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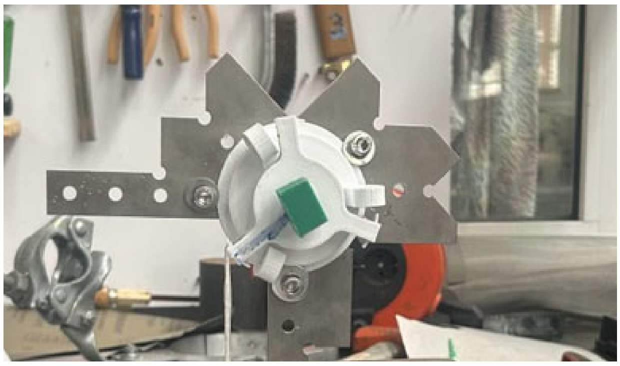
Design of a contactless

Nonlinear Energy Sink

for torsional vibration suppression



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School of Production Eng. & Management
Micromachining & Manufacturing Modeling Lab

Mihai Ionut Trandafir

Contents

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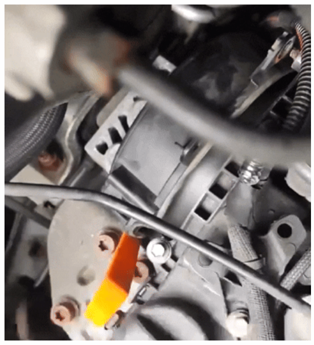
- All mechanical systems produce vibrations
- Internal Combustion Engines
- Backlash from Gears



- Vibrations have different frequencies
- Traditional Passive and Active Vibration Absorbers are tunned to a specific frequency

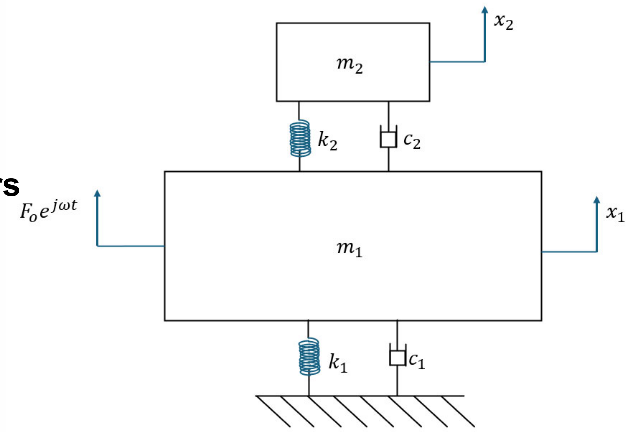
- Nonlinear Energy Sink is ideal for varying frequencies

- **Active Vibration Absorbers**

Sensors, Actuators, Controllers

- **Passive Vibration Absorbers**

For example : Tunned mass Dampers



$$\begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix} \ddot{X} + \begin{bmatrix} c_1 + c_2 & -c_2 \\ -c_2 & c_2 \end{bmatrix} \dot{X} + \begin{bmatrix} k_1 + k_2 & -k_1 \\ -k_1 & k_2 \end{bmatrix} X = \begin{bmatrix} F_o sin(\omega t) \\ 0 \end{bmatrix}$$

If the natural frequency of the absorber is equal or close to the natural frequency of the system, then the absorber will resonate with the system and absorb energy from it.

Permanent Magnets

- Cost Effective
- Good Magnetic Strength
- Good Thermal Stability

Neodymium Iron Born (NdFeB)

- Categorized based on the max temp. of operation (Nxx,NxxM,NxxH,NxxSh)
- Categorized based on the Max Energy Production (MEP) or BH_{max}

Units : Mega-Gauss-Oersteds (MGOe)

represents the maximum amount of magnetic energy stored per unit volume

N42 8x8 magnets

- Remanence (Br): 1.29 – 1.32 T
- Coercivity (Hc): 870 – 915 kA/m
- Max energy production (BHmax): ~ 330 – 342 kJ/m^3

1MGOe=7.958kJ/m^3

MEH ↗ = Strength ↗

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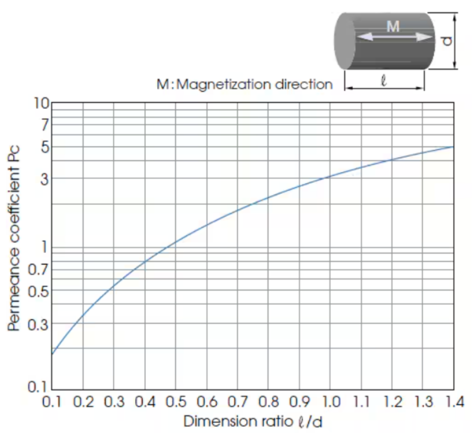
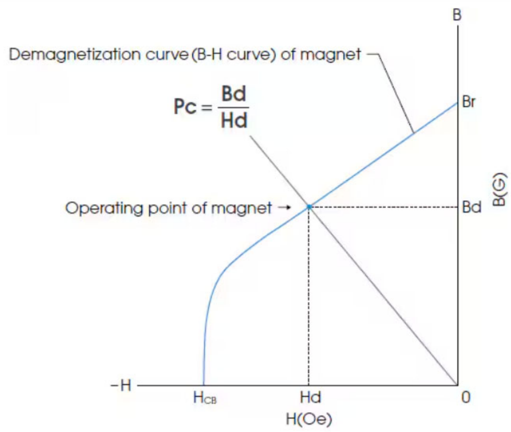
Demagnetization

Pc : Permeance coefficient ~ 3.2

The BH curve depends on the temperature.

