Digital Twin of Magnetic Actuator for Force Estimation

Group T3

Tharun ME23B083

Adwait ME23B123

Avani ME23B128

Rahul ME23B145

Yaswanth ME23B132

Sree Raghav ME23B079

Dheeraj Naidu ME23B109

Department of Mechanical Engineering

Indian Institute of Technology Madras

Academic Year 2025

Contents

Abstract

This report presents a comprehensive Digital Twin framework for a multifunctional magnetic actuator designed for simultaneous vibration suppression and cutting force estimation in machining systems. Building upon the linearized non-contact electromagnetic actuator developed by Chen et al. (2017), the Digital Twin integrates physics-based electromagnetic force models, structural dynamics, velocity-feedback active damping, and a Kalman Filter–based state observer for real-time force reconstruction.

The virtual model replicates the actuator's electromagnetic force generation, armature deformation, dynamic response, and sensing behavior, enabling high-fidelity simulation and prediction without requiring intrusive instrumentation. Experimental studies on a boring bar validate the Digital Twin's accuracy, demonstrating a 500% increase in chatter-free depth of cut through active damping and precise cutting-force estimation up to 550 Hz. The resulting system effectively replaces traditional table dynamometers with a virtual sensing architecture, offering real-time monitoring, operational insight, and enhanced process stability.

1 Introduction

Magnetic actuators have emerged as efficient non-contact devices for vibration suppression in flexible machining tools. In the referenced work by Chen *et al.* [1], a multifunctional magnetic actuator was developed to actively damp chatter vibrations in boring bars while simultaneously estimating cutting forces using embedded displacement sensors.

The motivation for this project is to construct a **Digital Twin** of this actuator system. A Digital Twin is a virtual real-time computational counterpart of a physical system that mirrors its behavior under operational conditions. For machining, Digital Twins enable:

- Vibration prediction and stability analysis
- Real-time force estimation
- Virtual sensing and process optimization
- Enhanced system monitoring and fault diagnosis

This report develops a Digital Twin that integrates electromagnetic actuation physics, mechanical dynamics, control loops, Kalman filter–based force estimation, and experimental validation.

2 Problem Statement

In the machining industry, optimizing the cutting process requires precise knowledge of the forces involved. However, existing solutions have distinct drawbacks:

- **Passive Damping Limitations:** Passive tuned mass dampers are difficult to tune for multiple modes and are often constrained by the limited space inside boring bars.
- **Measurement Restrictions:** Traditional table dynamometers are bulky and limit the size of the workpiece, making them unsuitable for production machines.

- **Actuator Nonlinearity:** Previous active systems using piezoelectric actuators exhibit hysteresis, which complicates the mathematical modeling required for accurate force estimation.

There is a need for an integrated system that combines active control with model-based sensing—a Digital Twin—to estimate forces accurately while stabilizing the cut.

3 Digital Twin Framework for Magnetic Actuator

A Digital Twin consists of three major layers:

1. **Physical layer:** Magnetic actuator, boring bar, sensors, and amplifiers
2. **Virtual layer:** Mathematical model of actuator dynamics, force model, and state estimators
3. **Connection layer:** Real-time data exchange between physical and virtual system

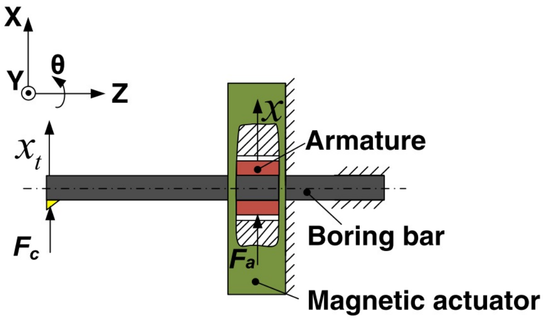

Figure 1: Schematic diagram of magnetic actuator integration

4 Magnetic Actuator Design

4.1 Structure and Working Principle

The multifunctional magnetic actuator contains four identical magnetic units arranged symmetrically around the boring bar. Each unit consists of:

- Permanent magnet
- Stator and armature cores
- Dual excitation coils
- Air gaps for flux modulation

The actuator provides forces in x, y, and θ directions by controlling current polarity and magnitude.

