SAND2007-6020C

Effective Use of Miniature, Multi-point, Field-Based Current Sensors Without Magnetic Cores

September, 25 2007

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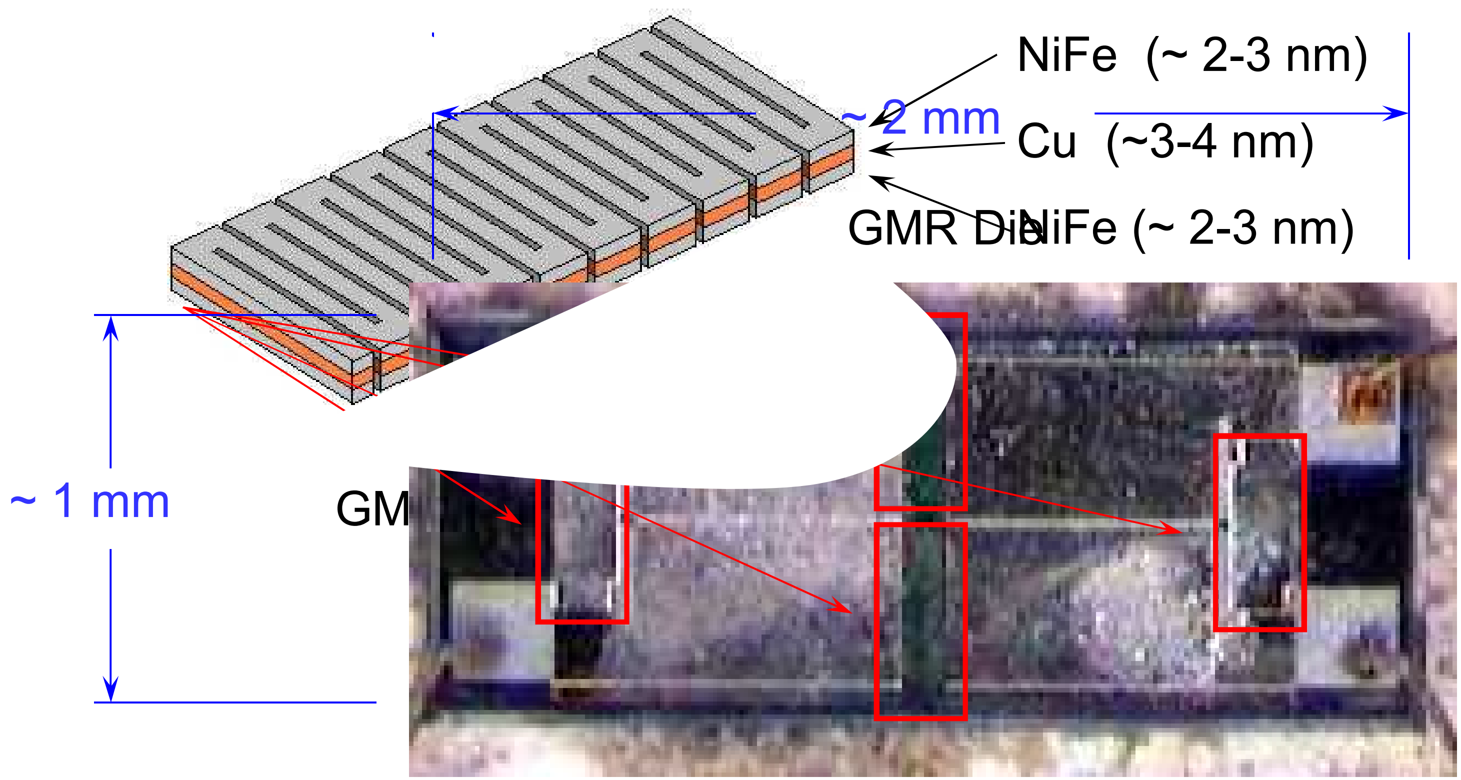
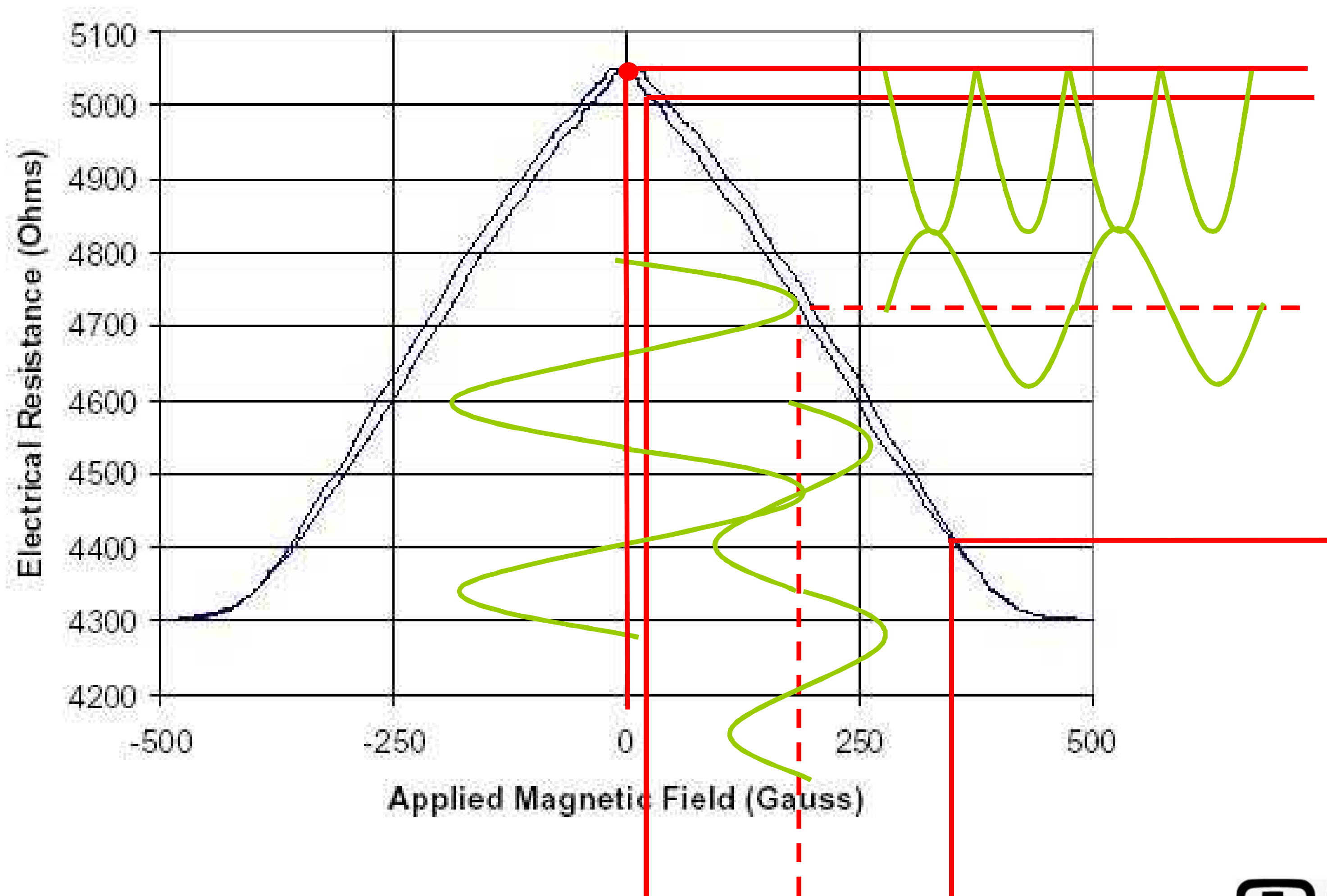
Outline

