Optimization of Friction-Induced Vibration System Using Stochastic Gradient Descent with Gradient Clipping

Project Overview

I developed a numerical solver to simulate a friction-induced vibration system using a second-order differential equation. The primary focus was on analyzing energy loss due to friction in a mass-spring-damper system by implementing an exponential friction model. The project aimed to optimize system parameters to minimize energy loss and improve the stability and accuracy of the simulation results.

System Model

The system was modeled using a mass-spring-damper setup governed by a second-order differential equation. The equation takes into account the forces due to mass inertia, damping, stiffness, and friction. The frictional force was modeled using an exponential friction model, which provided a more realistic representation of friction behavior in the system.

Optimization Strategy

To optimize the system parameters (damping coefficient, stiffness, friction coefficient, and friction sensitivity), you initially employed Bayesian optimization. However, for improved stability and to reduce the likelihood of exploding gradients, you replaced this with Stochastic Gradient Descent (SGD) with Gradient Clipping. Gradient Clipping was crucial in ensuring that the gradients remained within a reasonable range, preventing instability during the optimization process.

Performance Evaluation

The accuracy of the model's predictions against observed data was evaluated using the R^2 score. This metric provided a clear indication of how well the model explained the variance in the data, with higher R^2 values indicating better model performance.

Visualization and Analysis

You visualized the key system dynamics under optimized conditions using Matplotlib. The visualizations included:

- **Displacement**: How the position of the mass varied over time.
- **Velocity**: The rate of change of displacement with respect to time.
- **Acceleration**: The rate of change of velocity with respect to time.

- **External Force**: The force applied to the system externally.
- **Relative Velocity**: The velocity difference between the mass and the surface.
- **Total Energy**: The sum of kinetic and potential energy in the system, highlighting the energy loss due to friction.

Tools and Libraries Used

- **Python**: The primary programming language used for implementing the numerical solver, optimization, and simulation.
- **SciPy**: Specifically, the `solve_ivp` function was used to solve the ordinary differential equations (ODEs) governing the system dynamics.
- **Scikit-Optimize (skopt)**: Employed for the optimization process, particularly for implementing Stochastic Gradient Descent with Gradient Clipping.
- **Matplotlib**: Used for visualizing the simulation results, allowing for a clear understanding of how the system dynamics evolved over time.
- **Scikit-Learn (sklearn)**: Utilized the `r2_score` function to calculate the R^2 value, providing a metric for assessing the accuracy of the model's predictions.

Conclusion

The project successfully demonstrated the use of an exponential friction model in a mass-spring-damper system, with optimized system parameters resulting in minimized energy loss. The use of Stochastic Gradient Descent with Gradient Clipping enhanced the stability of the optimization process, and the R^2 score provided a reliable measure of model accuracy. The comprehensive visualization of system dynamics offered valuable insights into the behavior of the system under different conditions.