Design and Experimental Study of Array Eddy Current Sensor for Internal Inspection of Natural Gas Pipeline

Qingxiang Zhou¹, Gangqing Li¹, Kai Hou¹, Feng Cao¹ and Kai Song ²*
¹Crrc Qingdao Sifang Co. Ltd.
²Key Laboratory of Nondestructive Testing, Ministry of Education, Nanchang Hangkong University, Nan-chang, China
*Correspondence: kevin.song@crrcgc.cc

Abstract. Array eddy current detection (ECAT) technology has the advantages of fast scanning speed and high detection efficiency, and has a wide range of application prospects. However, the traditional array eddy current sensor has a poor coupling effect with the inner wall of the pipeline and is not suitable for in-pipe inspection. Based on the basic principles of ECAT, a flexible array eddy current sensor made by flexible printed circuit board (FPCB) technology is designed and developed, which can realize 360° detection of defects on the inner wall of natural gas pipelines. The paper uses ANSYS finite element software to establish a simulation model of multi-parameter effects, study the influence of sensor size parameters and detection parameters on eddy current signals, carry out detection experiments on blind hole defects in the inner wall of steel pipes, analyze the response characteristics of defect signals, and verify the feasibility of using the FPCB array eddy current sensor for internal inspection of natural gas pipeline.

1. Introduction
As a new and economical transportation method, pipeline transportation has the advantages of high efficiency, safety and economy, and less damage to the environment compared with other transportation methods. The natural gas pipeline is an important part of the urban gas pipeline network[1], with a small diameter and a large number, which meets the social energy demand. However, in the course of long-term service, the pipeline will gradually age due to chemical corrosion, erosion, wear and other problems, and defects such as cracks and perforations will appear, and the disasters caused by pipeline leakage will also increase[2,3], so the directional inspection and maintenance of natural gas pipelines is of great significance for preventing pipe-line leakage and preventing major malignant accidents.

For the internal inspection technology of natural gas pipelines, the commonly used methods include ultrasonic inspection, magnetic flux leakage inspection and eddy current inspection. Ultrasonic testing requires couplant, which has a great influence on slag inclusion in the cavity, and the ultrasonic testing of small-diameter pipes has problems such as curved surface coupling compensation and internal surface diffusion, which reduces the accuracy and reliability of the test results.[4] Magnetic flux leakage detection technology is an important method for pipeline detection. Under the impetus of the medium, a magnetic flux leakage detector is used to record data while detecting the pipeline. The magnetic flux leakage equipment is large in size, long in structure, and large in power consumption. Due to the small diameter of the pipe, it is prone to jamming due to the limitation of the internal space. [5]

Eddy current detection technology is widely used in natural gas pipeline detection due to its high detection efficiency, small sensor size, and high reliability of detection results. Duan Chenggong[6] used
the small-diameter pipeline experiment platform to simulate the actual pipeline environment and built a pulsed far-field eddy current detection system to realize the detection and display of defects. Zhang Zhihao, Sun Yinjuan[7] and others combined eddy current and ultrasonic testing technology to develop a pipeline corrosion detection robot to inspect and record the entire pipeline. Xing Lidong et al.[8] used the new far-field eddy current sensor to rotate at different angles along the pipe circumference, which can effectively obtain the pipe circumference crack defect information. Wang Xiaofeng et al.[9] designed four sensor models with different structures based on pulsed far-field eddy current technology, which can detect axial cracks in pipelines. Although the above research has achieved many instructive research results for engineering applications, the conventional eddy current detection technology has a small scanning range and low detection efficiency, and it is easy to cause missed detection. [10]

Eddy Current Array Testing (Eddy Current Array Testing, ECAT) technology has a wide detection range, which can scan a large area of the workpiece surface at one time, and has the same resolution as conventional eddy current point sensors[11], which has a wide range of application prospects. Li Xuechao[12] and others applied array-type pulsed far-field eddy current sensors to achieve quantitative detection of pipeline defects. Han Ning[13] and others designed a rotating magnetic field array sensor that can identify and locate pipeline defects in different orientations. Professor Luo Feilu et al.[14] proposed an oblique-angle array sensor, which can play a very good role in the quantitative measurement of large-area corrosion. Although some exploratory researches with practical application value have been carried out on the sensors designed in the above institutes, the traditional array eddy current sensors are mainly composed of coil-wound or Hall sensors, which have poor coupling effect with the inner wall of the pipeline and low detection accuracy.

