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The Forced Simple Pendulum

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ABSTRACT

1 Introduction

The equation of motion for a pendulum of a mass m and length of L is:

$$mL^2\frac{d^2\theta}{dt^2} + k\frac{d\theta}{dt} + mgL\sin(\theta) = FL\cos(\Omega t) \tag{1}$$

Where:

- m is the mass of the pendulum bob
- L is the length of the pendulum
- θ is the angular displacement of the pendulum from vertical
- $\dot{\theta}$ is the angular velocity (rate of change of θ)
- $\ddot{\theta}$ is the angular acceleration
- k is the damping coefficient (dependent on the specific damping mechanism)
- g is acceleration due to gravity
- F is the magnitude of the external force
- Ω is the frequency of the external force F
- t is the time

It is also useful to note that $k\dot{\theta}$ is the damping force. We measure time relative to the period of free oscillations of small amplitude, so we can introduce:

$$t = \tau\sqrt{\frac{L}{g}} \tag{2}$$

We introduce:

$$\Omega = (1-\eta)\sqrt{\frac{g}{L}} \tag{3}$$

To investigate the situation where the behavior of the pendulum when the forcing frequency, Ω is slightly less than the natural frequency, $\frac{g}{L}$.

To convert equation (**??**) into dimensionless form, we recall that: $t = \tau\sqrt{\frac{L}{g}}$ (equation (**??**)) and by the chain rule, $\frac{d\tau}{dt} = \frac{d\theta}{dt}\frac{dt}{d\tau}$ give the following equations:

$$\begin{aligned} \frac{d\theta}{dt} &= \sqrt{\frac{g}{L}}\frac{d\theta}{d\tau} \\ \frac{d^2\theta}{dt^2} &= \frac{g}{L}\frac{d^2\theta}{d\tau^2} \end{aligned} \tag{4}$$

Which can be substituted into equation (**??**) after dividing by mgL and substituting equation (**??**) and (**??**).

$$(\frac{L}{g})(\frac{g}{L})\frac{d^2\theta}{d\tau^2} + \frac{k}{mgL}\sqrt{\frac{g}{L}}\frac{d\theta}{d\tau} + \sin(\theta) = \frac{F}{mg}\cos((1-\eta)\sqrt{\frac{g}{L}}\sqrt{\frac{L}{g}}\tau) \tag{5}$$

The dimensionless form of equation (**??**) is then:

$$\frac{d^2\theta}{d\tau^2} = -\alpha\frac{d\theta}{d\tau} - \sin(\theta) + \beta\cos((1-\eta)\tau) \tag{6}$$

With parameters:

$$\begin{aligned} \alpha &= \frac{k}{mL\sqrt{gL}} \\ \beta &= \frac{F}{mg} \end{aligned} \tag{7}$$

[1]

To solve the equation, the RK4(5) (Runge–Kutta–Fehlberg) method will be used. I will be using `scipy.integrate.RK45` that uses the Dormand-Prince pair of formulas [**?**]. To solve a 2nd order differential equation with any Runge-Kutta method, the ODE in question will have to be expressed as a 1st order ODE. From equation (**??**) and taking the substitution:

$$\omega = \frac{d\theta}{d\tau} \tag{9}$$

The ODE will be a system of equations of the form $\vec{\mathbf{Y}}' = A\vec{\mathbf{Y}} - \vec{\mathbf{b}}$.

$$\begin{bmatrix} \theta' \\ \omega' \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ \text{-}\sin(\theta) & \text{-}\alpha \end{bmatrix} \begin{bmatrix} \theta \\ \omega \end{bmatrix} - \begin{bmatrix} 0 \\ \beta\cos((1-\eta)\tau) \end{bmatrix} \tag{10}$$

[1]Note that:

$$\frac{k}{mgL}\sqrt{\frac{g}{L}} = \frac{k}{mL\sqrt{g}\cdot\sqrt{g}}\sqrt{\frac{g}{L}} = \frac{k}{mL\sqrt{gL}} \tag{8}$$

2 Setup

The system is set up as follows:

- The pendulum has a mass m of 1kg
- The length of the string, L is 2 meters
- The damping coefficient k has a value of
- The factor η has a value of 0.01
- g is 9.81ms^{-1}

2.1 Areas of investigation