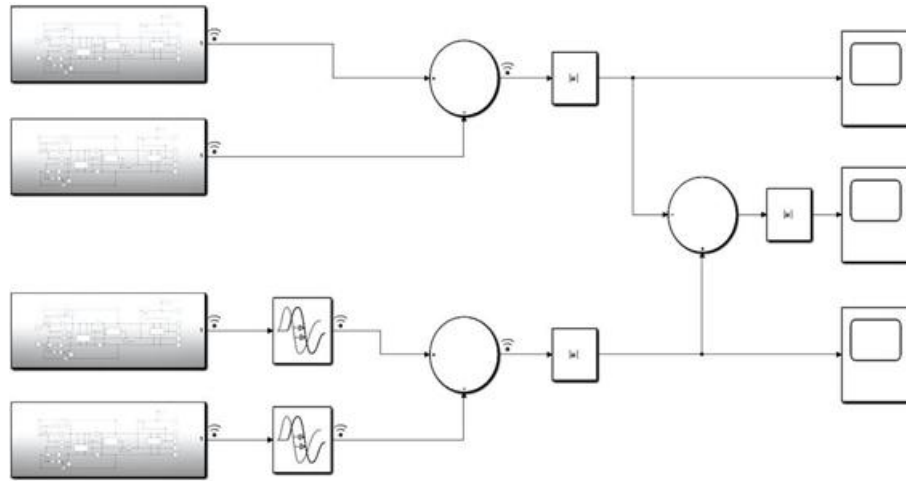
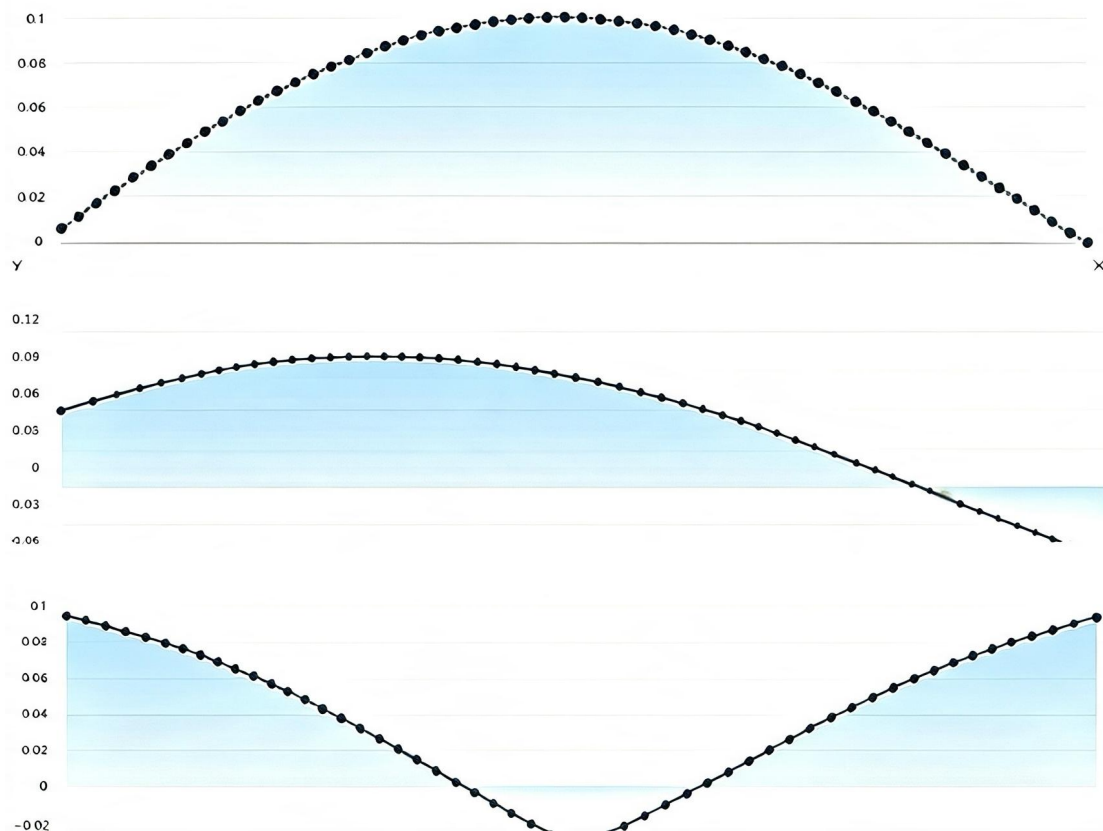


Figure 20. Foucault pendulum's total energy increment (cumulative energy) simulation model.

6.2. Extraction of Gravitational Wave Signal

To isolate the subtle signals of gravitational waves—which Einsteinian theory describes as a transverse wave separate from the Earth's primary gravitational field—this study utilizes a differential array methodology. The IoT infrastructure described previously is scaled here to synchronize data from pendulums located at different latitudes. By comparing the live angular curves of each unit in the array (Figure 21), we can identify phase shifts and amplitude variances caused by the time-of-arrival differences of a passing fluctuation signal.