In order to complete the 360° omni-directional inspection of the inner wall of the natural gas pipeline and realize the complete coupling with the inner wall of the pipe-line, this paper designs and develops an FPCB array eddy current sensor[15], uses finite element technology to establish a multi-parameter influence three-dimensional simulation model, and optimizes the sensor size parameters. The influence of the detection parameters on the eddy current signal is studied, and the feasibility of the FPCB array sensor for detecting the inner wall defects of the natural gas pipeline is verified.

2. The Principle of Array Eddy Current Testing Technology

As shown in Figure 1, it is assumed that the array eddy current sensor is placed above an infinite flat test piece with ideal defects[16]. The length of the test piece is \( l \), the width is \( w \), and the thickness is \( d \). The entire spatial field is set as a linear medium, and the sensor is composed of several close-turned coils of exactly the same size and material. The inner and outer diameters are \( r_1 \) and \( r_2 \), and the height is \( h \). The current \( i(t) \) in the coil is harmonic with time \( t \) Change, the total number of turns of the coil unit is \( W \), and the number of turns density can be obtained by formula (1).

\[
\eta_c = \frac{W}{h(r_2 - r_1)} \quad (1)
\]

The space occupied by the winding area of the coil unit is \( V_c \), which can be seen from the following formula:

\[
E = \frac{\partial A}{\partial t} - \nabla \phi \quad (2)
\]

In the formula: \( A \) is the magnetic vector potential, and \( \phi \) is the scalar potential. By transforming the formula (2), we can get:

\[
E = -\frac{\partial}{\partial t} \left( A + \int_{-\infty}^{t} \nabla \phi(t') dt' \right) \quad (3)
\]

Let \( A' \) be:

\[
A' = A + \int_{-\infty}^{t} \nabla \phi(t') dt' \quad (4)
\]
Then the electric field intensity $E$ and the magnetic induction intensity $B$ are as follows:

$$E = -\frac{\partial A^*}{\partial t}$$  \hspace{1cm} (5)

$$B = \nabla \times A = \nabla \times \left( A^* - \int_{-\infty}^{t} \nabla \varphi(t') dt' \right) = \nabla \times A^*$$  \hspace{1cm} (6)

According to formula (6), the flux linkage of the n-th turn of the wire of the coil unit is:

$$\psi_n(t) = \int_{S_n} B \cdot dS = \int_{S_n} \left[ \nabla \times A^* \right] \cdot dS = \int_{l_n} A^* \cdot dl$$  \hspace{1cm} (7)

In the formula: $S_n$ is the curved surface enclosed by the nth turn of the coil unit, and $l_n$ is the circumference enclosed by the nth turn of the coil unit.

From formula (7), the total flux $\psi(t)$ of the turns of the coil unit can be obtained as:

$$\psi(t) = \frac{1}{i(t)} \sum_{n=1}^{N} \psi_n(t) i_n(t) = \frac{1}{i(t)} \sum_{n=1}^{N} \int_{l_n} A^* \cdot dl$$  \hspace{1cm} (8)

In the formula: $i(t)$ is the total current in the coil, $i_n(t)$ is the current in the nth turn of the coil, so $i(t) = i_n(t)$. According to the previous assumptions, the following two substitutions are established:

$$\sum_{m=1}^{M} \phi_m \Rightarrow \int_{V_c}$$  \hspace{1cm} (9)

$$i_n(t) dl \Rightarrow J_e(t) dV$$  \hspace{1cm} (10)

Among them, $J_e$ is the current density in the coil unit, so that formula (8) can be rewritten as:

$$\psi(t) = \frac{1}{i(t)} \int_{V_c} A \cdot J_e dV$$  \hspace{1cm} (11)

Also, the current density at any point $Q$ on the coil unit is as follows:

$$J_e(t) = n_c(Q) i(t) e(Q)$$  \hspace{1cm} (12)

Combining equations (11) and (12), the total flux linkage of the turns of the coil unit can be calculated as follows:

$$\psi(t) = \frac{1}{i(t)} \int_{V_c} n_c(Q) A^*(Q) \cdot e(Q) dV(Q)$$  \hspace{1cm} (13)

In the formula: $e(Q)$ is the unit vector in the direction of the current at the point $Q \in V_c, |e| = 1$.