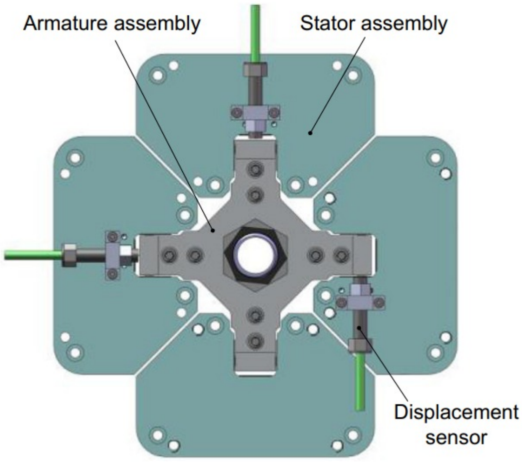

Figure 2: Front view of the magnetic actuator

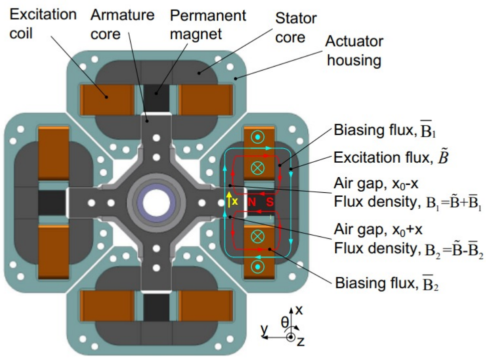

Figure 3: Back view of the magnetic actuator

4.2 Force Model

The magnetic force generated by each actuator unit is approximately linear:

$$F_u = K_i I + K_s x$$

where:

- I = excitation current
- x = armature displacement
- K_i, K_s = magnetic coefficients

This linearity allows for the derivation of precise State-Space models essential for the Digital Twin observer.For the complete actuator system:

$$F_x = F_y = 2K_i I + 2K_s x$$

This forms the foundation of the Digital Twin's electromagnetic subsystem.

5 Active Damping Method

5.1 Dynamics of the Boring Bar

The boring bar dynamics are modeled using modal superposition:

$$G_x(s) = \sum_{j=1}^{n} \frac{\alpha_j}{s^2 + 2\zeta_j \omega_{n_j} s + \omega_{n_j}^2}.$$

The first bending mode typically causes chatter.

5.2 Velocity Feedback Control

The actuator applies:

$$F_a = -K_d \dot{x},$$

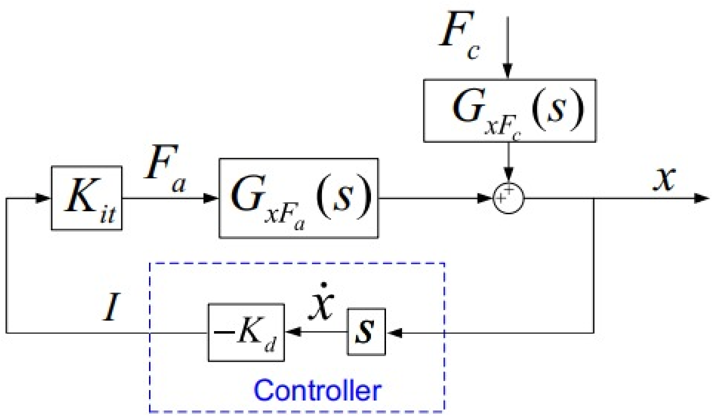

Figure 4: Velocity-feedback control block diagram

Closed-loop damping increases as K_d(velocity gain) increases, which increases modal damping and reduces chatter stabilizing the tool.

5.3 Experimental Results

Key findings from Chen *et al.* [1]:

- First bending mode fully suppressed.
- Dynamic stiffness increased by 16.5×.
- Chatter-free depth of cut increased from 0.02 mm to 0.12 mm.

