Non-Linear Modeling and Sensitive Analysis of a Magnetostrictive Force Sensor

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Outline

1. Introduction:

- Magnetostrictive materials and their applications
- Research background: Magnetostrictive force sensors

2**. Problem and Objectives:**

- Non-linear model of magnetostrictive force sensor
- Simulation of non-linear model

3**. Sensitive Analysis:**

- Specify the effective parameters on the sensor’s performance
- Investigate the linearity and sensitivity of the sensor

4**. Conclusions and Future Plans**

Introduction: Magnetostrictive Materials

Magnetostrictive Materials:

Exhibit changes in material properties in response to externally imposed magnetic field.

Five Effects:

1. Joule effect (actuator)
2. Villari effect (sensor & harvester)
3. Wiedemann effect (actuator)
4. Matteucci effect (sensor & harvester)
5. ΔE effect (actuator)

Introduction: Applications of Magnetostrictive

Magnetostrictive

Actuators
(Joule & Wiedemann & ΔE)

- ❖ Resonant actuator
- ❖ Non-resonant actuator

Sensors
(Villari & Matteucci)

- ❖ Force sensor
- ❖ Displacement sensor
- ❖ Magnetic flux sensor

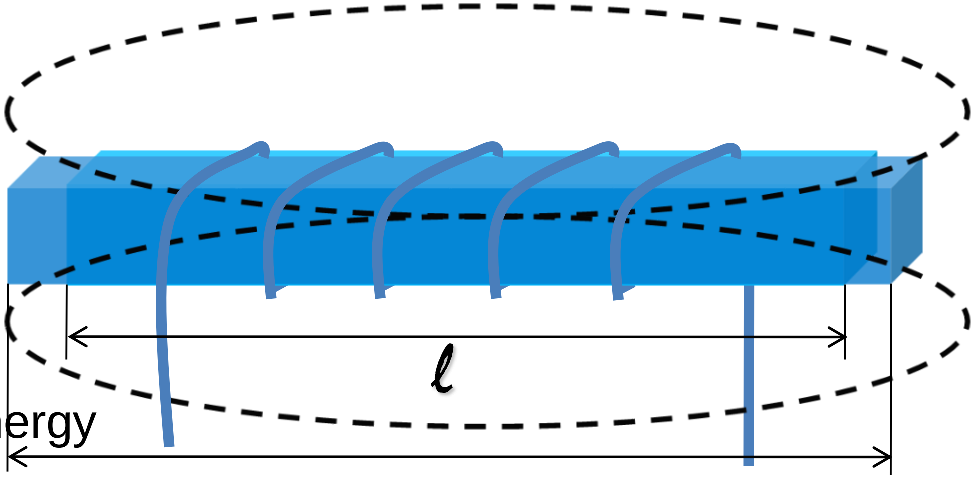
Energy Harvesting System
(Villari)

- ❖ Vibration base energy harvester

Introduction: Magnetostrictive Effects

Joule effect

Iron: 6 ppm
Nickel: -30 ppm
Permandur: 70 ppm
Terfenol-D: 2000 ppm (Brittle)