- GMR Field Detecors
- Field Decoupling (weighted summing)
- Disturbance Field Decoupling
  - 1 Dimensional DFD
  - 2 Dimensional DFD
- Decoupling Bias magnet Temperature Dependence
- Conclusions

GMR → Giant MagnetoResistance



Unipolar Field Response of GMR



Biasing Field

Linear Region

Field Decoupling

$$\begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \\ I_5 \\ I_6 \\ I_7 \end{bmatrix} = \begin{bmatrix} B_{11} & B_{12} & B_{13} & B_{14} & B_{15} & B_{16} & B_{17} \\ B_{21} & B_{22} & B_{23} & B_{24} & B_{25} & B_{26} & B_{27} \\ B_{31} & B_{32} & B_{33} & B_{34} & B_{35} & B_{36} & B_{37} \\ B_{41} & B_{42} & B_{43} & B_{44} & B_{45} & B_{46} & B_{47} \\ B_{51} & B_{52} & B_{53} & B_{54} & B_{55} & B_{56} & B_{57} \\ B_{61} & B_{62} & B_{63} & B_{64} & B_{65} & B_{66} & B_{67} \\ B_{71} & B_{72} & B_{73} & B_{74} & B_{75} & B_{76} & B_{77} \end{bmatrix} \begin{bmatrix} F_1 \\ F_2 \\ F_3 \\ F_4 \\ F_5 \\ F_6 \\ F_7 \end{bmatrix}$$

$$AI_n = F_n^{-1}$$

Weighted Summing

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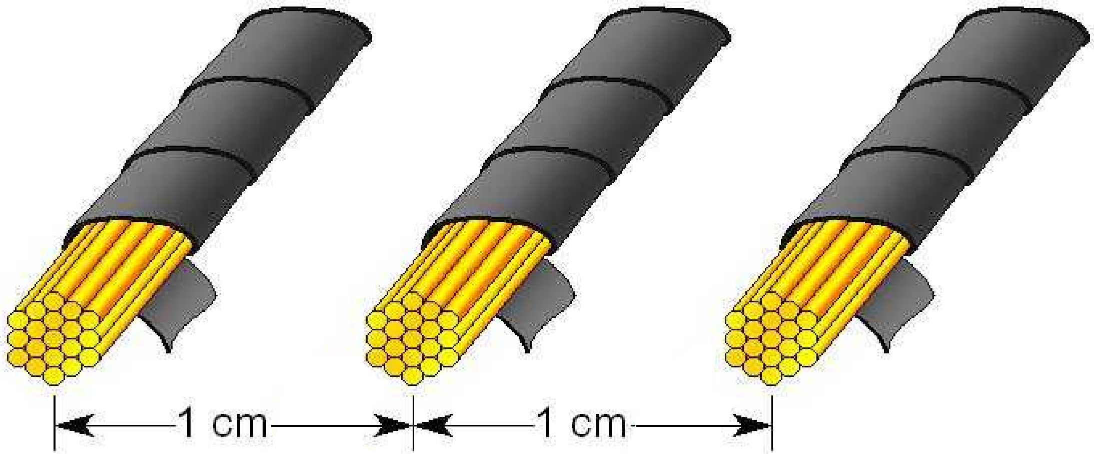
Weighted Summing Experiment