- High temperature
- Exposure to strong external opposing magnetic fields





1. Introduction
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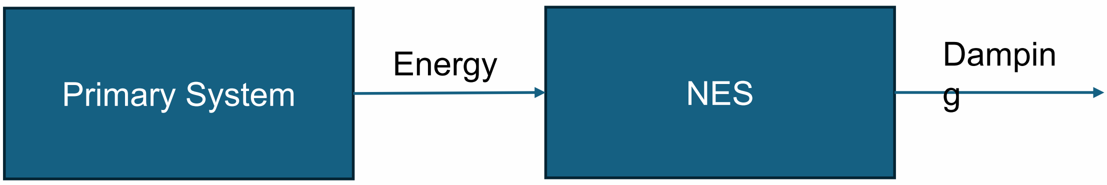
Nonlinear Energy Sinks

- Targeted Energy Transfer (TET)
  1. **Energy Input**
  2. **Detuning Effect**
  3. **Irreversibility**
- Efficiency of TET
  1. **Nonlinearity Strength**
  2. **Damping Char.**
  3. **Mass Ratio**

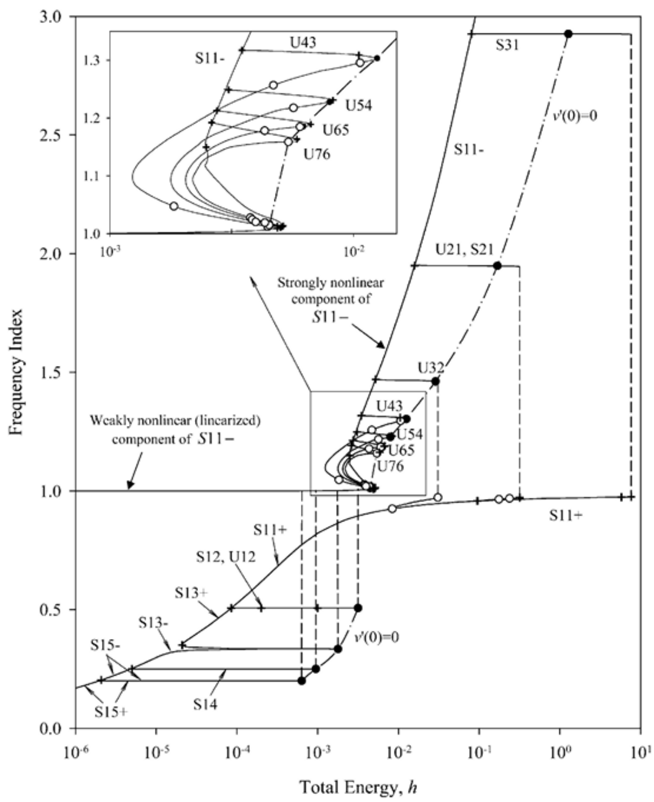
When the conditions are met :



Frequency Energy Plot

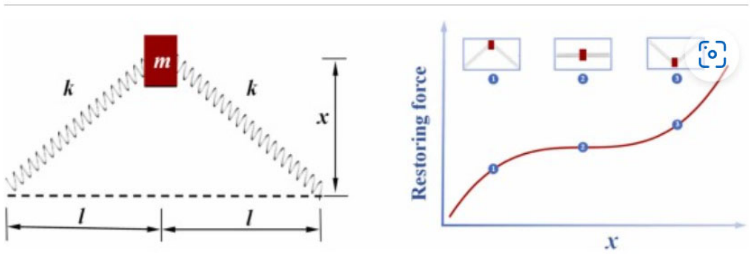
$$\ddot{x} + \omega_0^2 x + C(x-y)^3 = 0$$
$$\varepsilon\ddot{y} + C(y-x)^3 = 0$$

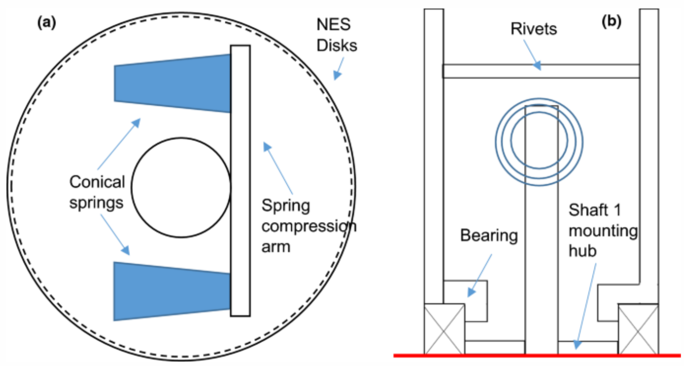
$\varepsilon = 0.05, \omega_o^2 = C = 1$



Nonlinear Energy Sinks

linear systems coupled together.





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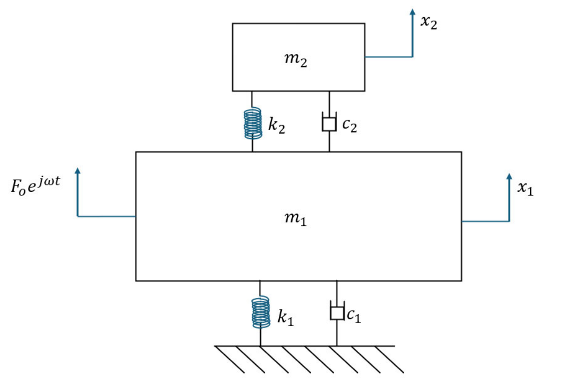
Nonlinear Energy Sinks



$$m_2\ddot{x}_2 + c_2(\dot{x}_2 - \dot{x}_1) + k_{2,L}(x_2 - x_1) + k_{2,NL}(x_2 - x_1)^3 = 0$$

$$\omega_{NES} = \sqrt{\frac{k_{2,L}}{m_2} + \frac{3k_{2,NL}A^2}{8m_2}}$$

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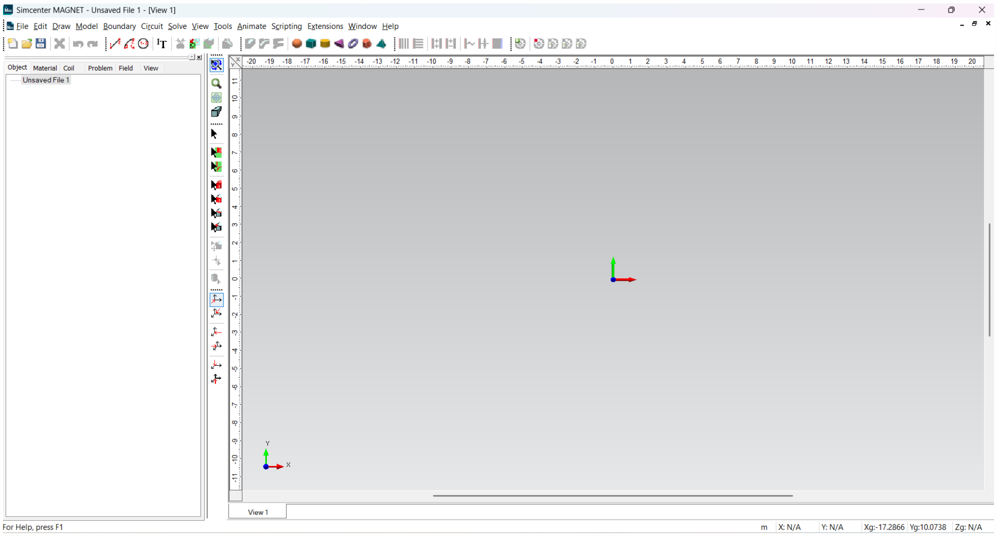
Simulation of the Contactless NES