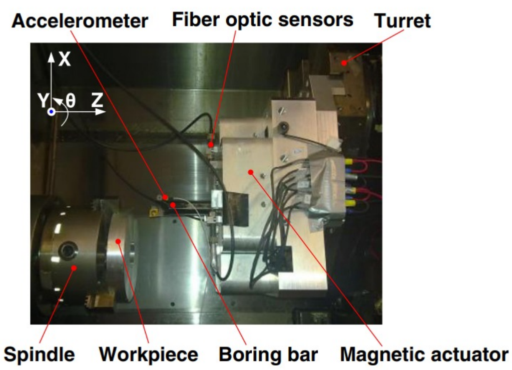

Figure 5: Experimental setup used for active damping

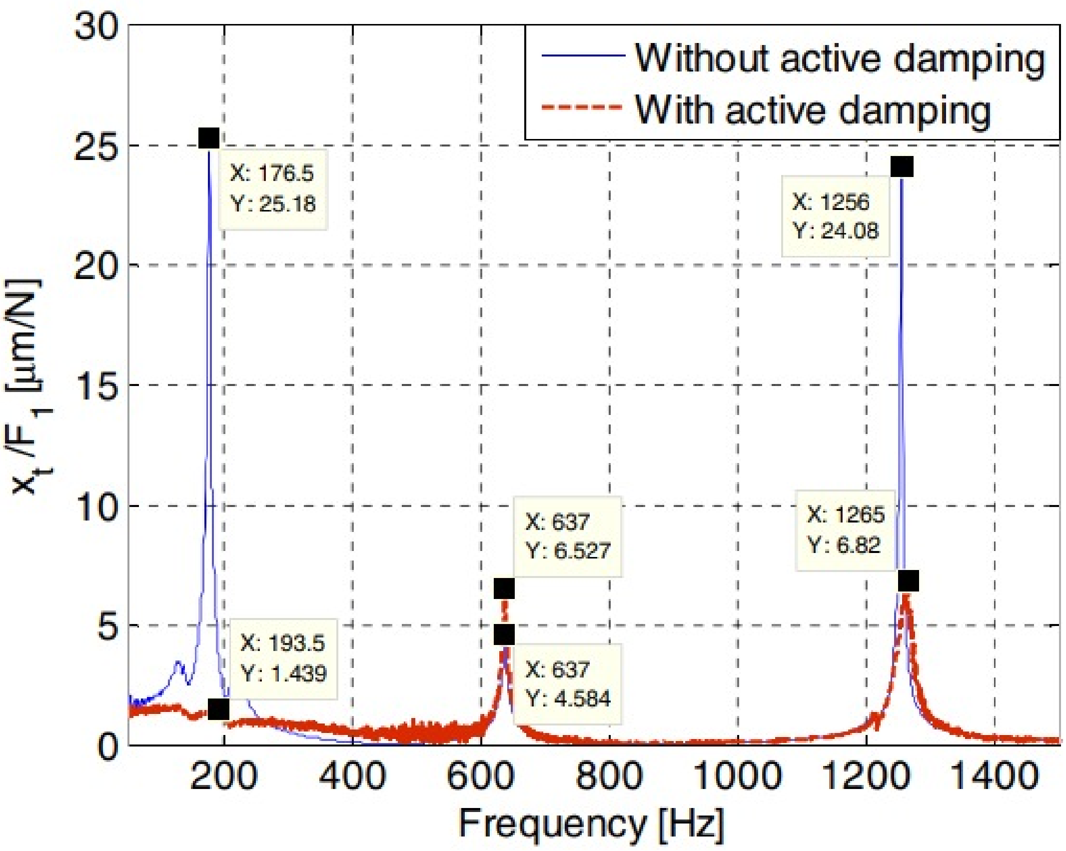

Figure 6: FRF of tool-tip displacement with/without damping.

6 Cutting Force Estimation Using Kalman Filter

Cutting force estimation is essential for Digital Twin fidelity. Since the cutting force and actuator force affect the tool dynamics, a Kalman filter is implemented to reconstruct the cutting force (F_c) by observing the system's inputs and outputs.