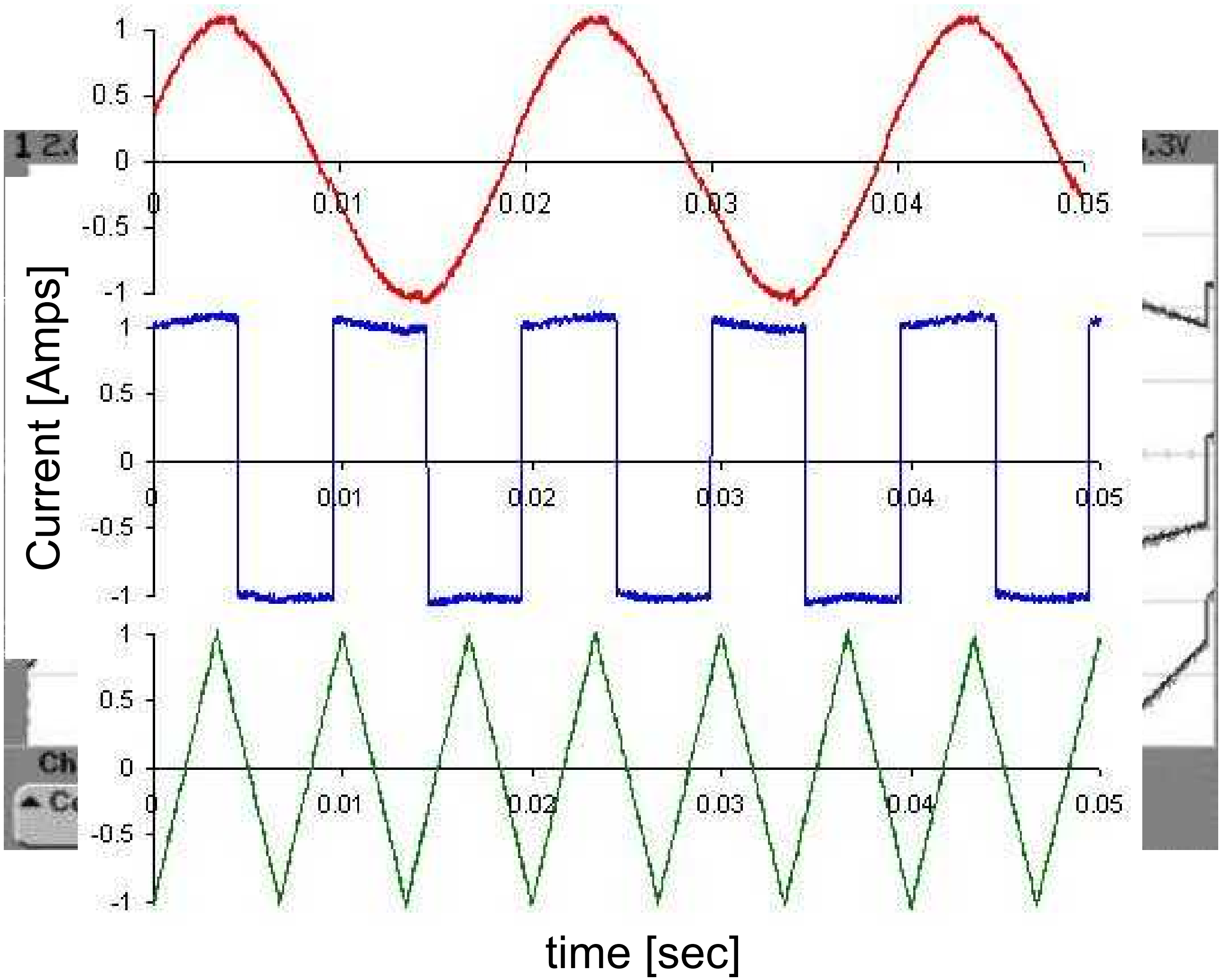


50 Hz 100 Hz 150 Hz

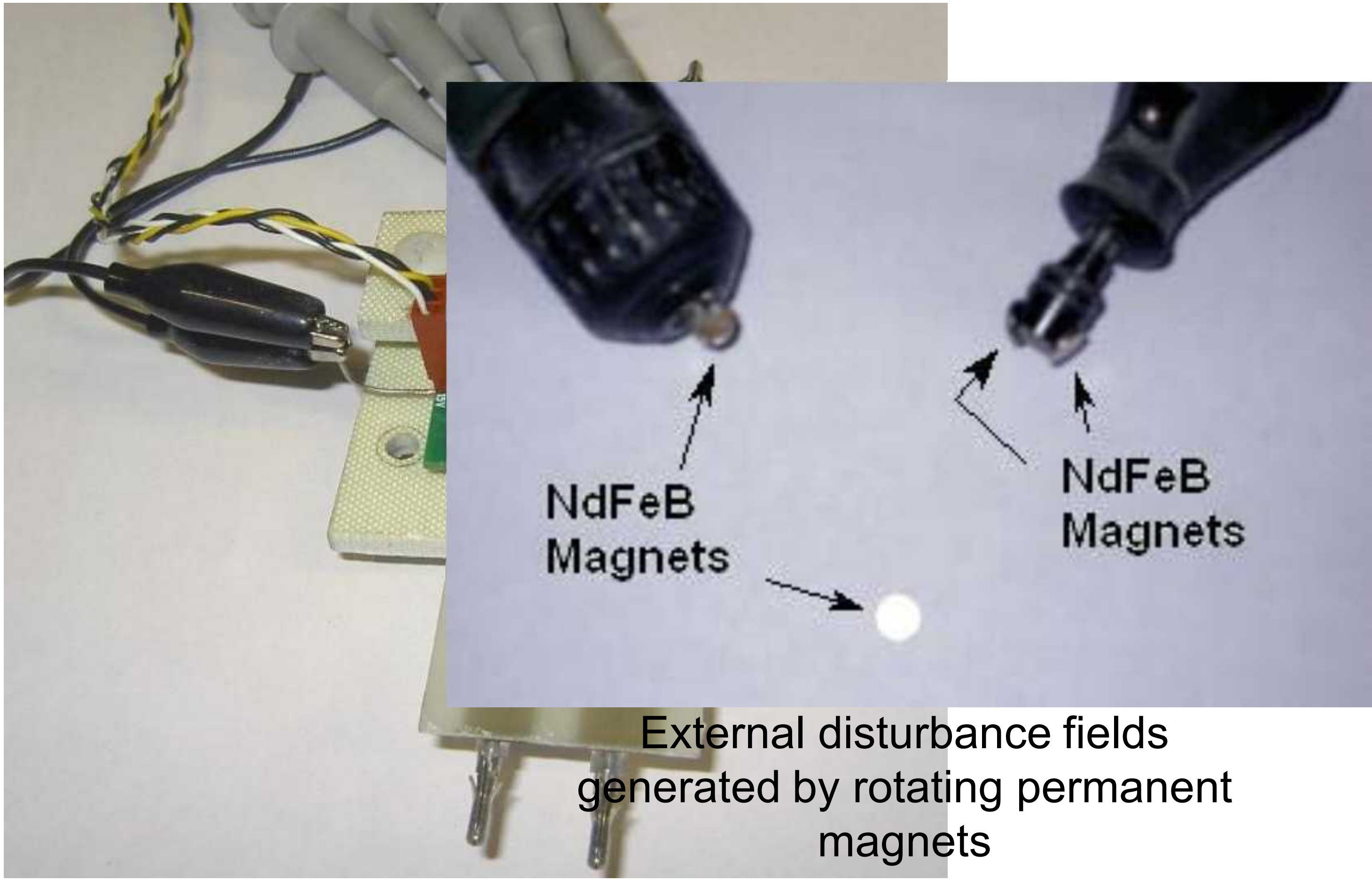
Weighted Summing Waveforms

Decoupled current signals

Cross-coupled field signals

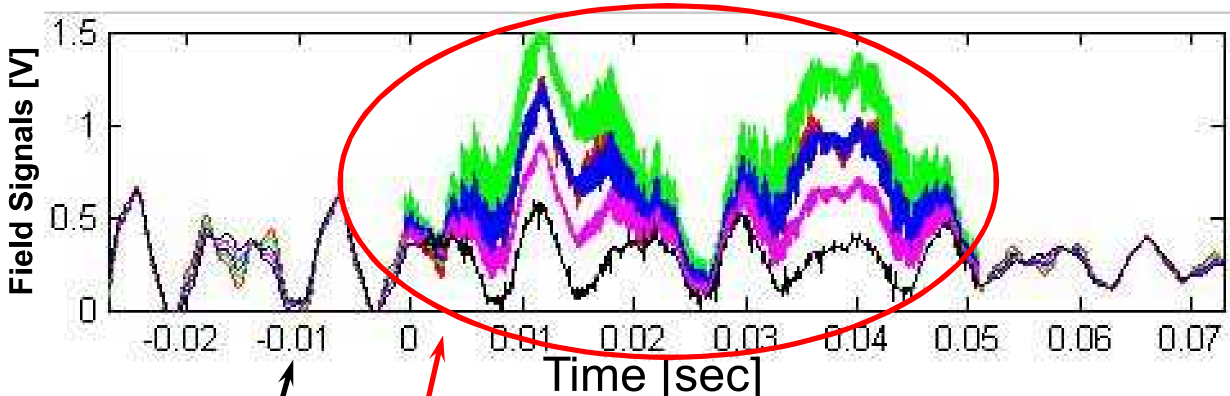


Disturbance Field Decoupling (DFD) Experiment