Simcenter MAGNET



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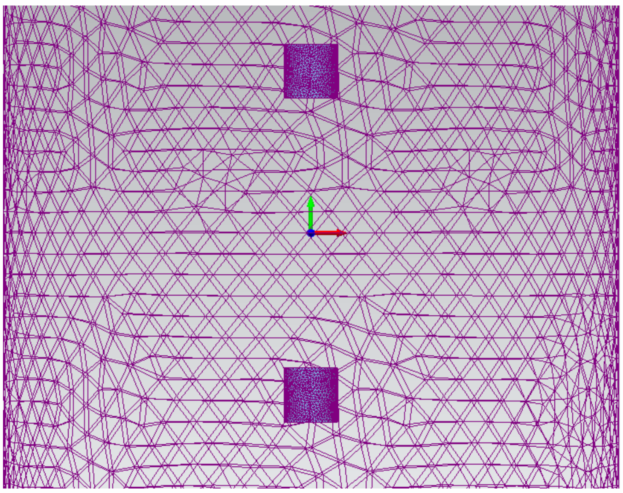
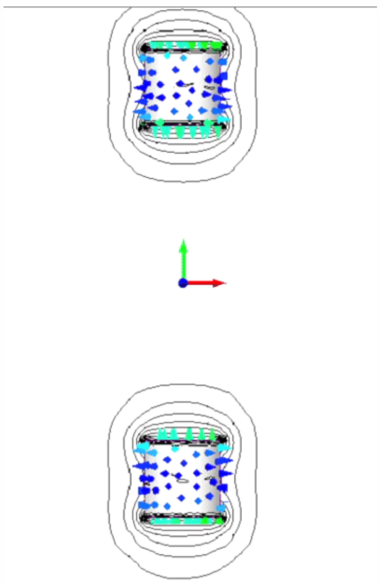
Simulation of the Contactless NES

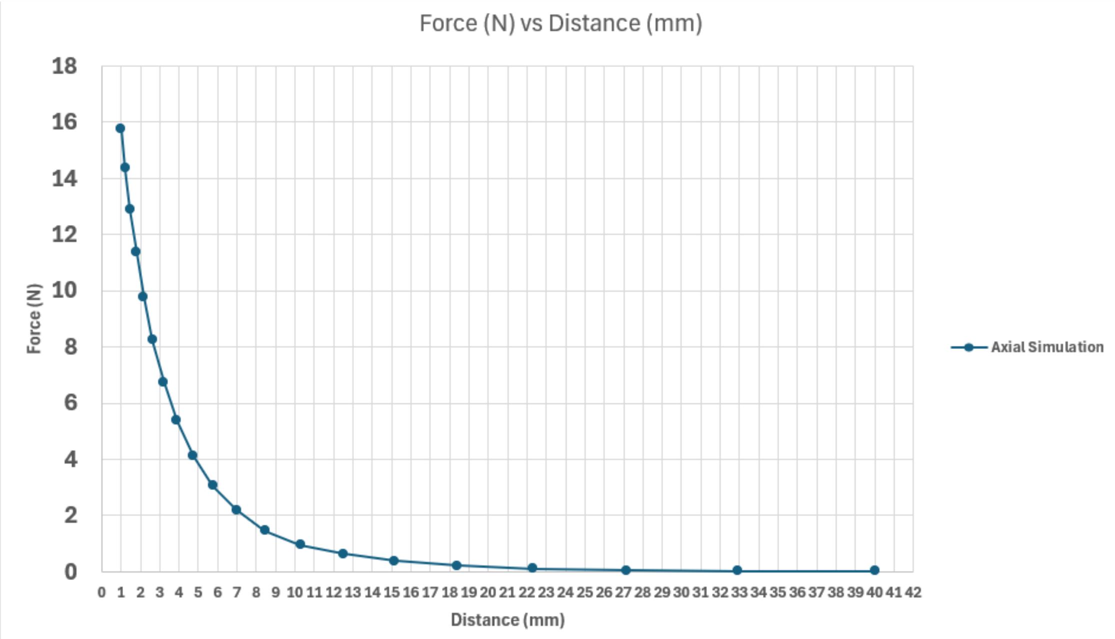
1) Axial Movement of the magnets





Simulation of the Contactless NES

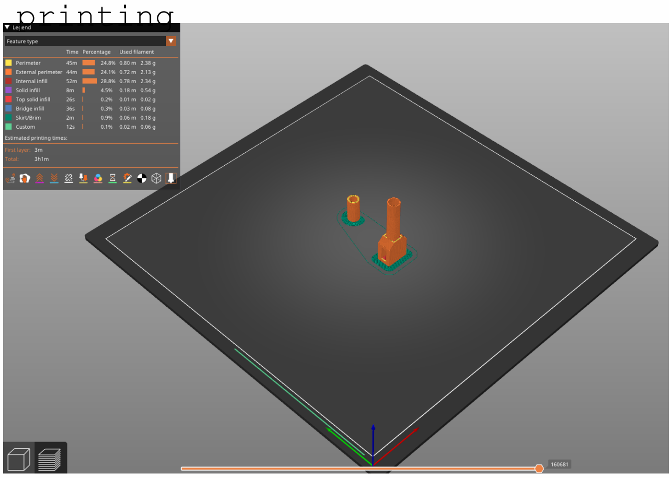
1) Axial Movement of the magnets - Result