Magnetic energy → **Mechanical** energy

Villari effect

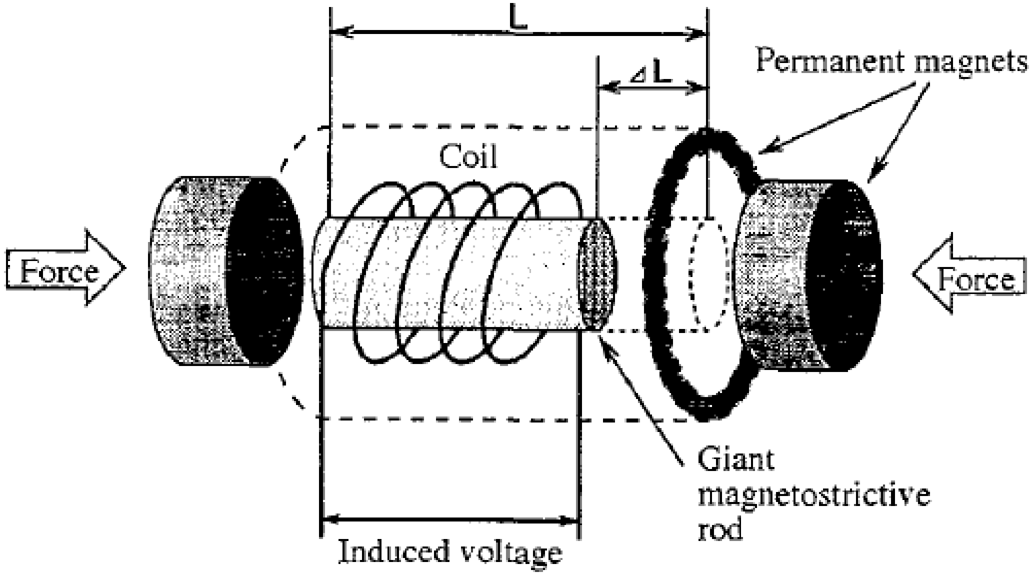
Applied the force

↓

Magnetisation along the direction of magnetic field will be change

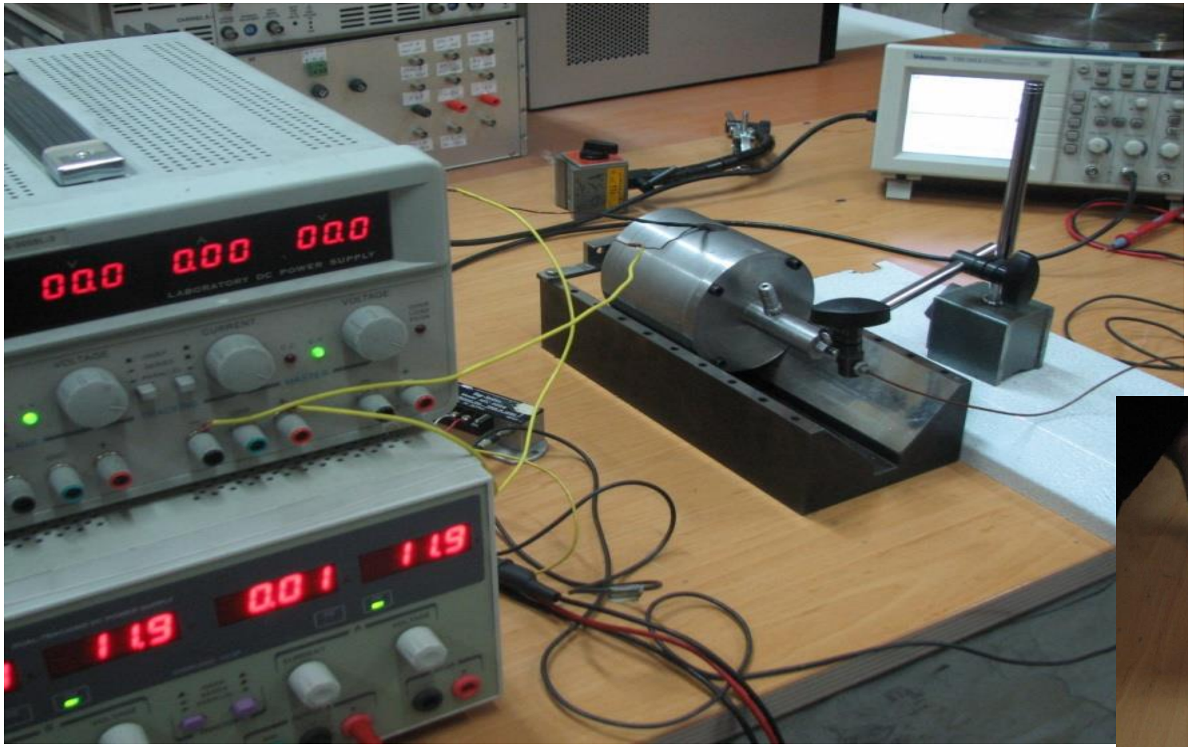
↓

The flux variation induced voltage in the coil



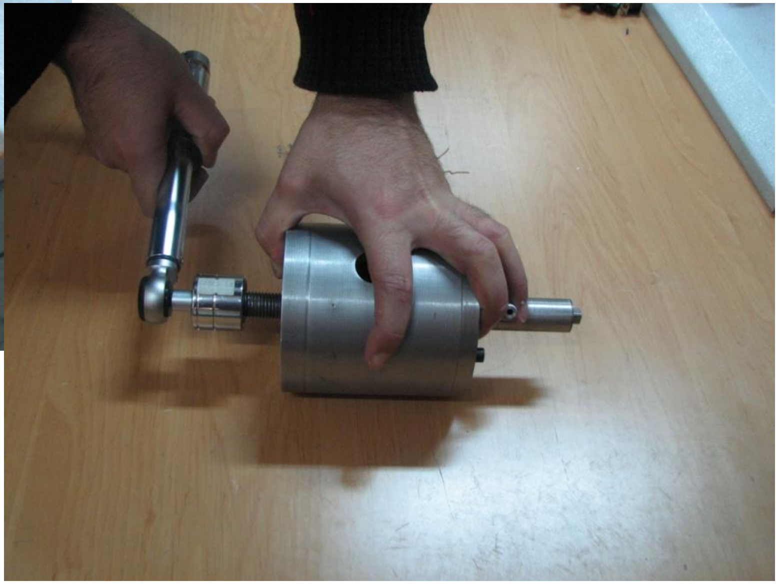
Mechanical energy → **change of magnetic** energy

5



Joule Effect

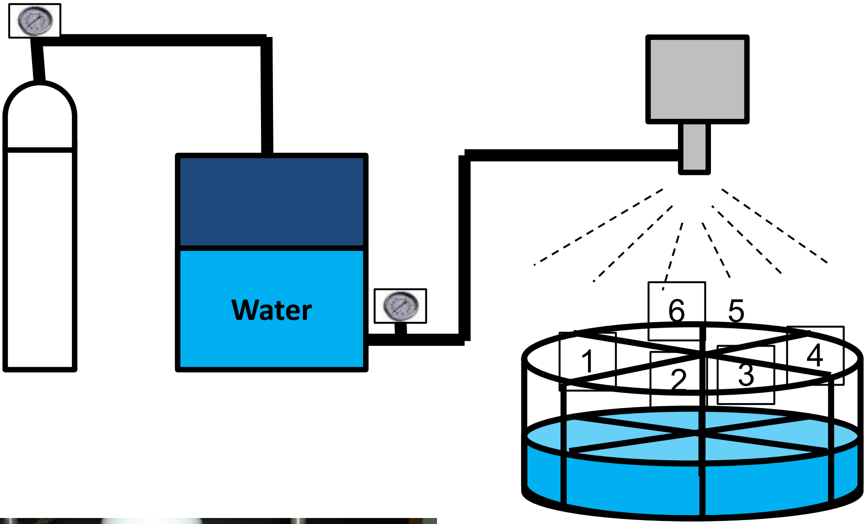
Non-resonant Actuator



Gasoline Direct Injector

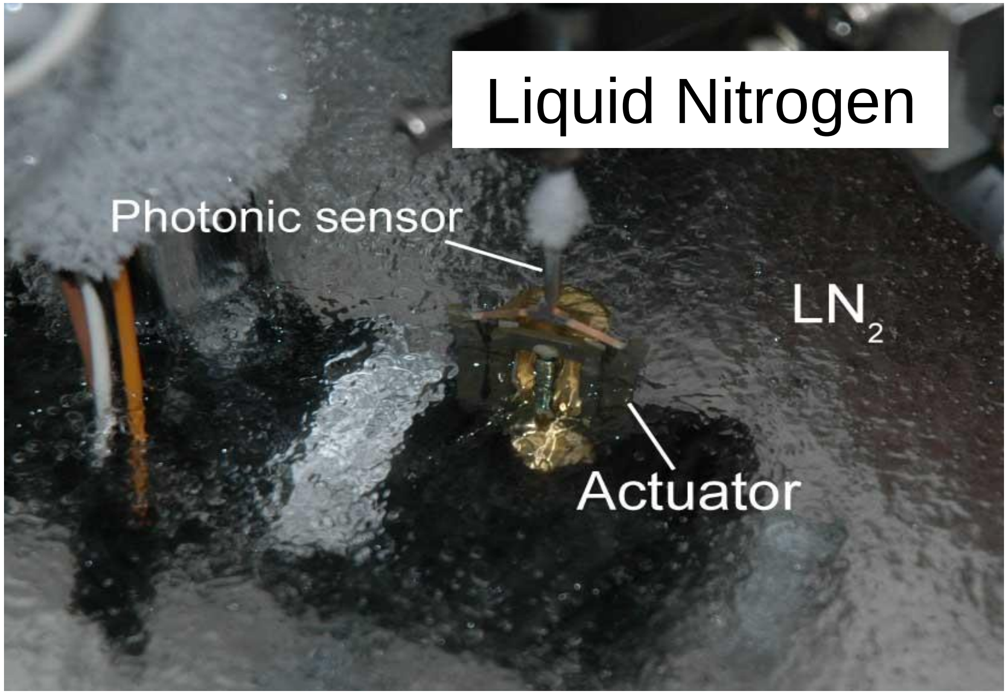
[Ghodsi, IEEE Industry Applications Magazine, 2017]

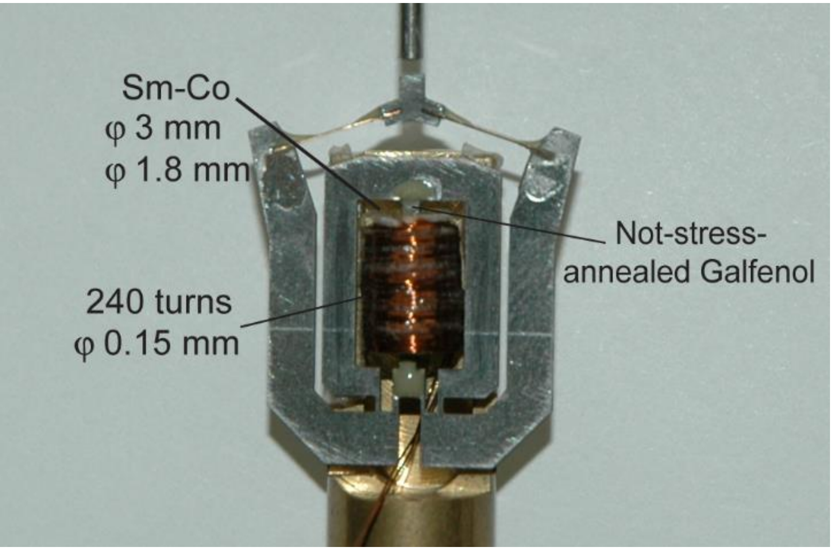
Cold Test: Experimental Results of Symmetrical Injection