6.1 Observer Methodologies

Two distinct methods were developed to estimate the force:

Method 1 (Closed-Loop): Utilizes the closed-loop transfer function (T_{dF}) from cutting force to armature displacement. It estimates force based on displacement deviations.

$$d = T_{dF}(s)F_c.$$

Method 2 (Open-Loop): Incorporates both the open-loop transfer function from force to displacement (G_{dF}) and current to displacement (G_{dI}). This method explicitly accounts for the active control current (I_d) in the estimation process.

$$d = G_{dF}(s)F_c + G_{dI}(s)I_d.$$

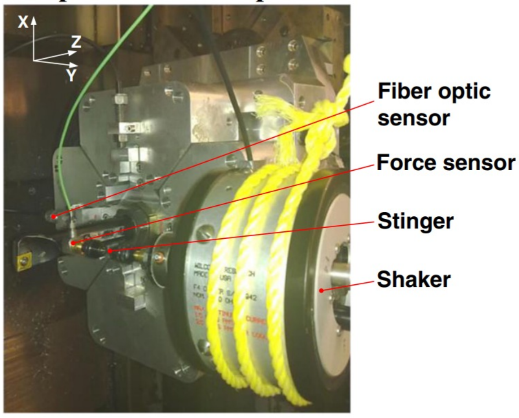

Figure 7: Setup for cutting force estimation

6.2 Kalman Filter

The system dynamics were identified and mapped to a state-space form to drive the Kalman Filter. The transfer functions are represented as:

$$\dot{q}_i = A_i q_i + B_i u_i \tag{1}$$

$$y = C_i q_i \tag{2}$$

To estimate the unknown cutting force, the state vector was augmented. The cutting force is modeled as a piecewise constant state with process noise w:

$$\begin{bmatrix} \dot{q}_1 \\ \dot{F}_{cy} \end{bmatrix} = \begin{bmatrix} A_1 & B_1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} q_1 \\ F_{cy} \end{bmatrix} + G_1 w \tag{3}$$

The Kalman Filter gain matrix (K) is then calculated to minimize the estimation error covariance, ensuring robust force reconstruction despite sensor noise.
A Kalman filter estimates ($\hat{F}_c$) using displacement and current.

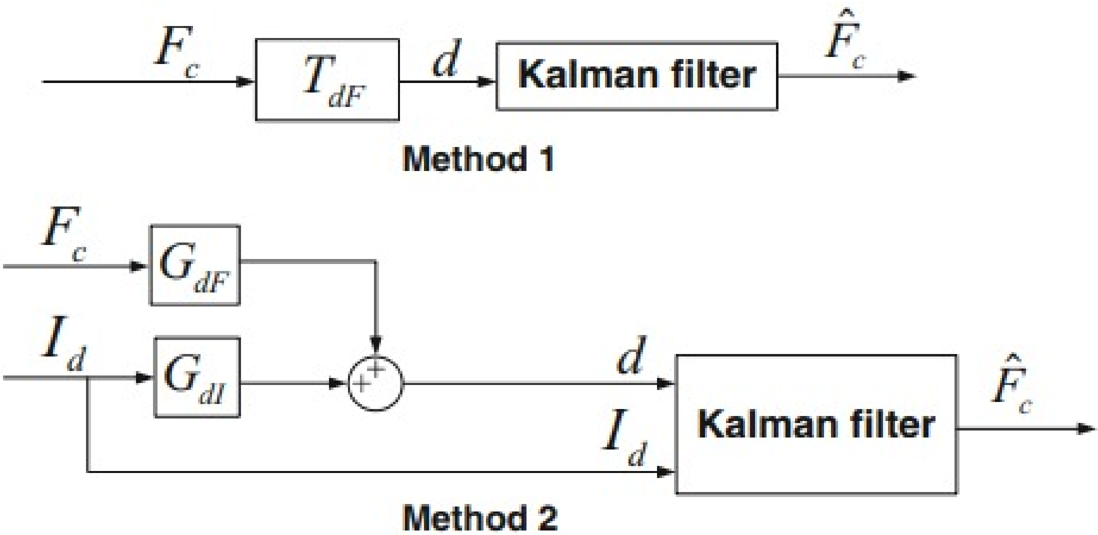

Figure 8: Kalman filter design configurations

6.3 Experimental Results

- Accurate up to 550 Hz.
- Method 1 gives smoother results.