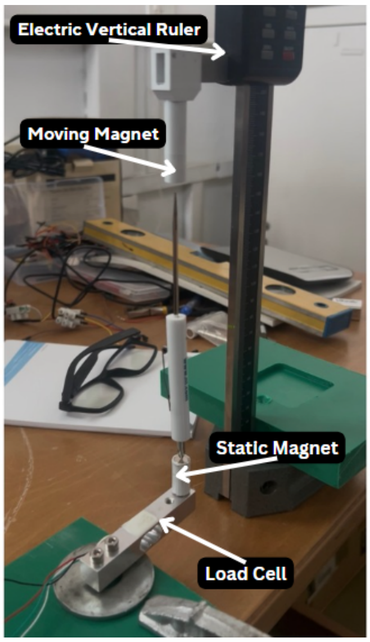


Simulation of the Contactless NES

1) Axial Movement of the magnets - Experiment

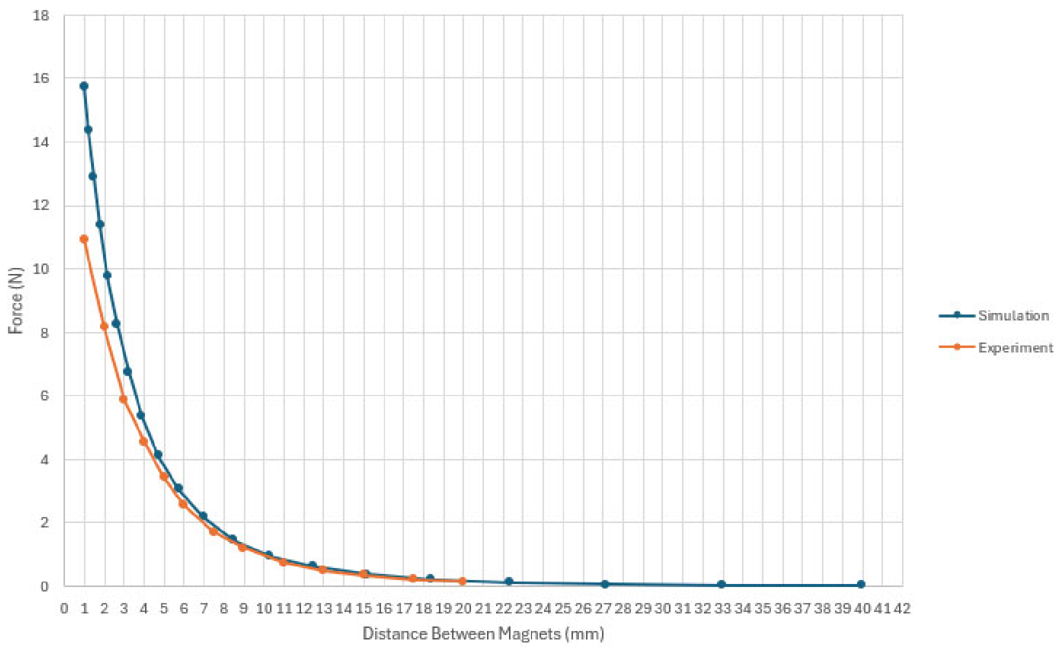
NX Siemens + PrusaSlicer for 3D printing