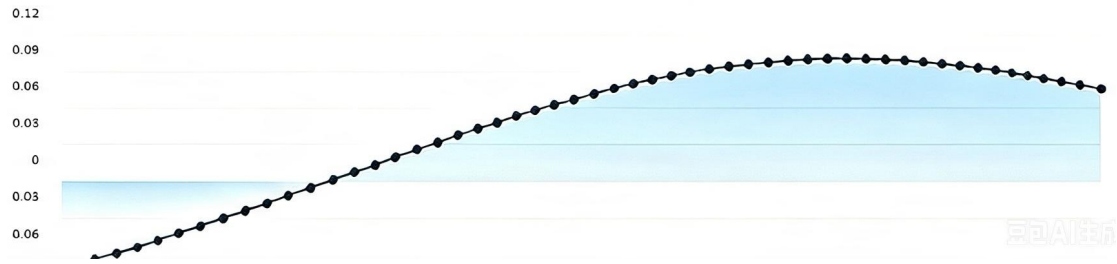


Figure 21. The swing angle curve of each Foucault pendulum in the Foucault pendulum array IoT in the same period.

The “Conceptual Curve of Gravitational Waves” is derived through a rigorous subtractive process in the array simulation model (Figure 22). Specifically, the total energy of a force-free system is subtracted from the total energy of a system subject to simulated gravitational stressors. By sequentially subtracting the energy increments from different latitudinal points in the array, the local environmental influences of Earth are filtered out, leaving only the “extra-terrestrial” influence. The final output, illustrated in Figure 23, represents a viable conceptual model for the visual detection of gravitational wave signatures using mechanical resonators.

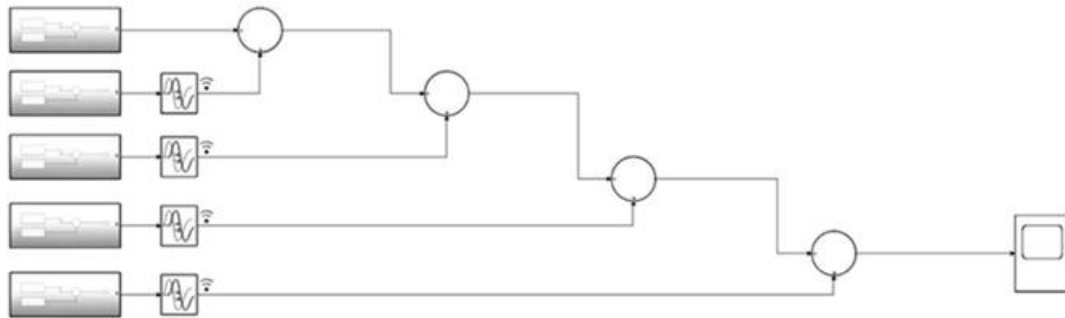


Figure 22. Foucault pendulum array simulation model.

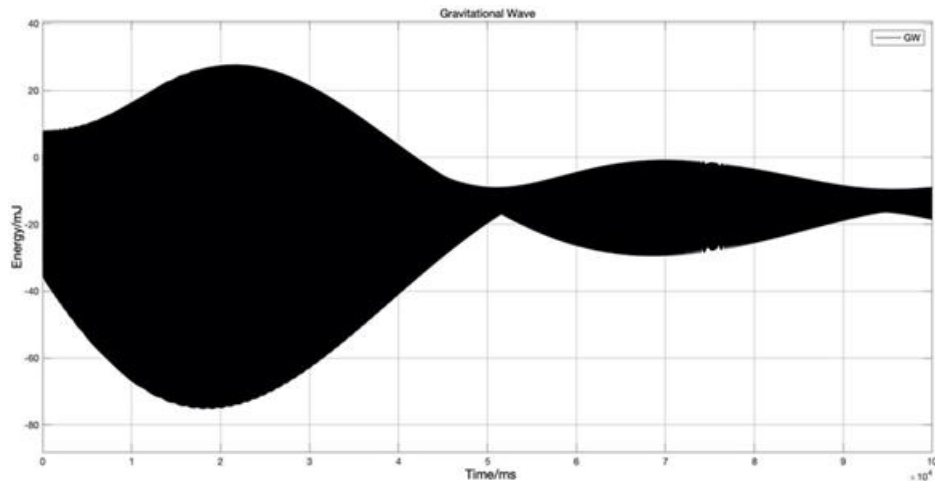


Figure 23. Conceptual curve of gravitational waves.

6.3. Feasibility and Cooperative Requirements

The use of an autonomous resonance energizing array for gravitational wave exploration is theoretically feasible because the system eliminates amplitude decay, allowing for standard sine wave outputs that are highly sensitive to external peaks or troughs in the gravitational field. However, given the extreme precision required and the global nature of these signals, such a project necessitates international scientific

cooperation. Establishing a synchronized Foucault pendulum array—bridging multiple disciplines and nations—could provide a cost-effective, ground-based complement to existing projects like LIGO or the Taiji program [12].

7. Conclusions

This research successfully developed a real-time Foucault pendulum array system designed specifically for the exploration of gravitational waves. By integrating an autonomous resonance energizing control system, the design converts internal potential energy into kinetic energy to overcome environmental attenuation, effectively creating a “long-lasting pendulum” capable of sustained, stable oscillation. The implementation of a digital twin framework and an IoT platform ensures high-fidelity synchronization between physical experiments at varying latitudes and their theoretical models. Through the comparative analysis of total energy variance and the use of the Qiantang River tide as a physical analogy for energy accumulation, this study provides a viable experimental method for isolating and visualizing gravitational wave signatures. Ultimately, this synchronized array approach offers a measurable path for detecting spacetime curvature fluctuations, highlighting the vital role of interdisciplinary and international cooperation in modern scientific discovery.

Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this article.

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