External disturbance fields generated by rotating permanent magnets

Field Decoupling Without DFD

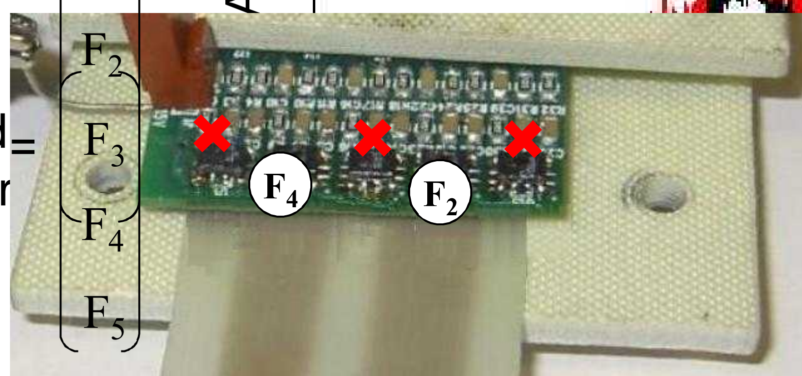


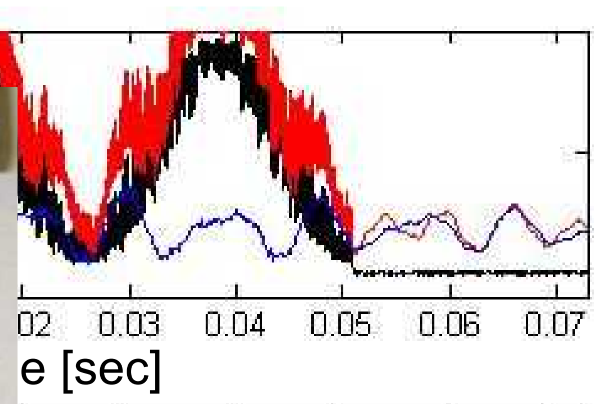
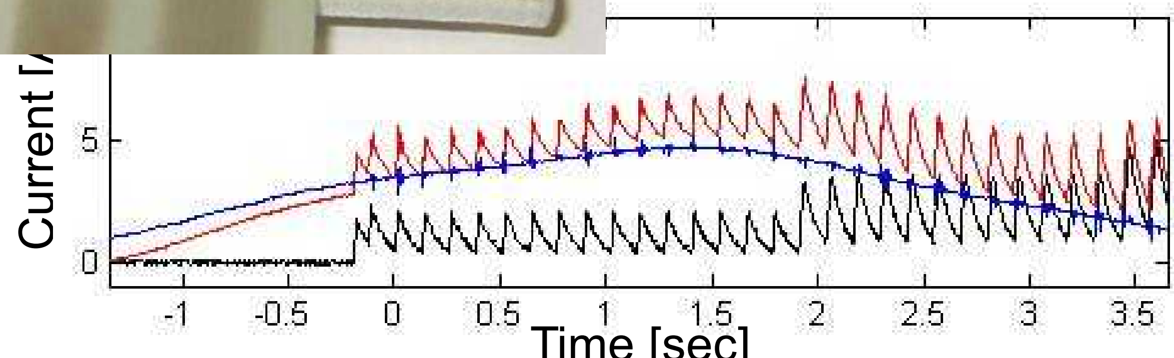
$$\begin{bmatrix} 0.0710 & 0.0193 \\ 0.108 & 0.0327 \\ 0.0718 & 0.0636 \\ 0.0385 & 0.102 \\ 0.00218 & 0.0500 \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix} = \begin{bmatrix} F_1 \\ F_2 \\ F_3 \\ F_4 \\ F_5 \end{bmatrix}$$

Cross-Coupling

Sinusoid PWM Curr

Disturbance field generated by rotating magnets



Zero Order DFD

Cross-

$$\begin{pmatrix} F_2 \\ F_3 \\ F_4 \end{pmatrix}$$

I_1 (Actual)