Joule Effect

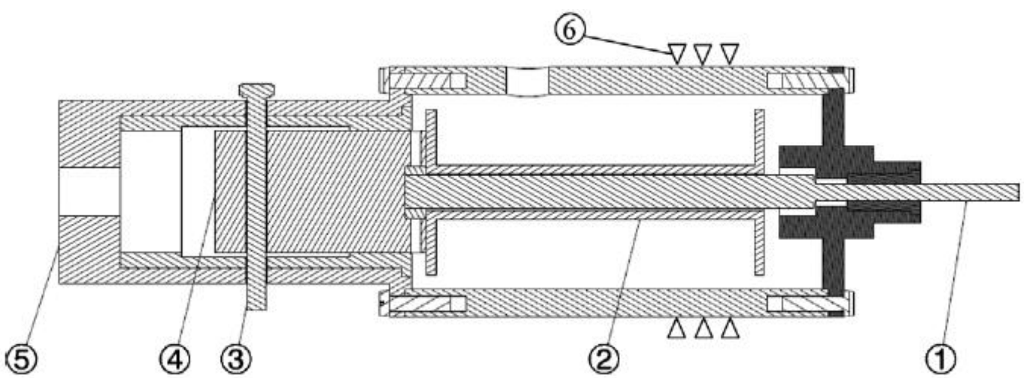
Actuator in liquid Nitrogen

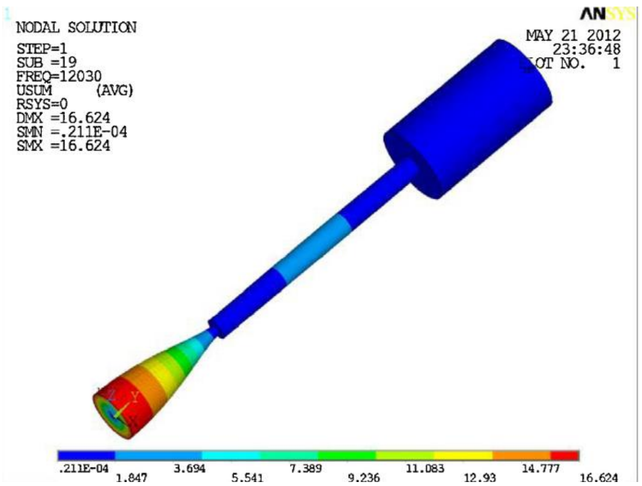


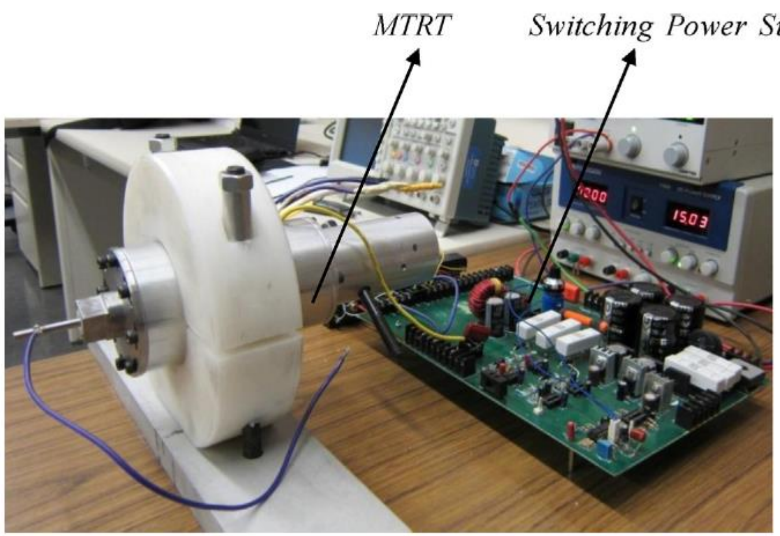


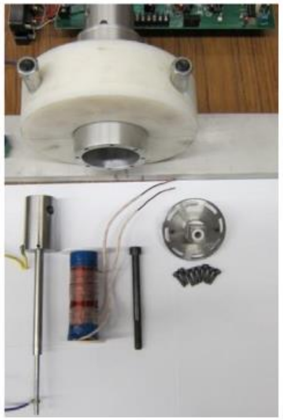
Magnification system using
Galfenol and Permendur
[Ghodsi, Ueno, Yano, Intermag 2008]

Introduction: Applications: Bone Drilling









Wiedemann Effect

Resonant Torsional Actuator

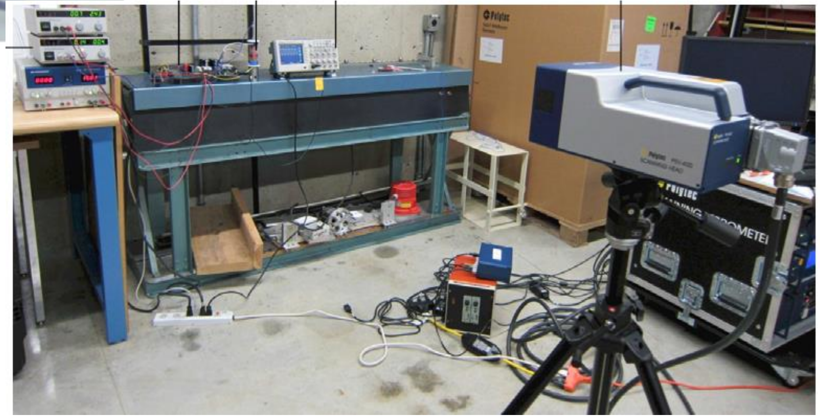
Wiedemann effect, [Ghodsi, Sensor and actuator, 2013]

Introduction: Applications: Bone Drilling

Wiedemann Effect

Hybrid Longitudinal-Torsional

[Ghodsi 2013]



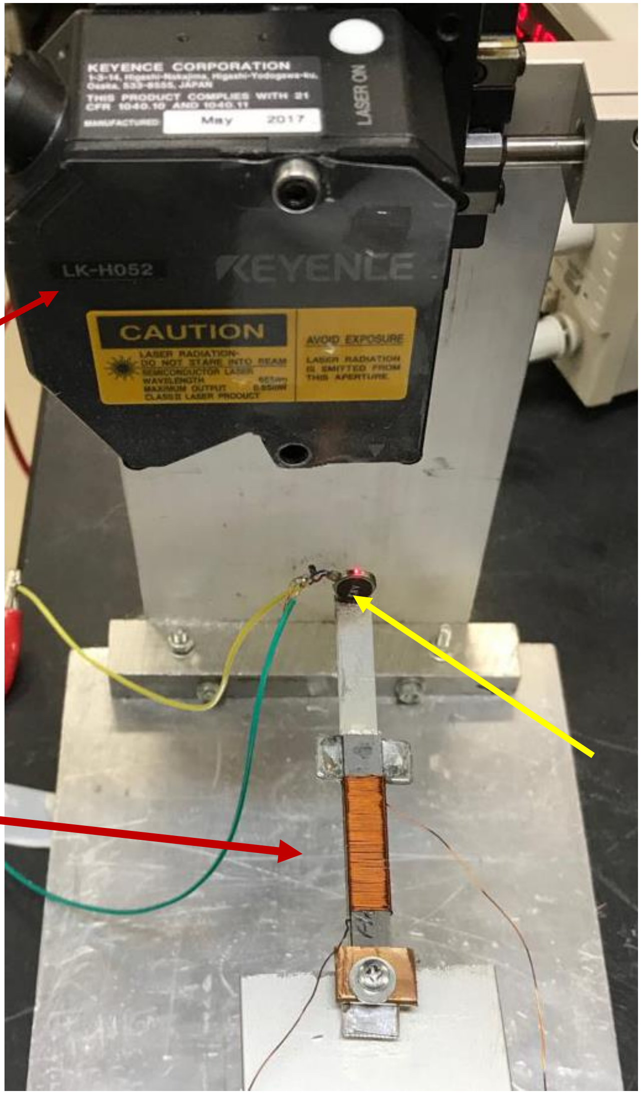
Introduction: Applications: Energy Harvester

Exciting the system in its natural frequency

Laser Displacement

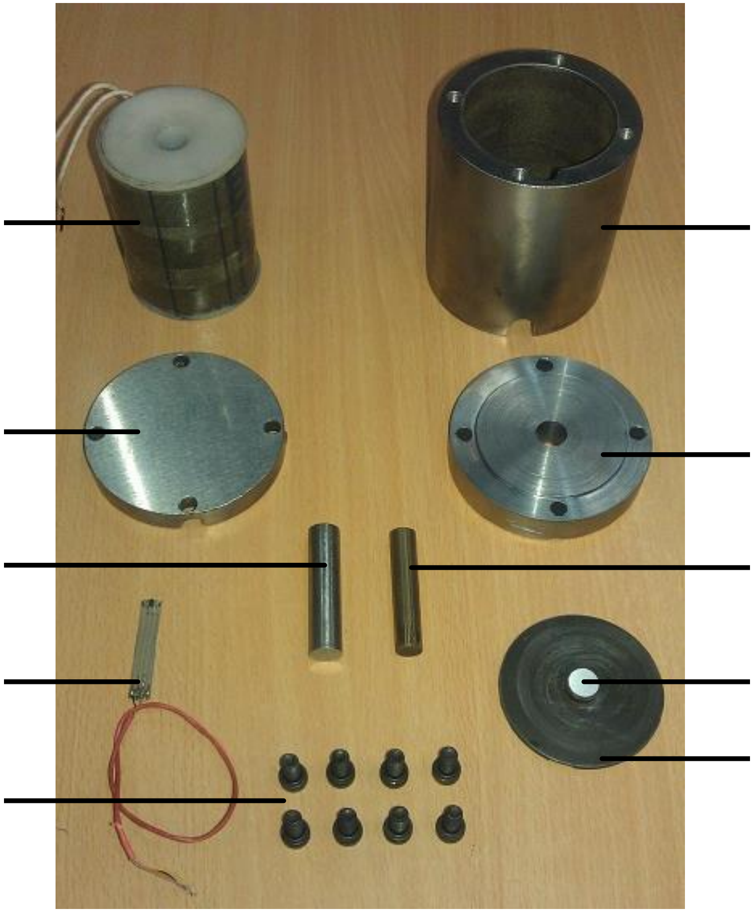
Pick-up coil

Rotating unbalance motor



[Ghodsi,Energy,2019]