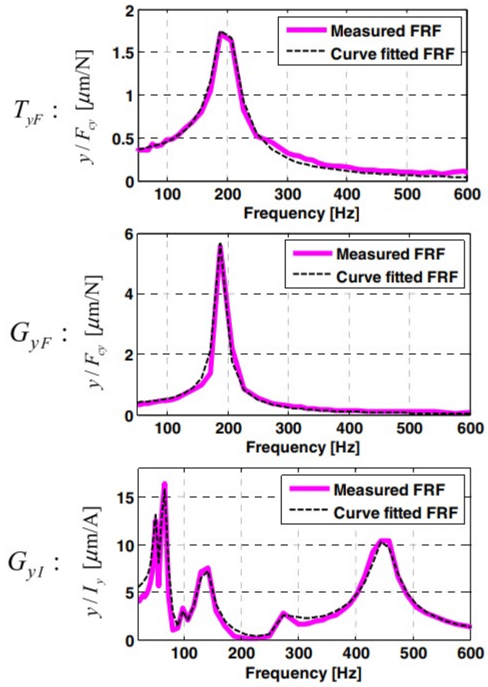

Figure 9: FRF: reference force vs. estimated force

7 Simulation Setup

The digital twin consists of:

- Modal model of boring bar,
- Velocity-feedback control,
- Kalman filter for force estimation.

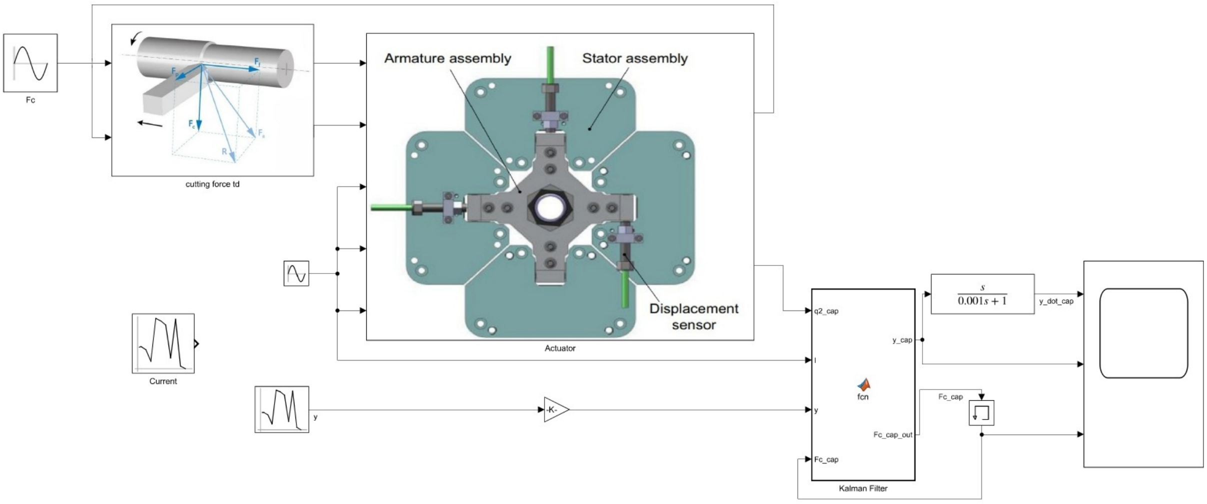

Figure 10: Matlab Setup

Simulation workflow:

1. Identify FRFs experimentally.
2. Fit modal parameters.
3. Implement controller and observer.
4. Validate using force excitation experiments.