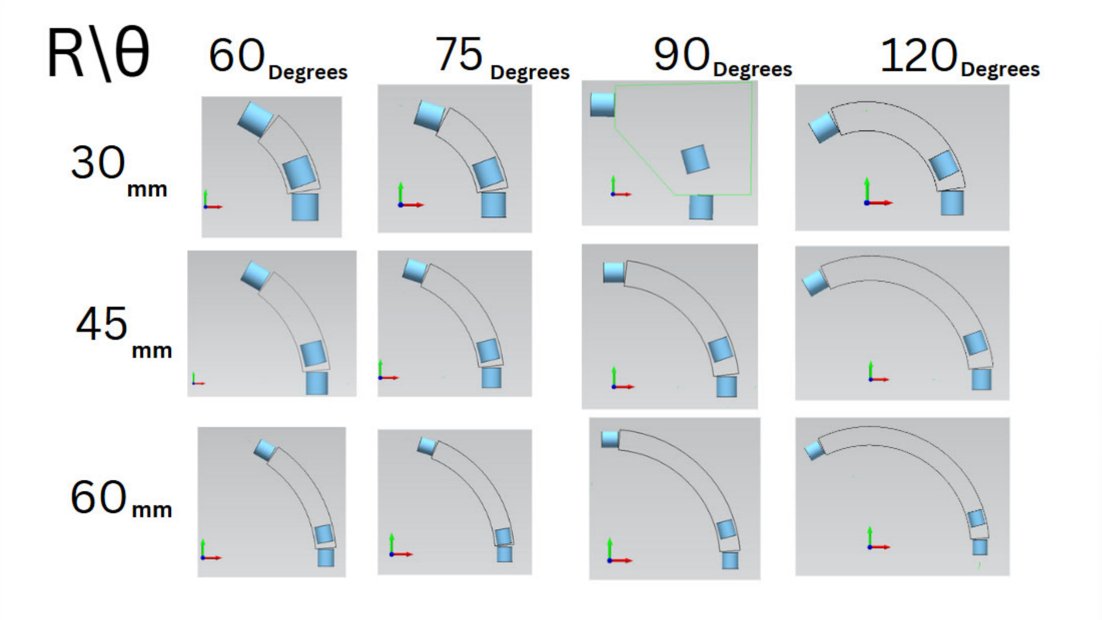
Simulation of the Contactless NES

1) Axial Movement of the magnets –



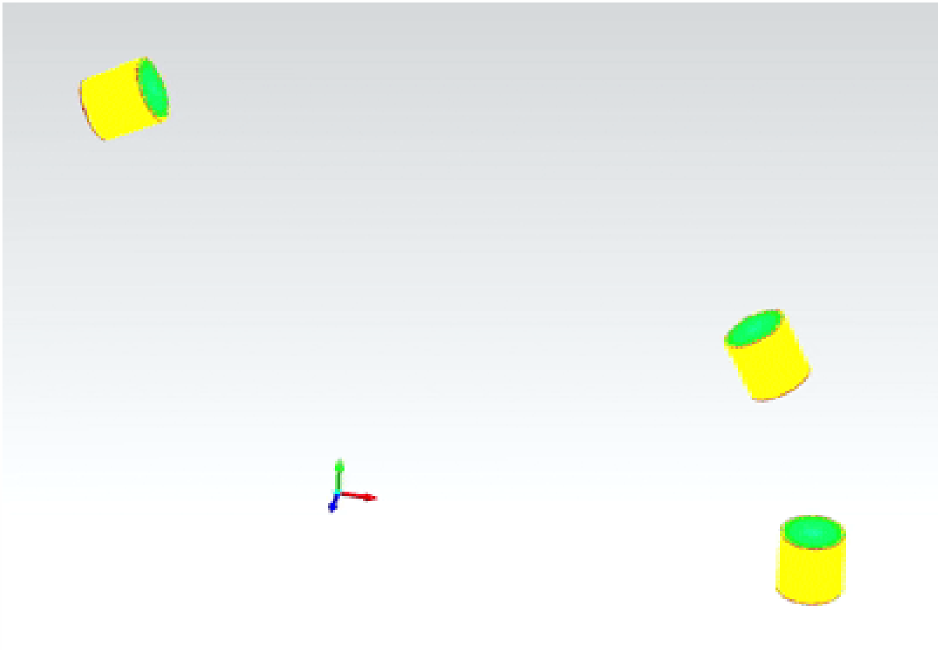
Simulation of the Contactless NES

2) Rotary Movement of the magnets



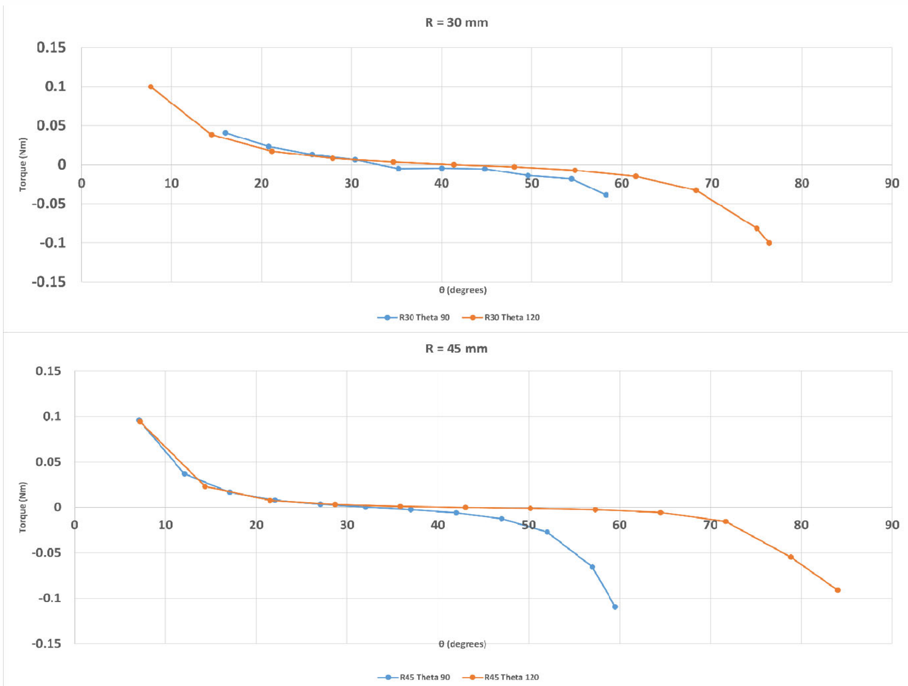
Simulation of the Contactless NES

2) Rotary Movement of the magnets (R:30mm θ:120 degrees)



Simulation of the Contactless NES

2) Rotary Movement of the magnets - Results



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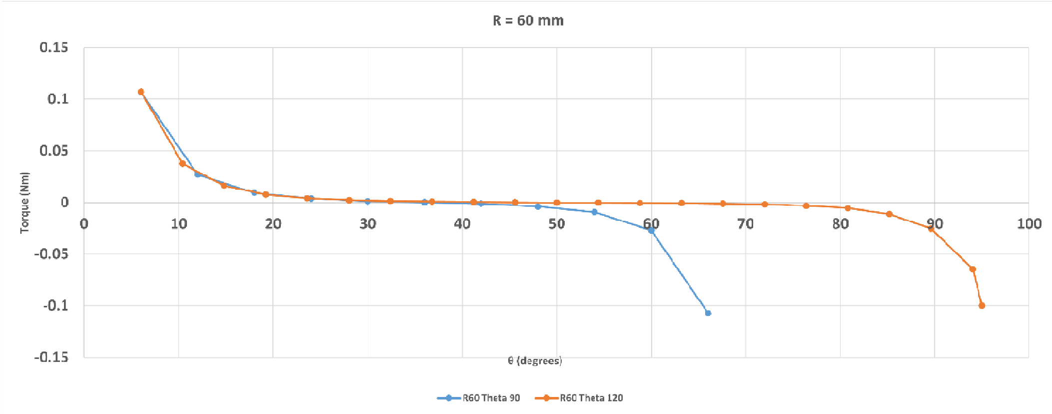
Simulation of the Contactless NES

2) Rotary Movement of the magnets - Results



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Simulation of the Contactless NES

2) Rotary Movement of the magnets – Post processing

$$T(\theta) = a\theta^3 + b\theta$$

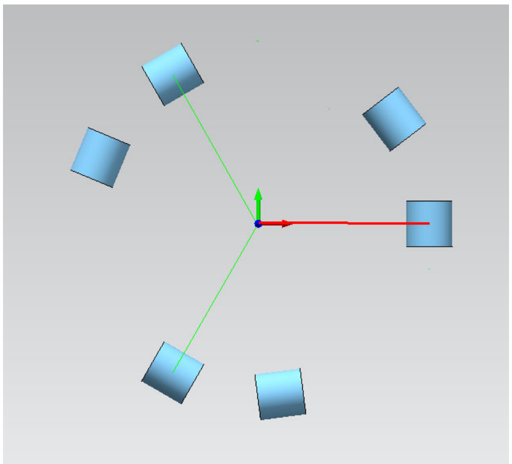
MATLAB's Curve Fitter for fitting and R^2 analysis

R/θ	R30 θ90	R30 θ120	R45 θ90	R45 θ120	R60 θ90	R60 θ120
a	0.518	0.4339	0.9954	0.2741	0.6493	0.1486
b	0.0342	0.001	0.0001	0.001	0.001	0.001
a*θmax	0.1909	0.2599	0.4552	0.1837	0.34	0.1154
b*θmax	0.0126	5.99e-04	4.572e-0.5	6.7021e-04	5.236e-04	7.7667e-04