According to the total flux linkage $\psi(t)$ of the turns of the coil unit in equation (13) and Faraday's law of electromagnetic induction, the induced voltage of the coil unit can be calculated as follows:

$$u(t) = \frac{d\psi(t)}{dt} = \int_{V_c} n_c(Q) \frac{\partial A^*}{\partial t} \cdot e(Q) dV(Q)$$  \hspace{1cm} (14)
3. Design of FPCB Array Eddy Current Sensor

3.1. Model building
Using ANSYS finite element software to establish a three-dimensional simulation model, as shown in Figure 2. The whole model mainly includes two parts: natural gas pipeline and FPCB array eddy current sensor. In order to enhance the sensitivity of the sensor to defects in the inner wall of the pipeline, the sensor is connected in the form of a bridge, it is composed of a double-layer multi-channel FPCB board, and the coil is a plane spiral structure, which can be approximately composed of several concentric current loops of different diameters, as shown in Figure 3. The sensor is time-sharing switching in time sequence, that is, there is only one channel for detection at a certain time. In order to facilitate experimental research, a single-channel simplified model is adopted. Considering that the inner wall of the natural gas pipeline is a plane relative to the FPCB array eddy current sensor, Use steel plates instead of pipes for testing.

![Figure 2. 3D simulation model diagram](image)

![Figure 3. Multi-turn concentric current loop](image)

In the model, the length L of the steel plate is 150mm, the width W is 100mm, the thickness D is 6mm, and the electrical conductivity σ is 36Ms/m. The initial inner diameter r1 of the coil is 8.5mil, the number of turns n is 60 turns, the excitation frequency f is 700kHz, the lift-off height lift is 4mm, and the coil conductivity ρ is 58.8 Ms/m. The overall simulation model parameters are shown in Table 1.

| Steel plate parameters | Numerical value | Coil parameters | Numerical value |
|------------------------|-----------------|----------------|----------------|
| L/mm                   | 150             | r1/mil         | 8.5            |
| W/mm                   | 100             | n              | 60             |
| D/mm                   | 6               | ρ(Ms/m)        | 58.8           |
| σ(Ms/m)                | 36              | lift /mm       | 4              |
Considering the open domain of the electromagnetic field, it is necessary to establish a large enough near-field air area and far-field air area around the model to eliminate the truncation effect. In order to ensure the quality of the grid and improve the calculation accuracy and efficiency, the coils and steel plates with regular shapes are meshed by the mapping division method, and the near and far-field air areas are meshed by the free division method. The model after the mesh is divided as shown in Figure 4.

![Model meshing](image)

**Figure 4. Model meshing**

### 3.2. Parameter optimization

#### 3.2.1. Coil diameter optimization

The wire diameter size directly affects the amount of current passing through the coil, and the wire diameter needs to be optimized first. Set the wire diameters to 3mil, 4mil, 5mil and 6mil respectively, the turn pitch is 4mil, and a blind hole with a diameter of 10mm and a depth of 2mm is set at the center of the steel plate. Under the action of a sinusoidal excitation signal of 5V, 600kHz, the sensor selects the optimal wire diameter by the induced electromotive force when the sensor passes through the blind hole of the steel plate. The test results are shown in the figure below.

![Test results under different wire diameter conditions](image)

**Figure 5. Test results under different wire diameter conditions**

From the analysis of Figure 5, it can be seen that the change trend of the sensor induced electromotive force amplitude characteristic curve under different wire diameter conditions is the same. The detection signal increases as the coil approaches the blind hole, and decreases as the coil moves away from the blind hole, reaching a peak value near ±3mm from the center of the blind hole. When the wire diameter is 4mil, the sensor induced electromotive force peak value reaches $5 \times 10^{-4}$V, compared with 4mil, when the wire diameter is 3mil, 5mil, and 6mil, the induced electromotive force is $4.16 \times 10^{-4}$V, $4.64 \times 10^{-4}$V, $4.03 \times 10^{-4}$V, attenuated by 21.8%, 9.27% and 25.8% respectively. In order to improve the detection sensitivity of the FPCB array eddy current sensor, the wire diameter should be 4mil.
3.2.2. Coil pitch optimization
Under the wire diameter is 4mil and other parameters remain unchanged, a simulation study is carried out on the turn pitch between the coils. The turn pitch is increased from 3 mil to 6 mil in steps of 1 mil and compare the magnitude of the electromotive force induced by the sensor under different turn pitch conditions. The test results are shown in the figure below.