Introduction: Applications: Force Sensor



[Ghodsi,2012]

Villari Effect

Force Sensor

[Strainsense]

[Ghodsi, 2015]

Conventional Force sensor (Strain gauge)

- Static applications

Smart material force sensor

- Dynamic applications

Research Background: Magnetostrictive Force Sensors

Year	Author	Mechanism	Material	Description
2015	Ghodsi	Rod configuration	Terfenol-D	Linear Modeling
2017	Zhu	Rod configuration	Terfenol-D	Frequency effect
2018	Li	Cantilever beam	Galfenol	Small force range (0-5 N)
2020	Shu	Cantilever beam	Galfenol	Suitable for Impact force

Challenge and Objectives

Challenge:

The developed Magnetostrictive force sensors suffer from low sensitivity and linearity.

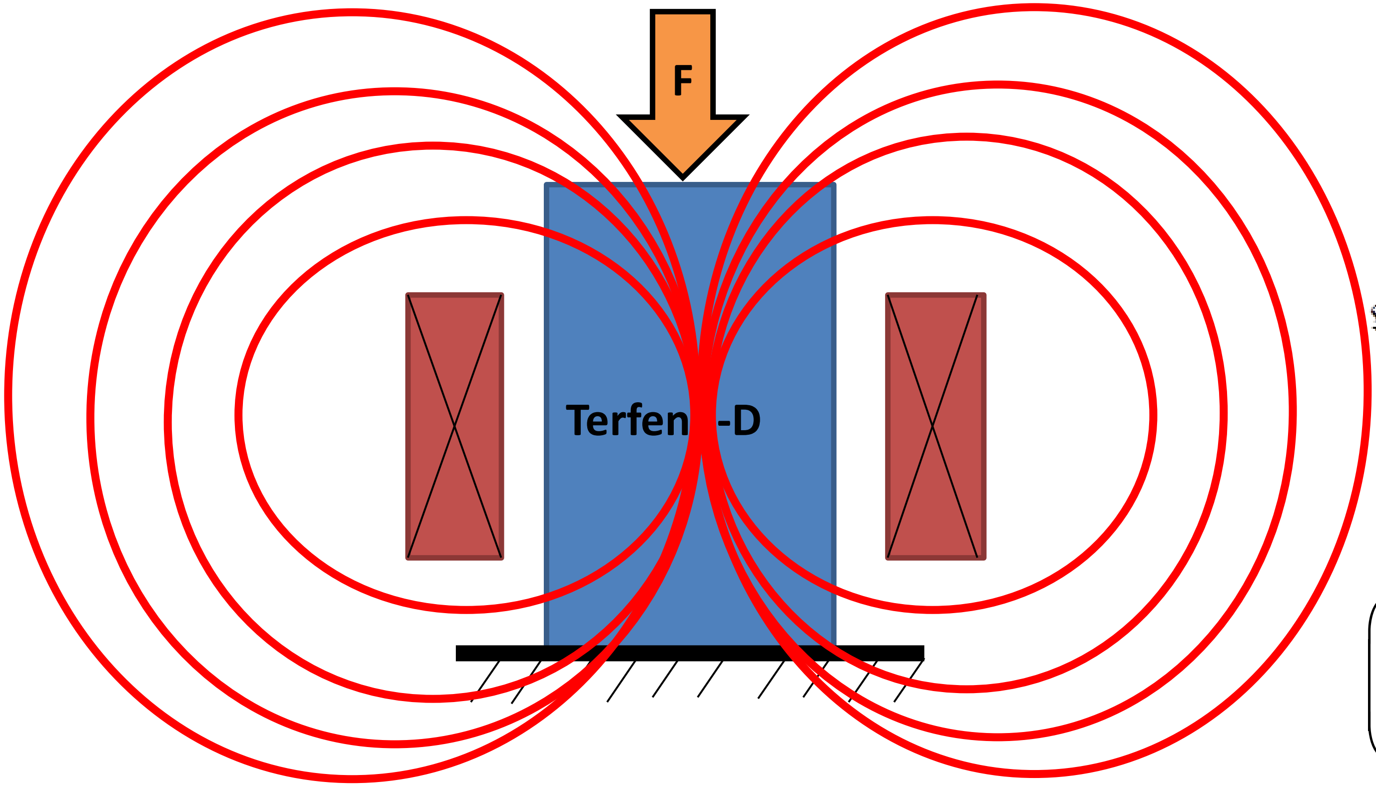
Objective I:

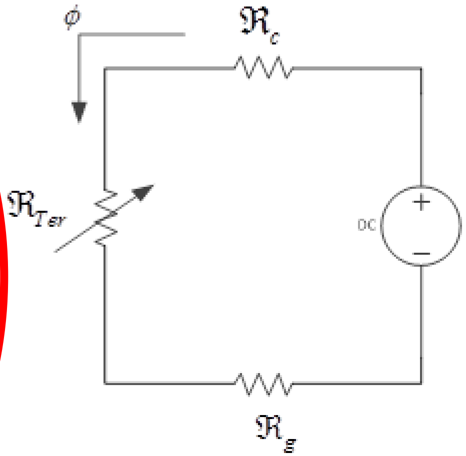
Develop an accurate model to predict the **sensitivity** of the sensor by combining the non-linear magneto-mechanical model and the Faraday's law.

Objective II:

Find the effective parameters on sensitivity and non-linearity to optimize the performance of the force sensor.