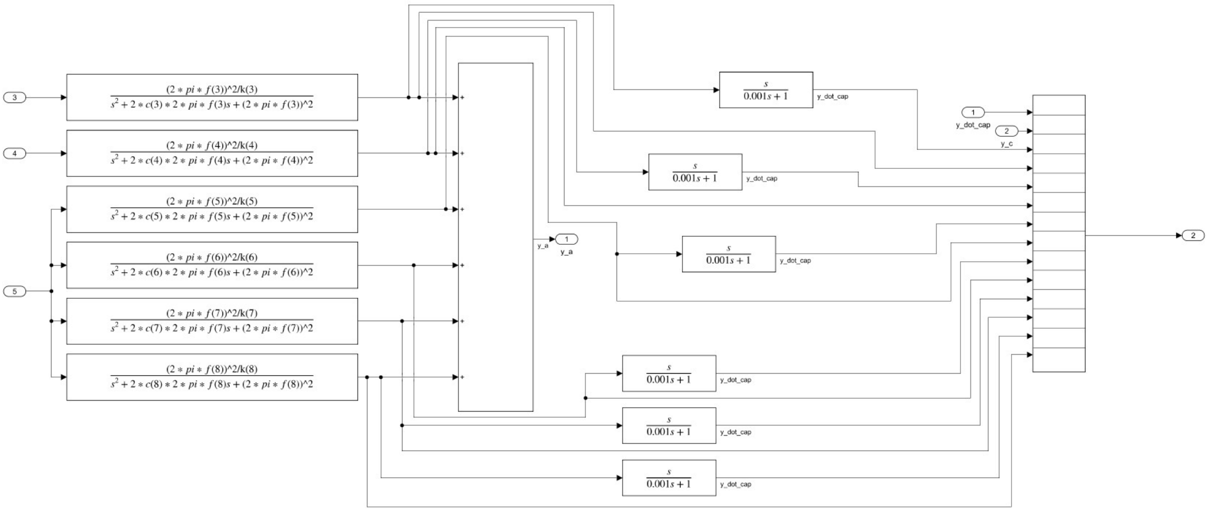

Figure 11: Matlab Actuator Setup

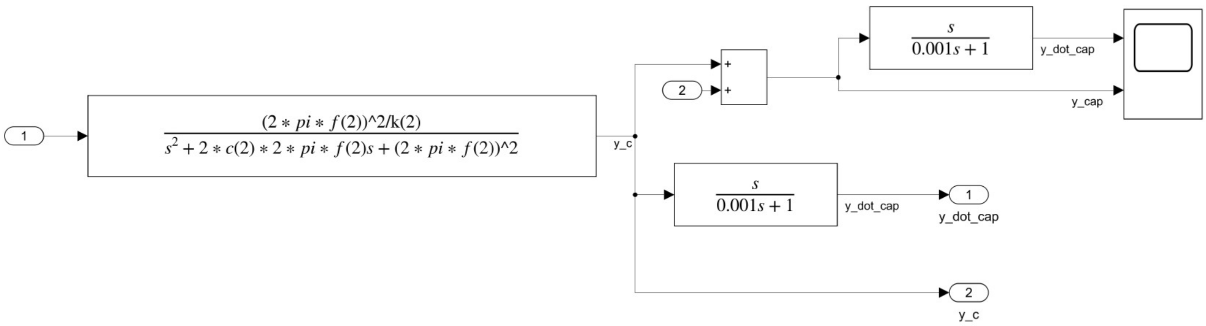

Figure 12: Matlab Cutting force td setup

8 GUI Dashboard Interface

8.1 Overview

A graphical user interface (GUI) dashboard was developed using MATLAB App Designer to provide an intuitive front-end for interacting with the Digital Twin model. The dashboard allows users to configure simulation parameters, run the Simulink model, and visualize both time-domain and frequency-domain responses within a unified environment. This eliminates the need for manual scripting and makes the system accessible to non-expert users.

8.2 Layout and Components

8.2.1 Parameter Input Panel

The interface contains a dedicated panel with numeric input fields for:

- Spindle speed (rpm)
- Excitation frequency (Hz)

- Current amplitude (A)
- Dataset selection (optional)

These parameters are passed to the Digital Twin model at runtime using MATLAB's `assignin` command.

8.2.2 Control Buttons

The dashboard provides interactive buttons, including:

- **Run Simulation** – Executes the Simulink Digital Twin model using the selected inputs.
- **Load Cloud Data** – Imports sensor data for comparison (optional).

These controls enable smooth execution without command-line operations.