R:30mm θ:120º with R squared of 0.9895

Simulation of the Contactless NES

2) Rotary Movement of the magnets – NES Simulation



$$T(\theta) = 1.2701\theta^3 + 0.001\theta$$

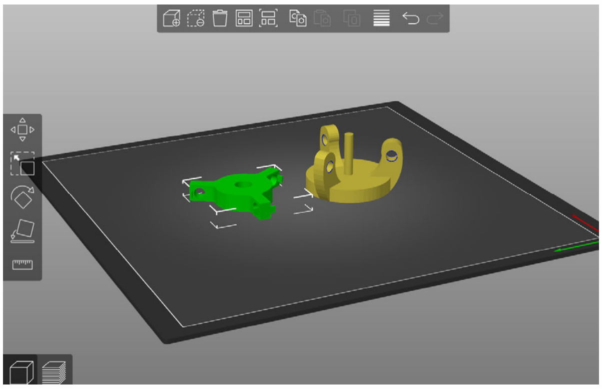
R30θ120 with R squared of 0.9895

4. Experimental Analysis

1) Printing the NES's components

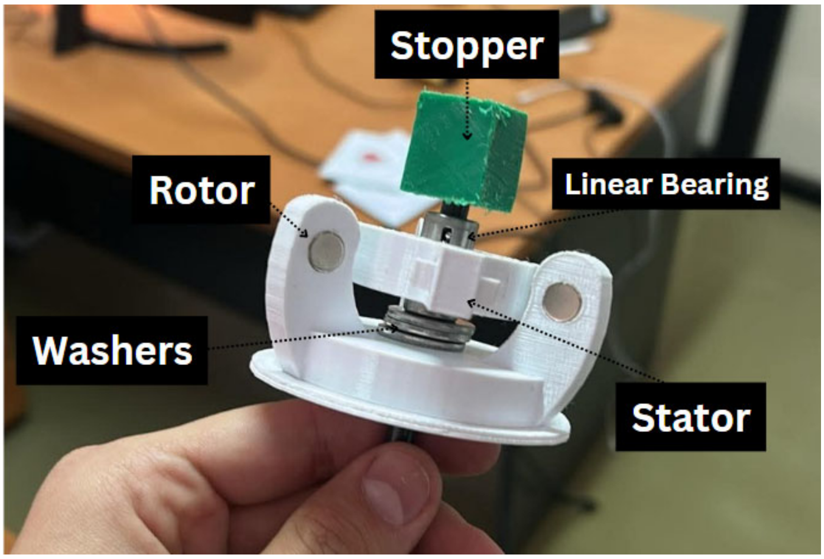
Raise3D Pro2 Plus

PrusaSlicer Interface



4. Experimental Analysis

2) Assembly of the NES

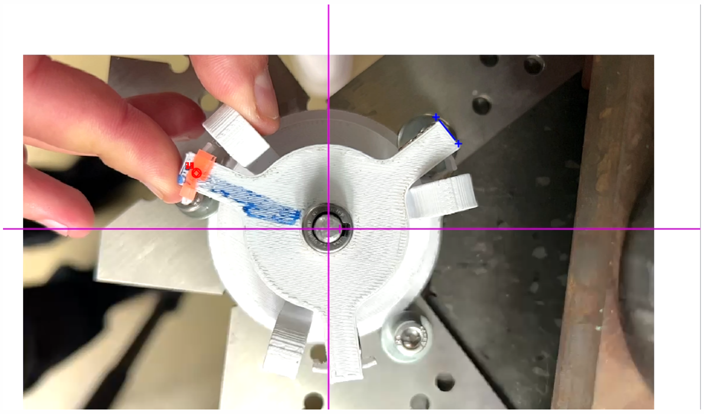


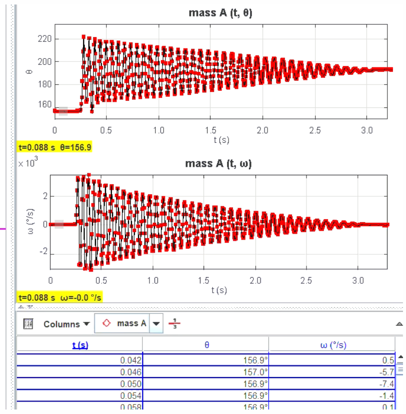
Moment of Inertia (Stator) :11.199 Kg*mm^2

4. Experimental Analysis

3) Free vibration Test

Tracker Software



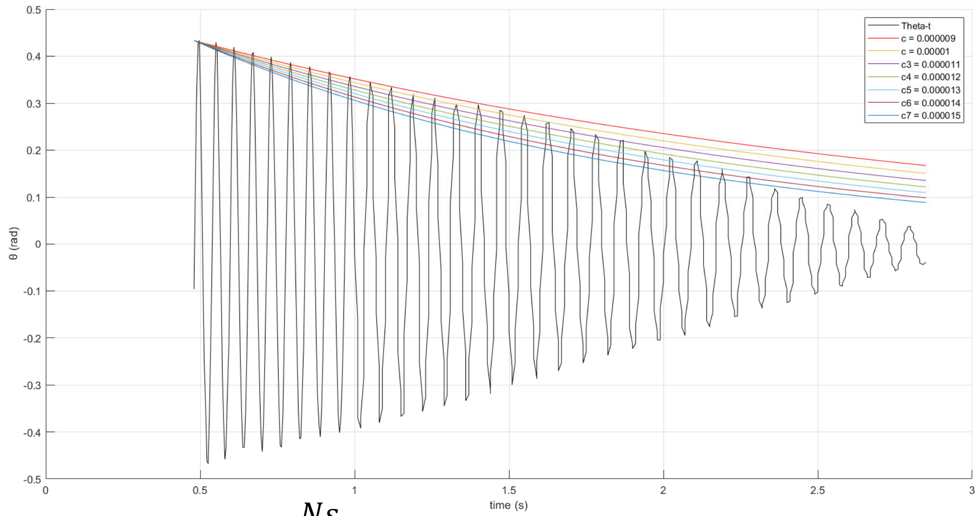


4. Experimental Analysis

4) Exponential Decay

$$\zeta = c/2\, I_{xx}$$

$$K(t) = \theta(t = t_o) * \exp\left(-c * \frac{t - t_o}{2 * I_{xx}}\right) \qquad t \in [t_o, t_f]$$