Principle of Force Sensor

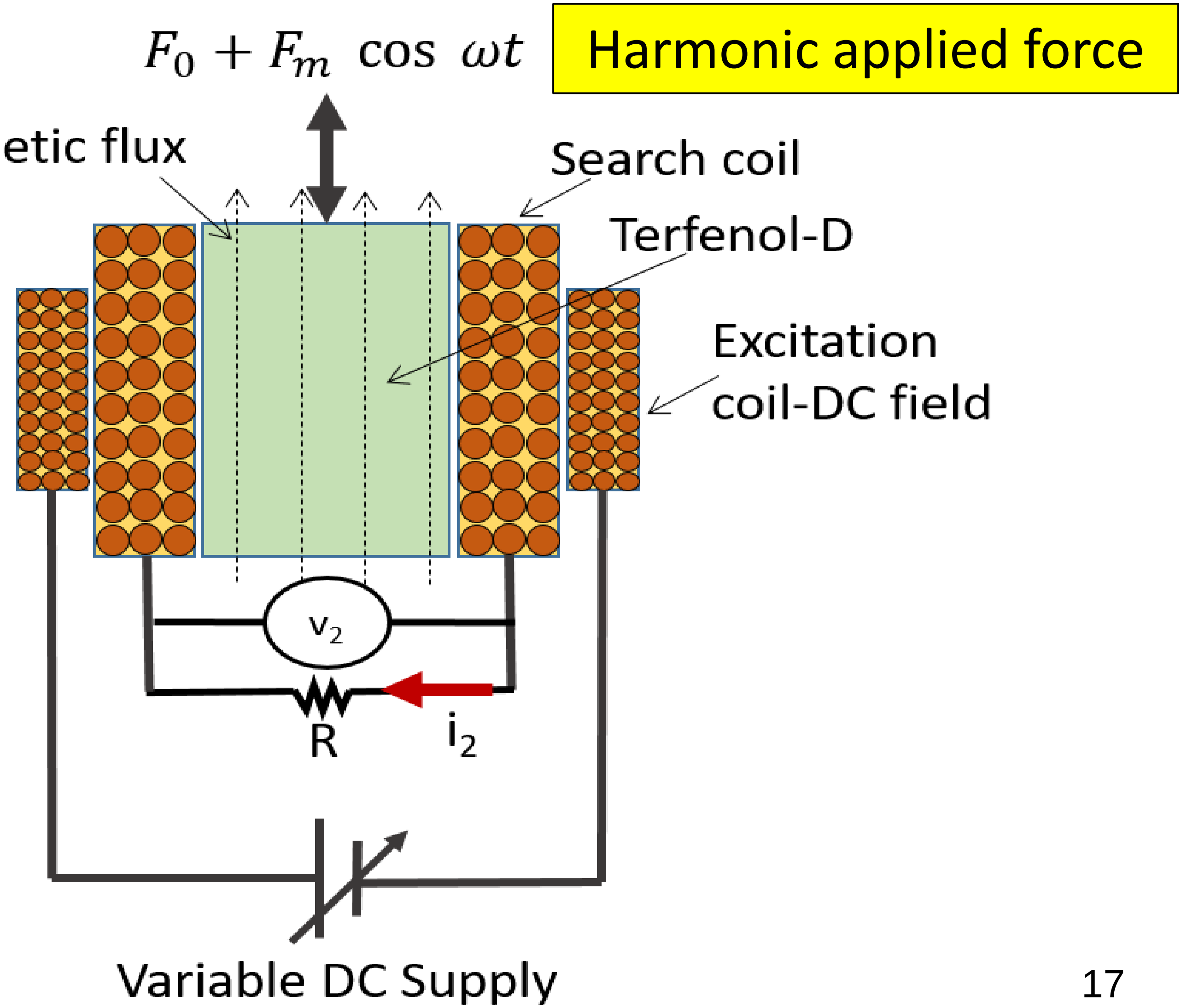




$$\left(\Re_{Ter} = \frac{L_{Ter}}{\mu_0 \mu_{r_{Ter}} A_{Ter}} \right)$$

Villari Effect

Structure of the Force Sensor



Mechanical Modelling of Force Sensor

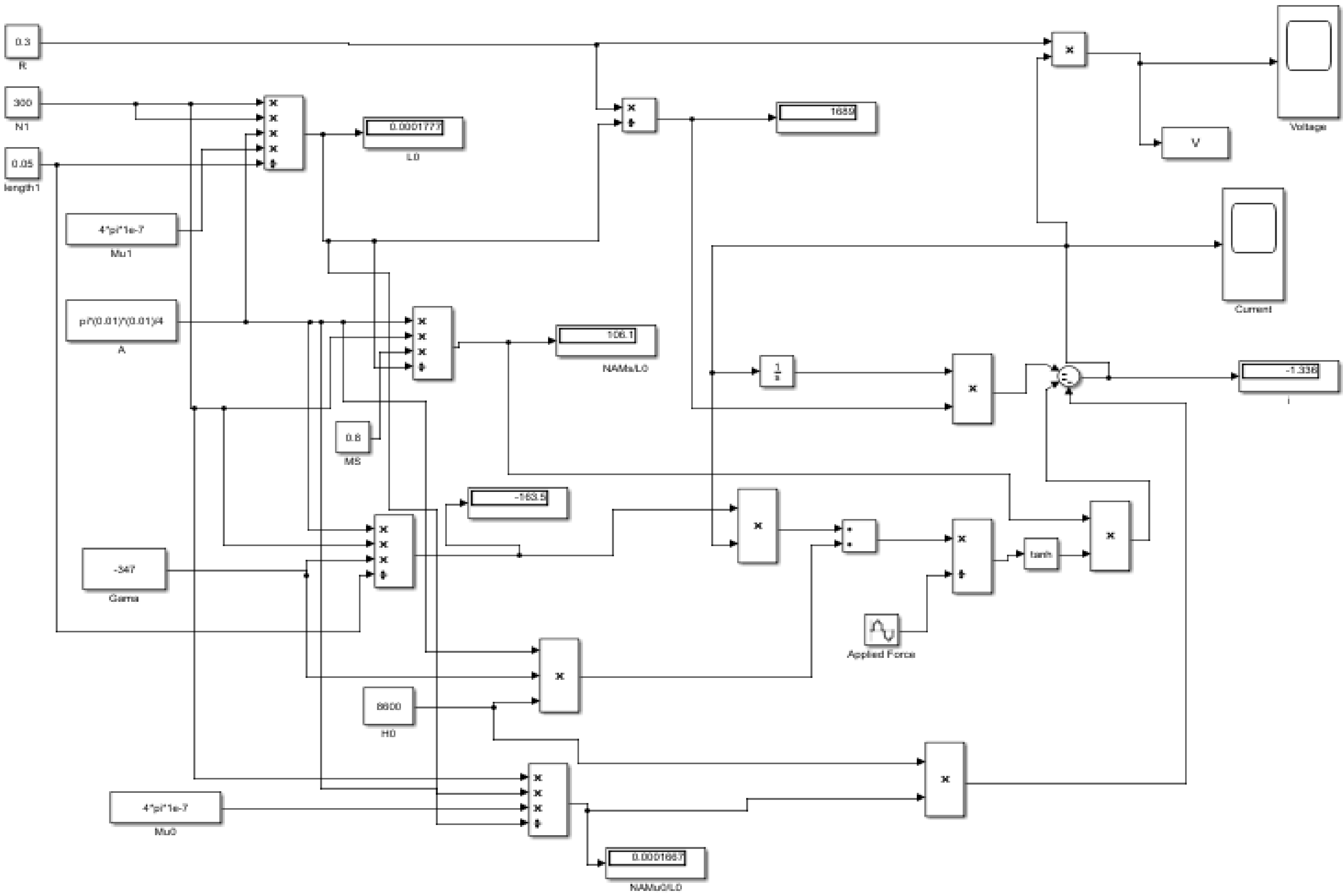
Non-linear magneto-mechanical relation:

$$\begin{cases} \varepsilon = \dfrac{\sigma}{E} - \dfrac{M_s}{\gamma}\left[\dfrac{\gamma H}{\sigma}\tanh\left(\dfrac{\gamma H}{\sigma}\right) - \ln\left(\cosh\left(\dfrac{\gamma H}{\sigma}\right)\right)\right] \\ B = \mu_0 H + M_s \tanh\left(\dfrac{\gamma H}{\sigma}\right) \end{cases}$$