I_2 (Actual) = 0 (not shown)

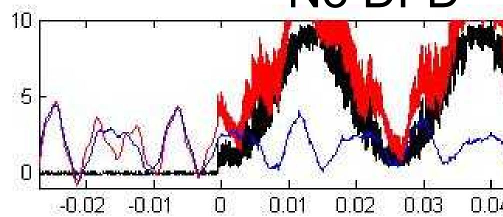
I_1 Decoupled

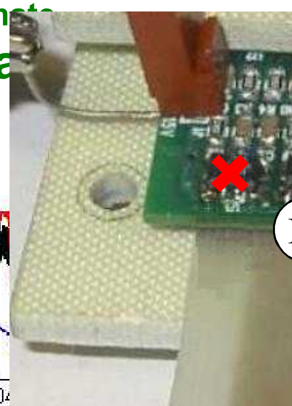
I_2 Decoupled

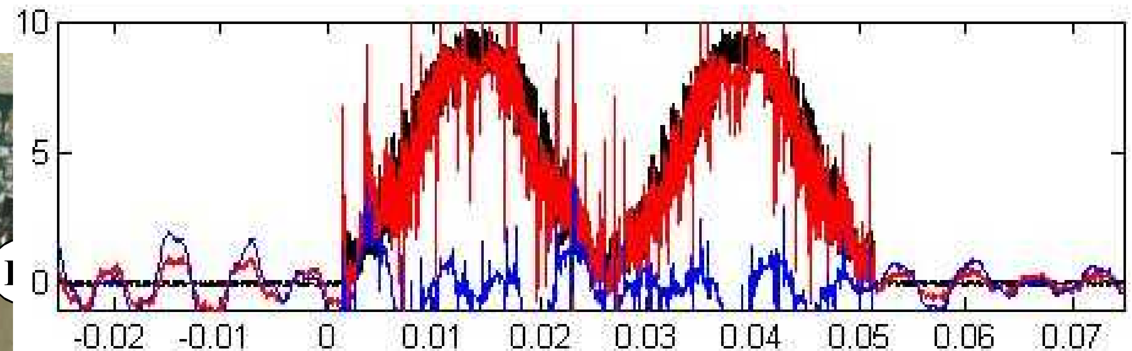
Polynomial Disturbance Field Estimate

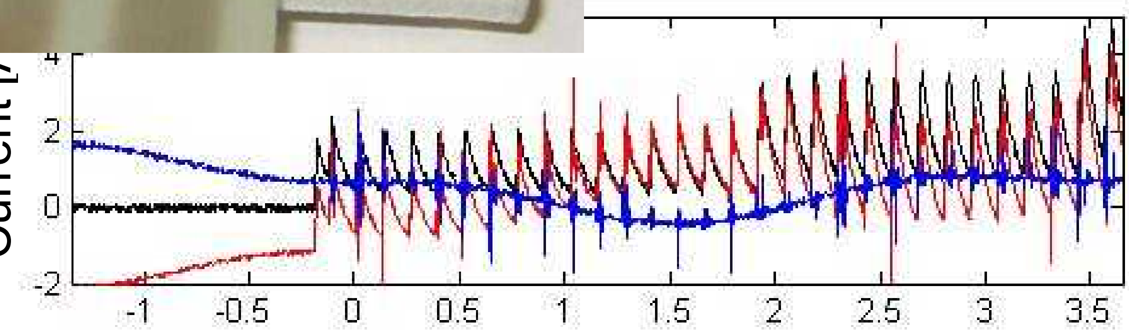
$f_d(x) = a$

No DFD









1^{st} Order DFD

$$\begin{pmatrix} F_1 \\ F_2 \\ F_4 \\ F_5 \end{pmatrix}$$

Δ = 7.5 mm

(Detector Spacing)

I_1 (Actual)

I_2 (Actual) = 0 (not shown)