$$c = 1 * 10^{-5}\ \frac{Ns}{m} \qquad \zeta = 0.4504$$

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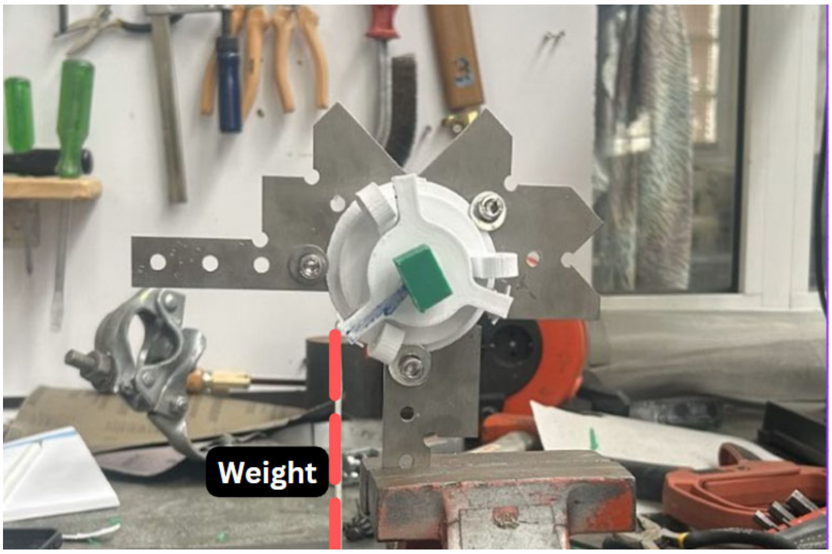
4. Experimental Analysis

5) Measuring Static Restoring Torque



$$T(\theta) = m * g * \cos(\theta) * 0.035\ (Nm)$$

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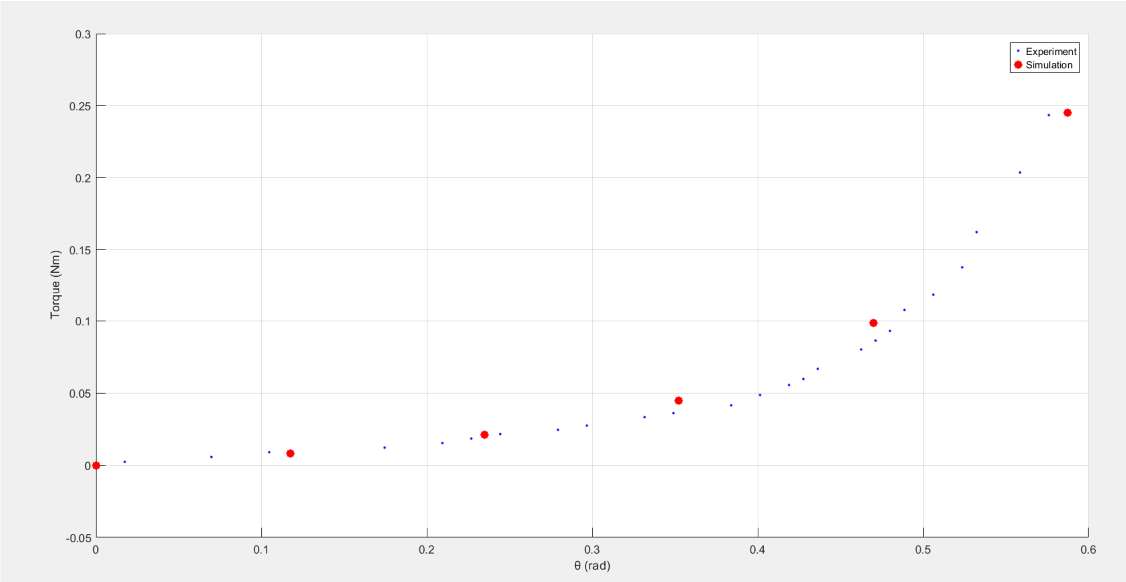
4. Experimental Analysis

5) Static Restoring Torque vs Simulated R.T



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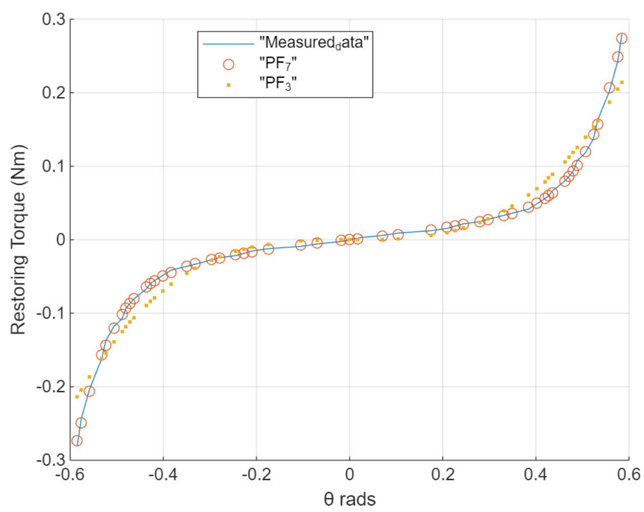
4. Experimental Analysis

5) Static Restoring Torque - Fitting



$T(\theta) = 1.0682\theta^3 + 0.001\theta$ (a) R^2 =0.956

$T(\theta) = 14.904\theta^7 - 3.0257\theta^5 + 0.4762\theta^3 + 0.0633\theta$ (b) R^2 =0.998

4. Experimental Analysis
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4. Experimental Analysis

$$Ixx * \ddot{\theta} + c * \dot{\theta} + T(\theta) = 0$$

$T(\theta) = 1.0682\theta^3 + 0.001\theta$ (Experiment "fitted")

$T(\theta) = 1.2701\theta^3 + 0.001\theta$ (Simulation "Theoretical")