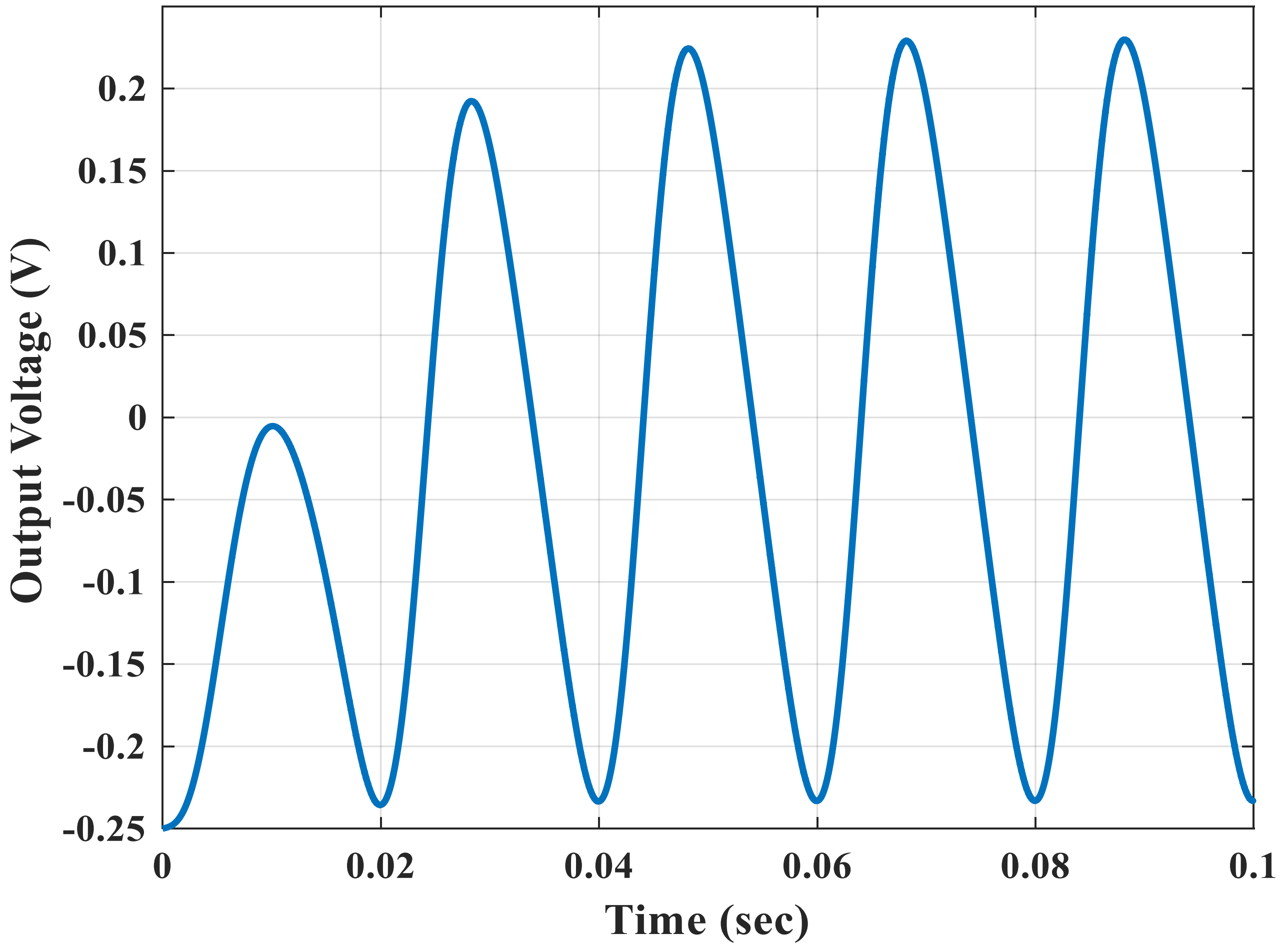
$$\varphi = BA = -\frac{1}{N}\int v_2 dt$$

$$-\frac{R}{L_0}\int_0^\tau i_2\, dt = i_2 + \frac{NAM_s}{L_0}\tanh\left(\frac{\frac{\gamma ANi_2}{l_0} + \gamma AH_0}{F_0 + F_m\cos\omega t}\right) + \frac{NA\mu_0}{L_0}H_0$$