![Figure 6. Test results under different turns](image)

It can be seen from Figure 6 that the sensor has a minimum value at the center of the blind hole, and has good symmetry relative to the remaining scanning positions on both sides of the blind hole center. This is because the coil is an axisymmetric structure. The eddy current field is disturbed twice, so the detection signal has double peaks. When the turn pitch is increased from 3mil to 6mil, the peak values of the induced electromotive force are 4.43×10⁻⁴V, 5.7831×10⁻⁴V, 6.13×10⁻⁴V and 6.48×10⁻⁴V respectively. Considering that the coil is too large and the sensor volume is too large, which brings difficulties to the subsequent FPC board production. When the turn pitch is 4mil, compared with the 6mil turn pitch, the induced electromotive force is only reduced by 5.4%, and the amount of change between the two is almost equal, and can detect defects effectively. Therefore, in the case of ensuring the sensitivity of the sensor, the turn pitch is selected to be 4mil for the next step of research.

3.2.3. Coil spacing optimization
The distance between the upper and lower coils of a single channel of the FPCB array eddy current sensor affects the magnitude of the differential voltage signal. In order to study the effect of the coil distance on the detection sensitivity, under the condition of the other parameters unchanged, the simulation and analysis of the sensor’s impact on the blind hole under different coil distances The detection sensitivity is shown in Figure 7.

![Figure 7. Test results under different center distance conditions](image)
Analysis of Figure 7 shows that when the coil spacing increases from 2mm to 5mm, the peak values of the induced electromotive force are 4.596×10^{-4}V, 4.951×10^{-4}V, 5.08×10^{-4}V and 0.55×10^{-4}V in sequence. Compared with the coil pitch of 2mm, when the coil pitch is 3mm, 4mm, and 5mm, the peak change amount increases respectively by 0.35×10^{-4}V, 0.49×10^{-4}V and 0.55×10^{-4}V, and in the process of increasing the coil spacing from 3mm to 5mm, the increase in the change amount slows down, that is, as the coil spacing increases, the detection sensitivity of the sensor becomes higher. This is because within a certain range, the farther the two coils are, the greater the differential signal output by the sensor. Therefore, on the premise of ensuring the miniaturization of the sensor, the coil spacing should be increased as much as possible.

3.2.4. The influence of eccentricity on detection signal
Due to the existence of the coil spacing, the curvature of the upper and lower layers of the FPC board is inconsistent, so the centers of the upper and lower coils of each channel cannot be completely overlapped, and there is a certain eccentricity. In order to study the influence of the eccentricity on the detection signal, the offset between the upper and lower coils in a single channel was changed to detect the blind hole shown above. Set the eccentricity to 0.5mm, 0.8mm, 1mm and 1.5mm respectively, and the test results are shown in Figure 8. It can be seen from the figure that when the eccentricity is increased from 0.5mm to 1.5mm, the detection results are almost the same. This is because when the current is constant and the eccentricity changes little, the induced voltage of the two coils in the sensor is almost the same.

Figure 8. Effect of eccentricity on detection signal

3.2.5. The influence of excitation frequency on detection signal
Since the frequency of the excitation signal affects the sensitivity of the sensor, it is necessary to conduct a simulation study on the excitation frequency. Based on the established sensor simulation model, the excitation signal frequency range is set to 200kHz to 800kHz, and the simulation is performed every 200kHz step, and the maximum voltage when the sensor passes through the blind hole of the steel plate is extracted. The detection result is shown in Figure 9.

Figure 9. Effect of excitation frequency on the detection signal
It can be seen from Figure 9 that as the excitation frequency increases, the sensor's induced electromotive force amplitude increases linearly. When the excitation frequency is 800kHz, the induced electromotive force is 0.55mV, which is an increase of 175% compared to the excitation frequency of 200kHz. This is because the higher the excitation frequency, the greater the eddy current density on the surface of the steel plate, and the higher the detection sensitivity of the sensor. However, due to the influence of the skin effect, according to $\delta = \frac{1}{\sqrt{\pi f \mu \sigma}}$, the higher the excitation frequency, the lower the depth of eddy current penetration of the steel plate. The eddy current distribution cloud diagram of blind hole defects of steel plate under different excitation frequencies is shown in the figure below.