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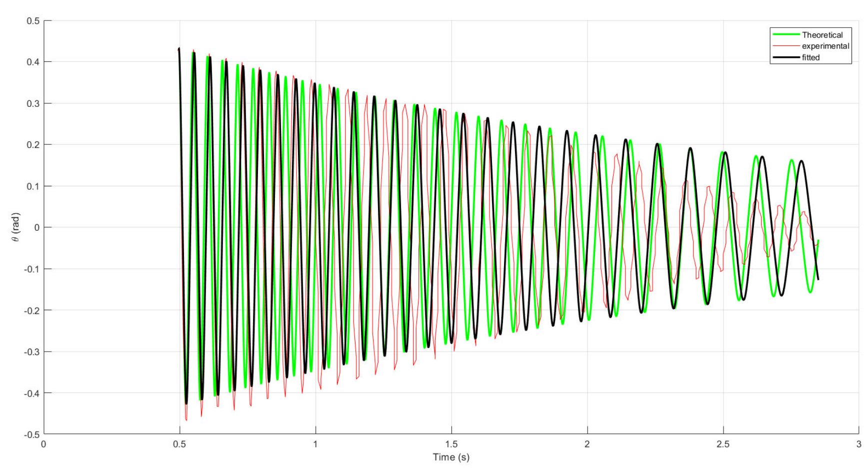
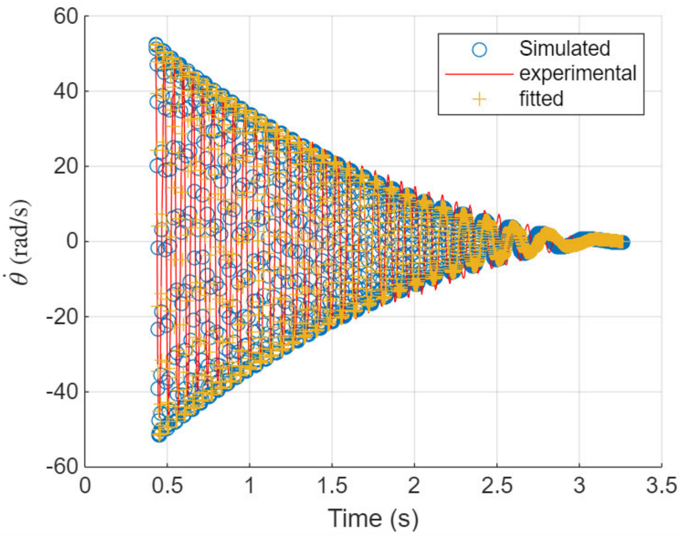


4. Experimental Analysis

$$Ixx * \ddot{\theta} + c * \dot{\theta} + T(\theta) = 0$$

$T(\theta) = 1.0682\theta^3 + 0.001\theta$ (Experiment "fitted")

$T(\theta) = 1.2701\theta^3 + 0.001\theta$ (Simulation "Theoretical")



Variable	Value
Coulomb Friction (F_c)	9N
Breakaway Friction (F_{brk})	14N
Breakaway Velocity threshold (v_{brk})	15 rad/s
Coulomb Velocity threshold (v_c)	v_{brk} / 10
Stribeck Velocity threshold (v_{st})	1.414v_{brk}

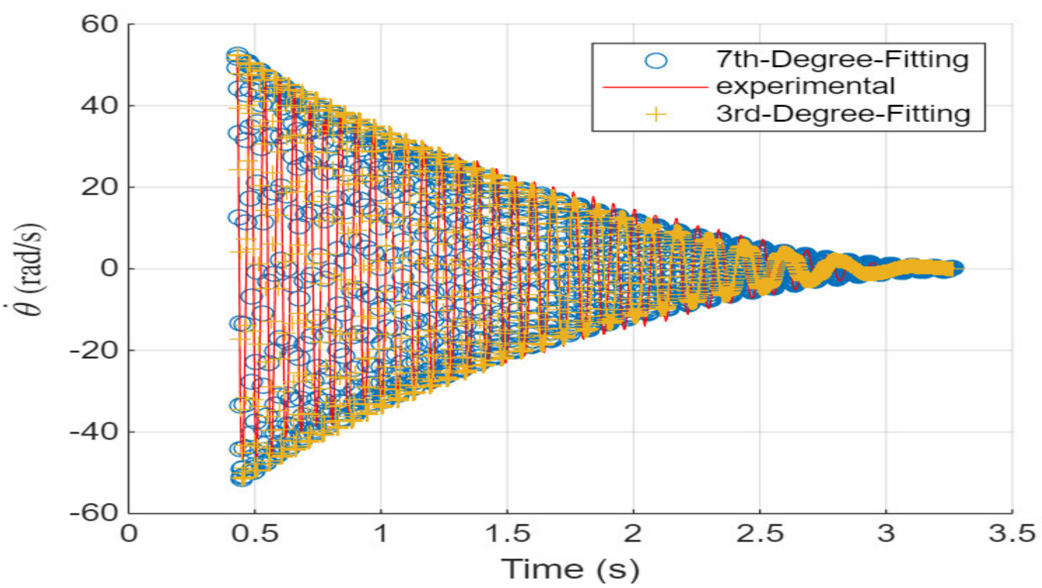
$$F = \sqrt{2e}\,(F_{brk} - F_c)\,e^{-\left(\frac{v}{v_{st}}\right)^2} \frac{v}{v_{st}} + F_c \tanh\left(\frac{v}{v_{Coul}}\right) + f_v$$

4. Experimental Analysis

$$Ixx * \ddot{\theta} + c * \dot{\theta} + T(\theta) = 0$$

$$T(\theta) = 1.0682\theta^3 + 0.001\theta$$

$$T(\theta) = 14.904\theta^7 - 3.0257\theta^5 + 0.4762\theta^3 + 0.0633\theta$$



5. Conclusion

- Magnets should not come closer than 4mm.
- NES Parameters : R=30mm θ=120 degrees.

$$T(\theta) = 1.2701\theta^3 + 0.001\theta$$

- The Measured Restoring Torque IS valid and is close to the simulated one.

$$T(\theta) = 1.0682\theta^3 + 0.001\theta \text{ , } 3rd\ degree\ fitting$$

$$T(\theta) = 14.904\theta^7 - 3.0257\theta^5 + 0.4762\theta^3 + 0.0633\theta \text{ , } 7th\ degree\ fitting$$

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Thank you very much for your attention !

Questions ?