Solve Equations: Simulation-Simulink

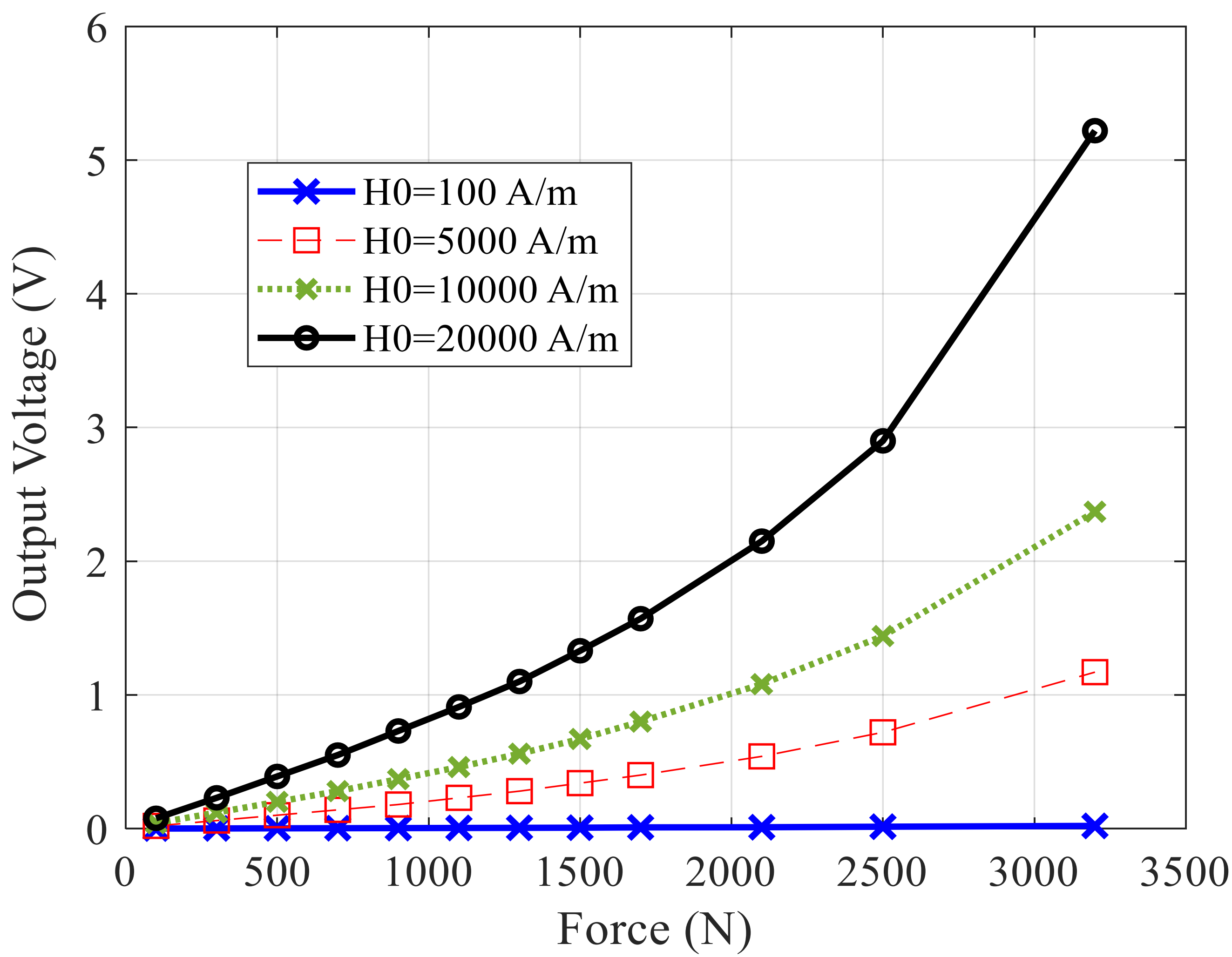


Simulation : Output Voltage of Sensor



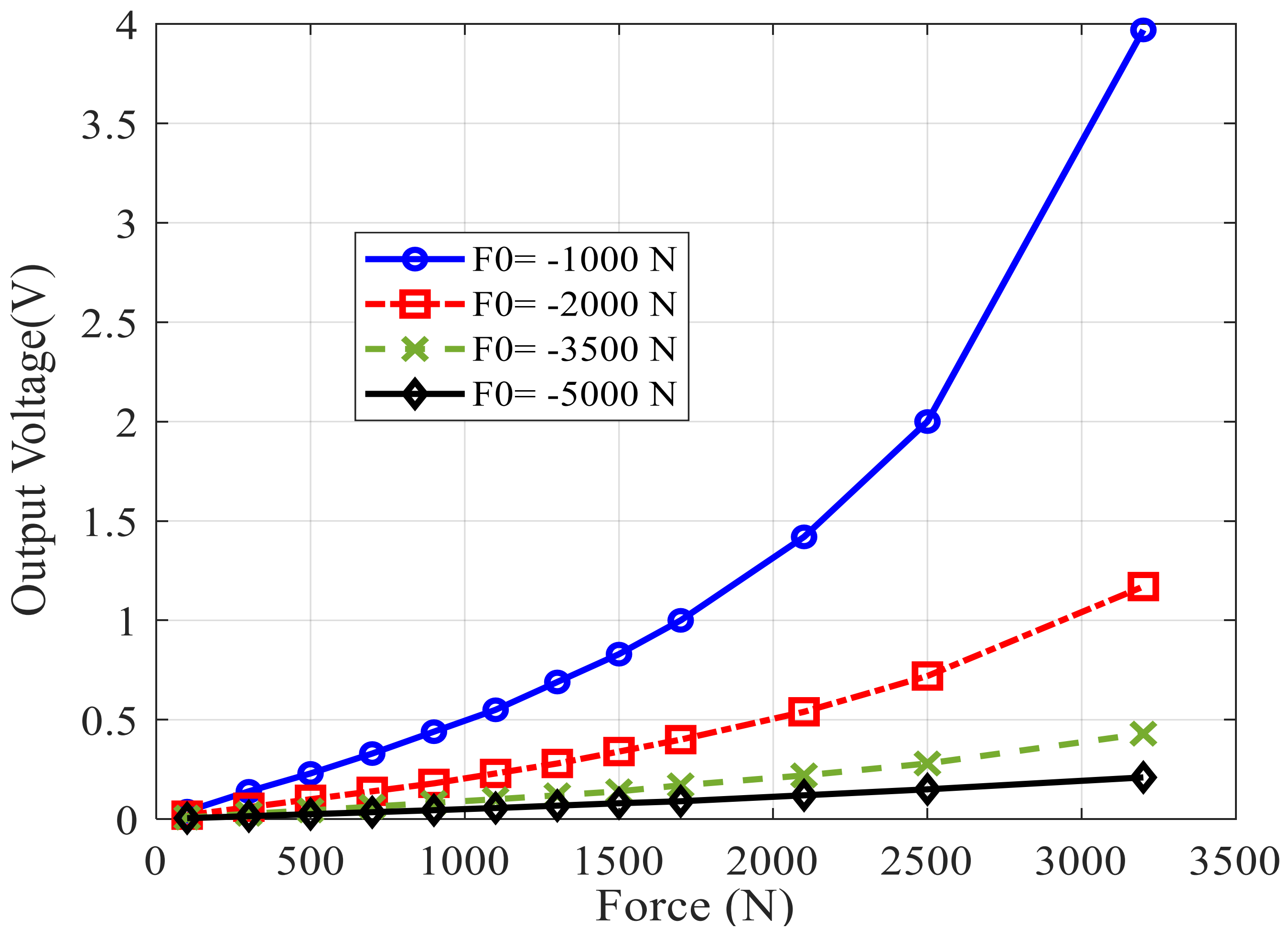
Output voltage of search coil, R=0.3 Ω, H_0=5 kA/m, F_0= -1060 N, F_m= 1000 N, f= 50 Hz

Simulation result : Output Voltage



Output voltageof force sensor (V_{pp}); R=0.3 Ω ; F_0 = -1000 N

Simulation result : Output Voltage



Output voltage of force sensor (V_{pp}); R=0.3 Ω ; H_0 = 5000 A/m

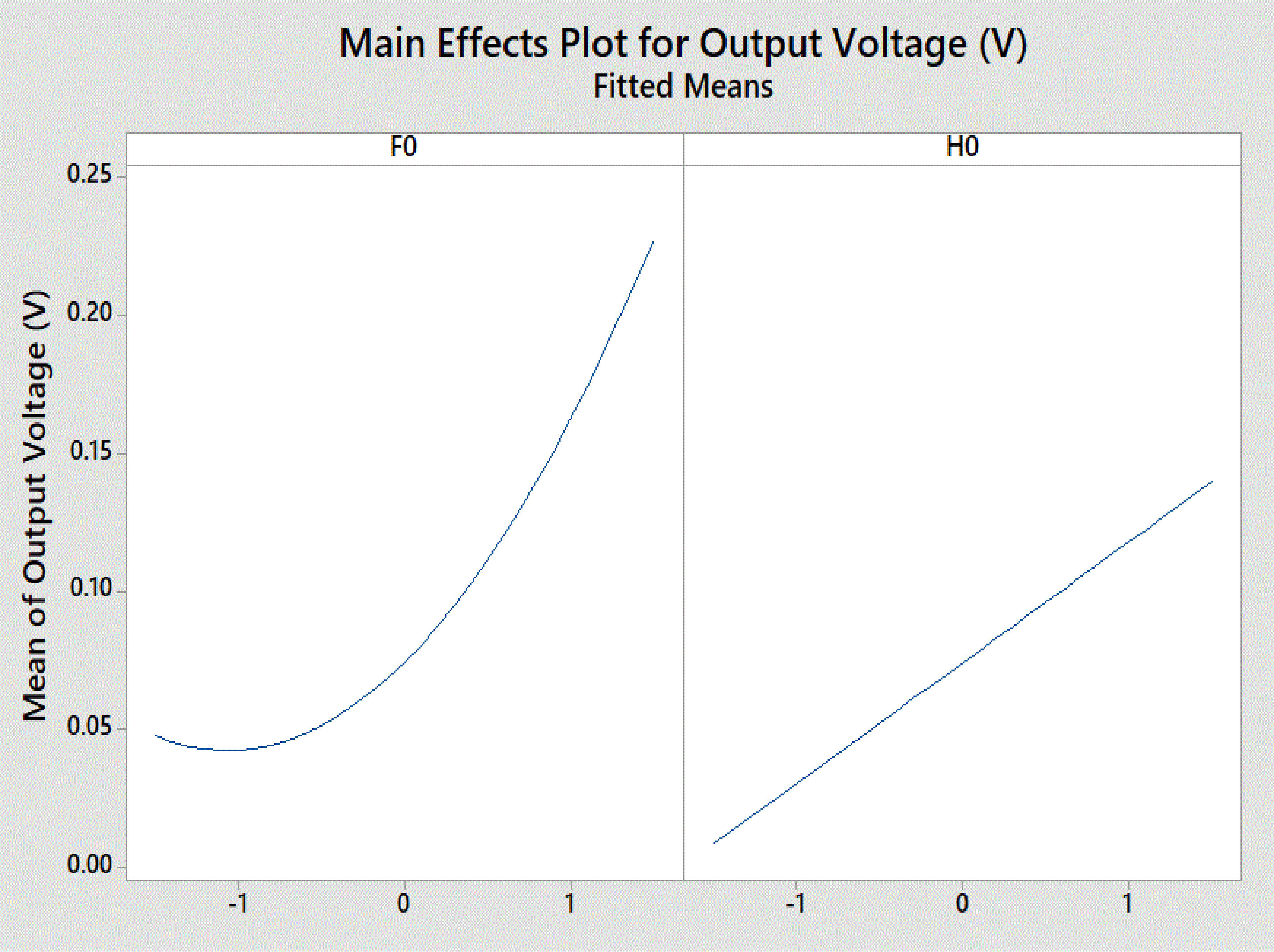
Sensitive analysis: Response Surface Method

Factors	- a	-1	0	1	+ a
F_0	-3940	-3500	-2500	-1500	-1060
H_0	1400	2500	5000	7500	8600

Order	F_0 (N)	H_o (A/m)	V_m (v)
1	-3500	2500	0.023
2	-1500	2500	0.075
3	-3500	7500	0.07
4	-1500	7500	0.225
5	-3940	5000	0.038
6	-1060	5000	0.23
7	-2500	1400	0.0215
8	-2500	8600	0.13
9	-2500	5000	0.075