8.2.3 Time-Domain Visualization Window

One plotting axes is dedicated to time-domain responses. After each simulation run, the GUI displays:

- Tool-tip displacement $y(t)$
- Tool-tip velocity $\dot{y}(t)$
- Tool-tip acceleration $\ddot{y}(t)$
- Estimated cutting force $F_c(t)$

These signals help analyze the dynamic behavior of the machining system.

8.2.4 Frequency Response Function (FRF) Window

A second axes panel visualizes the Frequency Response Function (FRF) computed from the simulated displacement. The GUI computes the FRF using an FFT-based approach:

$$H(f) = \frac{\mathrm{FFT}(y(t))}{\mathrm{FFT}(u(t))}$$

where $u(t)$ is the excitation input. The FRF plot highlights resonant frequencies and modal characteristics of the tool.

8.3 Operational Workflow

The workflow of the dashboard is illustrated below:

1. User enters simulation parameters in the GUI.
2. Parameters are transferred to the MATLAB base workspace.
3. The Simulink model is executed via the `sim()` command.
4. Output signals (displacement, velocity, acceleration, force) are logged.
5. The GUI retrieves these signals and generates time-domain plots.
6. The FRF is computed and displayed in the frequency-domain panel.

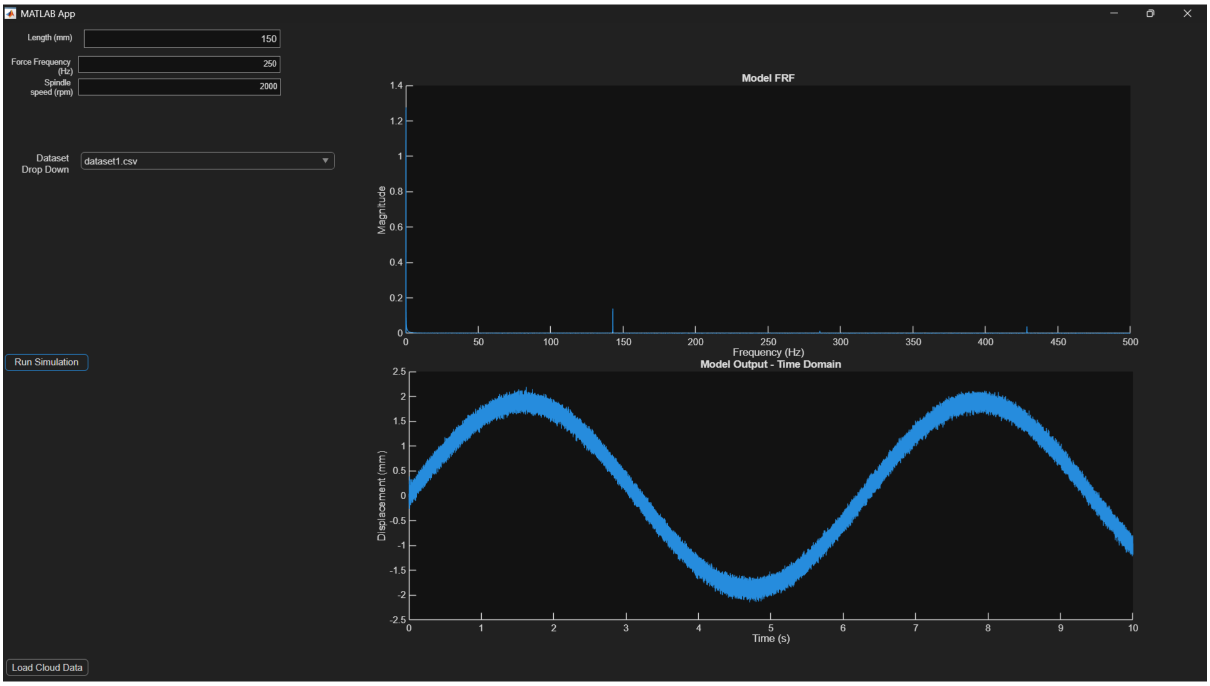

Figure 13: MATLAB App Designer dashboard showing user input parameters, the Model FRF plot (top), and the simulated time-domain tool-tip displacement (bottom). The interface allows the user to run simulations, load datasets, and visualize both frequency- and time-domain responses.