![Eddy current cloud image of steel plate section under different excitation frequencies](image)

Figure 10. Eddy current cloud image of steel plate section under different excitation frequencies: (a) Cloud diagram of eddy current cross section of steel plate at f=200kHz; (b) Cloud diagram of eddy current cross section of steel plate at f=400kHz; (c) Cloud diagram of eddy current cross section of steel plate at f=600kHz; (d) Cloud diagram of eddy current cross section of steel plate at f=800kHz.

It can be seen from Fig. 10 that the intensity of the magnetic field in the steel plate gradually decays as the penetration depth increases. When the excitation frequency is 800kHz, compared with the excitation frequency of 200kHz, the induced eddy current is mainly concentrated near the metal surface, at this time the magnetic field intensity is the strongest on the surface of the steel plate. Therefore, the detection depth and surface sensitivity of the eddy current sensor are contradictory, and it is difficult to achieve both. The optimal excitation frequency must be selected according to actual needs.

4. Experimental Research

4.1. Test verification
In order to detect defects on the inner wall of the natural gas pipeline, verify the detection effect of the optimized FPCB array eddy current sensor, and make the sensor according to the simulation optimization parameters. The physical map of the single-layer 16-channel FPCB array eddy current
sensor is shown in Figure 11. Set up the corresponding eddy current inspection system to inspect the steel pipe. The block diagram of the eddy current inspection system is shown in Figure 12.

![Single layer 16-channel FPCB array eddy current sensor physical map](image1)

Figure 11. Single layer 16-channel FPCB array eddy current sensor physical map

![Block diagram of eddy current testing system](image2)

Figure 12. Block diagram of eddy current testing system

The eddy current detection system is mainly composed of signal generator, power amplifier, time division multiplexing module, FPCB array eddy current sensor, signal conditioning module, A/D signal acquisition card and signal analysis software system. After the signal generator is energized, the excitation signal is generated, which is loaded on the coil of the sensor after passing through the power amplifier. The detection coil receives the induced signal, passes through the pre-amplification module and the effective value detection module, and sends it to the A/D data acquisition card, which is processed and analyzed by the computer software.

4.2. Test results and analysis

Use this eddy current inspection system to inspect a 45# steel pipe with a size (length×outer diameter×wall thickness): 400×90×5mm, and process three blind holes with a diameter of 10mm and a depth of 1mm, 2mm, and 3mm are machined on the inner wall of the steel pipe. Set the excitation sinusoidal signal voltage to 5V and frequency to 600kHz, use a single detection channel in the FPCB array eddy current sensor to detect the blind hole, and extract the amplitude of the induced voltage through the effective value detection module. The detection signal change is shown in Figure 13. It can
be seen from the figure that when detecting blind holes of different depths, the induced voltages all exhibit double peaks. When the sensor moves to ±3mm from the center of the blind hole, the induced voltage has a maximum value, which is consistent with the simulation result. Comparing with the blind hole depth of 1mm, the maximum induced voltage increases by 132.42mV and 414.43mV when the depth is 2mm and 3mm, indicating that as the depth of the blind hole increases, the detection signal amplitude increases, which verifies the use of the FPCB array The feasibility of eddy current sensor for steel pipe defect detection.

![Figure 13. Time-varying characteristic curve of detection signal](image)

5. Results
(1) A new type of array eddy current sensor made by FPCB technology is proposed, and the finite element software is used to analyze the influence of the sensor's size parameters and detection parameters on the detection performance of the sensor. On the premise of keeping the sensor miniaturization, the optimal parameters of wire diameter and turn pitch are both 4mil, and the sensitivity of the sensor can be improved by appropriately increasing the coil spacing;

(2) For a single channel, the eccentricity of the upper and lower coils inside the sensor varies within the range of 0.5mm-1.5mm, that is, when the eccentricity is small, it will not affect the detection sensitivity;

(3) The higher the excitation frequency, the higher the sensor sensitivity, and the smaller the depth of eddy current penetration of the steel plate. Therefore, the detection depth and sensitivity of the eddy current sensor are contradictory, and the highest possible excitation frequency must be selected according to actual needs;

(4) In actual testing, the FPCB array eddy current sensor can effectively detect blind hole defects with a diameter of 10mm and a depth of 1mm, 2mm, and 3mm respectively. The deeper the defect depth, the greater the detection signal, which verifies the use of the FPCB array eddy current sensor for the feasibility of inner wall defect detection of steel pipes.