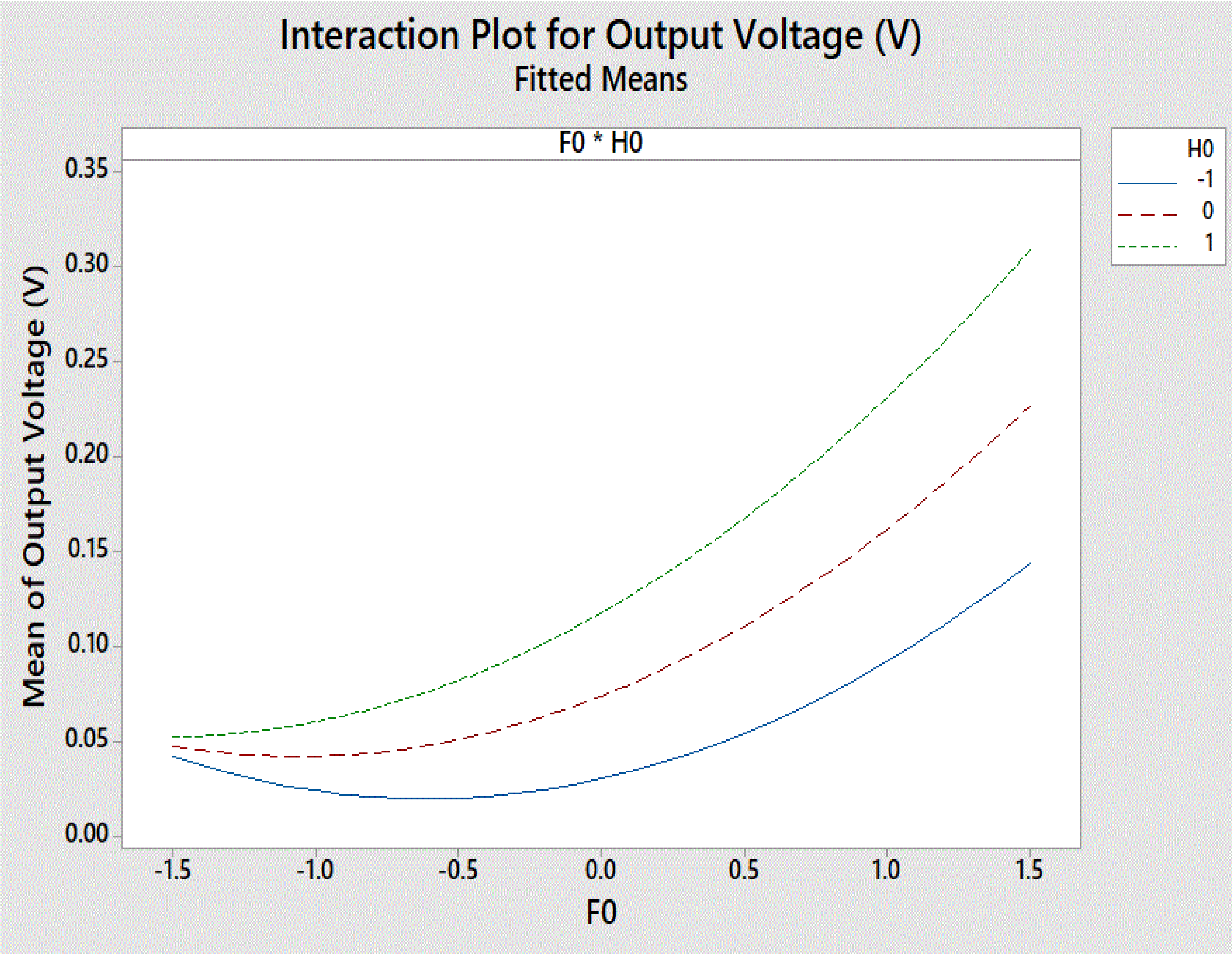
$$V = 0.07411+0.05982\ F_0 + 0.04381\ H_0 + 0.02801\ F_0 \times F_0 + 0.02575\ F_0 \times H_0$$

Sensitive analysis: Main Effects



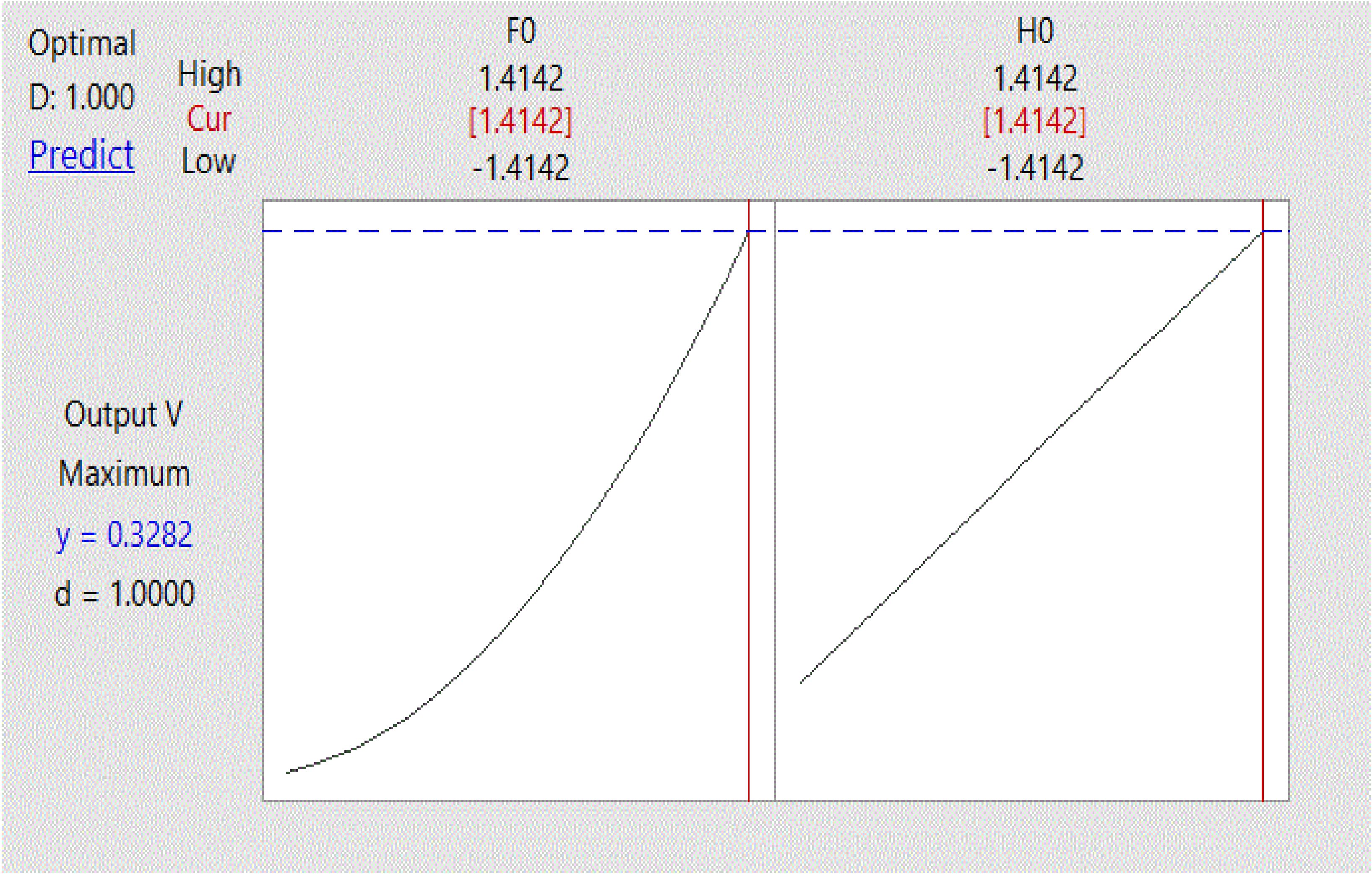
Relationship between Output voltage and main effects, F_0 and H_0

Sensitive analysis: Interactive between Factors



Interaction between F_0 and H_0

Sensitive analysis: Minitab-Optimizser



RSM optimizer to predict the maximum output

Conclusions and Future Plans:

Conclusions:

- A non-linear magneto-mechanical magnetostrictive force sensor was modeled.
- It is found that pre-stress and bias magnetic field are the significant parameter's on sensitivity and nonlinearity of the force sensors.
- Sensor's sensitivity $\propto$ bias magnetic field.
- Sensor's linearity $\propto \frac{1}{\text{bias magnetic field}}$

- Trade-off between sensitivity and non-linearity of sensor

Future Plans:

- Verify the simulation results by experimental results