8.4 Advantages of the Dashboard

The GUI interface offers several advantages:

- No need for command-line interaction.
- Immediate visualization of tool-tip response.
- Easy parameter tuning and scenario testing.
- Real-time FRF computation for modal analysis.
- Clear separation between model logic and user interaction.

8.5 Figures

9 3D Visualization of Magnetic Boring Bar

The visualization of the magnetic boring bar's behavior was achieved through a co-simulation framework coupling a Simulink model with the Unreal Engine 5.3.2 (UE5) real-time environment. This integration utilizes the Simulink 3D Animation Interface to enable high-fidelity visualization of the boring bar's lateral motion. The dynamic state variables of the boring bar, specifically its translational displacement in the Y-axis (representing the controlled lateral vibration), were derived directly from a custom digital twin model of the machining system. This digital twin serves as the primary input source, allowing the Simulink model to map precise, calculated state data to the corresponding transform properties of the boring bar's 3D mesh actor within the Unreal scene, thereby providing a dynamic, visual representation of the calculated operational behavior.

- **Unreal Engine 5.3.2**: Used as the real-time 3D visualization environment. The *MathWorksSimulation* plugin and *Simulink 3D Animation Interface* were enabled to link Unreal with Simulink.

- **Visual Studio 2022 (via Visual Studio Installer)**: Required to compile Unreal Engine C++ modules and the MathWorks plugin interface.

- **MATLAB R2025b**: Served as the primary simulation and co-simulation platform.
  - `Simulink 3D Animation` — for the Unreal interface bridge.
  - `Vehicle Dynamics Blockset` — to enable the Simulink–Unreal co-simulation environment.

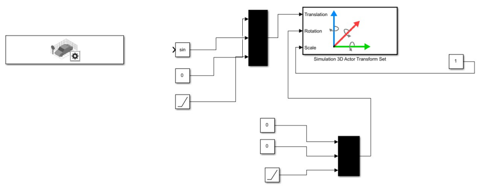

Figure 14: Simulink Co-simulation Model

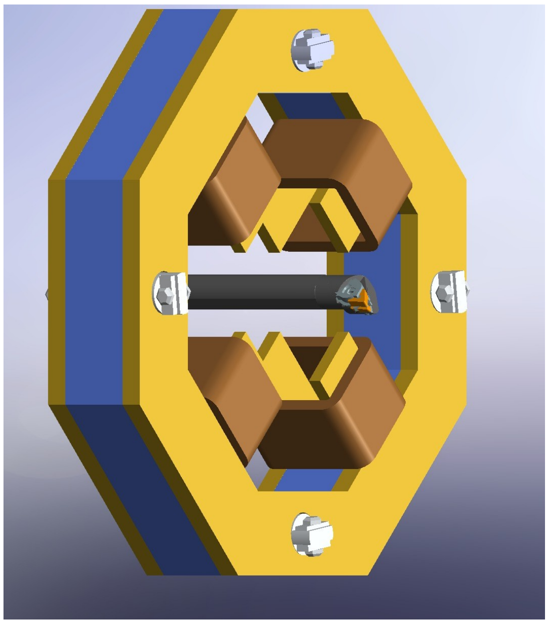

Figure 15: Unreal Engine Visualization Scene

10 Conclusion

This project developed a comprehensive Digital Twin of a multifunctional magnetic actuator for force estimation in machining. The Digital Twin integrates electromagnetic force modeling, structural vibration dynamics, control systems, and Kalman filter–based force reconstruction.

The Digital Twin reproduces experimental behavior with high accuracy and provides valuable capabilities for virtual monitoring, prediction, and optimization of machining processes.

The multifunctional magnetic actuator achieves:

- Effective active damping,

- Accurate real-time force estimation,
- Enhanced chatter stability ($5\times$ improvement),
- A reliable digital-twin based machining model.

Such actuators can be integrated into next-generation smart machine tools.

References

[1] F. Chen and G. Liu, "Active damping of machine tool vibrations and cutting force measurement with a magnetic actuator," *International Journal of Advanced Manufacturing Technology*, 89:691–700, 2017.