Author Contributions:
Q.Z. designed the sensor; G.L. did the simulation experiment; K.H. established the eddy current detection system; F.C. analyzed the simulation results and reached a conclusion; K.S. organized the experimental data and test results. All authors have read and agreed to the published version of the manuscript.

Funding:
This research was financially supported by the National Natural Science Foundation of China (Grant No.51865033), the Foundation of Key Laboratory of nondestructive testing technology of Ministry of Education (Grant No.EW201908438).

Institutional Review Board Statement:
Not applicable.
Informed Consent Statement:
Not applicable.

Data Availability Statement:
Not applicable.

Acknowledgments:
The authors would like to thank Professor Song Kai of Nanchang Hangkong University for valuable guidances.

Conflicts of Interest:
The authors declare no conflict of interest.

References
[1] Wang Chongxun. Research and Design of Small Diameter Polyethylene Gas Pipeline Inspection Robot[D]. Beijing Jiaotong University, 2019.
[2] Yang Lijian, Geng Hao, Gao Songwei. Magnetic leakage internal detection technology for long-distance oil and gas pipelines [J]. Journal of Instrumentation, 2016, 37(08): 1736-174.
[3] Dengi Zhou, Qinbo Yao, Hang Wu, Shixi Ma, Huisheng Zhang. Fault diagnosis of gas turbine based on partly interpretable convolutional neural networks [J]. Energy, 2020.
[4] Wei Tongfeng. Correction coefficient of coupling surface for ultrasonic testing of small-caliber pipeline [J]. Oil and gas storage and transportation, 2014, 33(06): 629-631+652.
[5] Yu Jiangtao. Simulation and experimental verification of small-diameter pipelines based on pulse eddy current technology [D]. Beijing Jiaotong University, 2018.
[6] Duan Chenggong, Gao Songwei. Pulsed far-field eddy current detection system for small-caliber pipelines [J]. Electronic product reliability and environmental testing, 2013, 31(05): 53-57.
[7] Zhang Zhihao, Sun Yijun, Yang Hao, Wang Qianzhong, Sun Fangping, Luo Huijuan. Research and Application of Inner Inspection Robot for Small Caliber Pipeline in Changqing Oilfield [J]. Petroleum and Natural Gas Chemical Industry, 2020, 49(01): 93-97.
[8] Xing Lidong, Yu Shenglin, Qu Minxin. Design and experimental study of 3D far-field eddy current sensor [J]. Journal of Instrumentation, 2006, 27(11).
[9] Jing Yifei, Wang Xiaofeng, Yang Binmin, Zhang Hui, Kang Zhibin, Li Shuifang. Design and simulation analysis of pulse far-field eddy current probe for pipeline axial crack detection [J]. Journal of Air Force Engineering University (Natural Science Edition), 2011, 12(06): 74-78.
[10] Liu Bo, Luo Feiulou, Hou Lianjie. Research on the crack feature extraction method of eddy current array detection [J]. Journal of Instrumentation, 2011, 32(03): 654-659.
[11] Song Kai, Liu Tangxian, Li Laipeng, et al. Array Eddy Current Test Simulation of Aeroengine Turbine Blade Cracks [J]. Journal of Aeronautics, 2014, 35(08): 2355-2363.
[12] Li Xuechao, Feng Enxin, Feng Fei. Array-type pulse far-field eddy current pipeline defect detection method [J]. Metrology Technology, 2008, 09(09): 6-11.
[13] Han Ning, Zhang Zhijie, Yin Wuliang. Design of rotating magnetic field array sensor and simulation study of pipeline defects [J]. Instrument Technology and Sensors, 2019 (12): 17-22.
[14] Yang Binmin, Luo Feiulou, Cao Xiaohong, Xu Xiaojie. Application research of pulsed eddy current corrosion imaging array probe [J]. Journal of Sensing Technology, 2005 (01): 112-115.
[15] Olivera, J.; Aparicio, S.; Hernández, M.G.; Zhukov, A.; Varga, R.; Campusano, M.; Echavarria, E.; Anaya Velayos, J.J. Microwire-Based Sensor Array for Measuring Wheel Loads of Vehicles. Sensors 2019, 19, 4658.
[16] Apicella, V.; Clemente, C.S.; Davino, D.; Leone, D.; Visone, C. Review of Modeling and Control of Magnetostrictive Actuators. Actuators 2019, 8, 45.