I_1 Decoupled

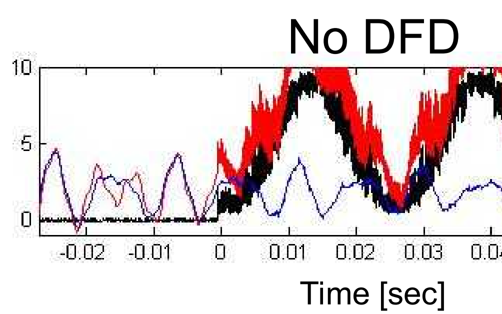
I_2 Decoupled

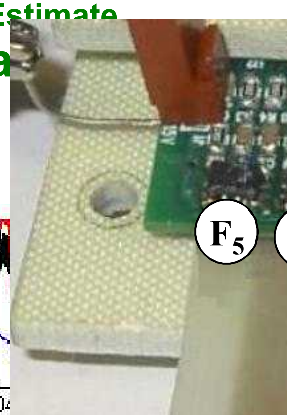
Coupling

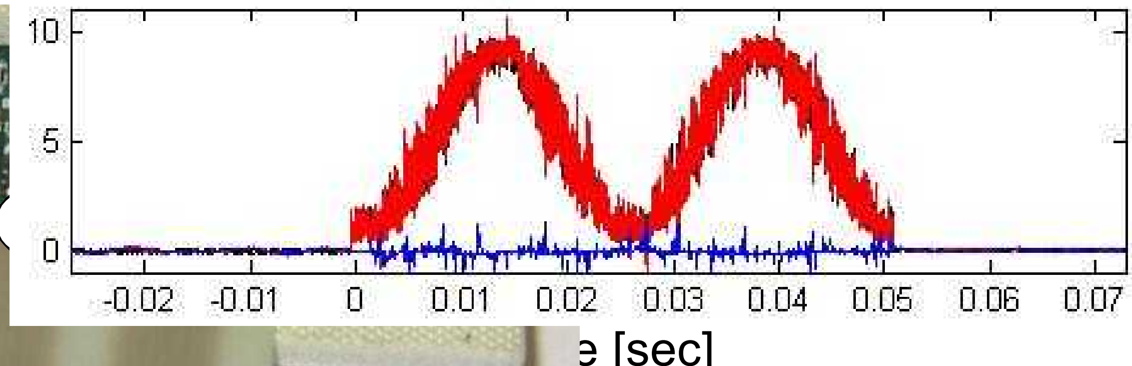
...e

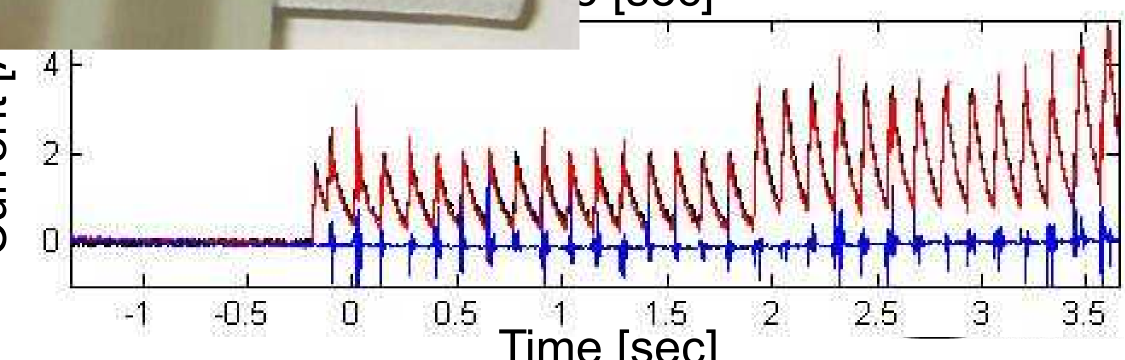
Field Estimate

$f_d(x) = a$









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2^{nd} Order DFD

$$\begin{pmatrix} F_1 \\ F_2 \\ F_3 \\ F_4 \\ F_5 \end{pmatrix}$$

Δ = 7.5 mm

(Detector Spacing)

— I_1 (Actual)

I_2 (Actual) = 0 (not shown)

— I_1 Decoupled

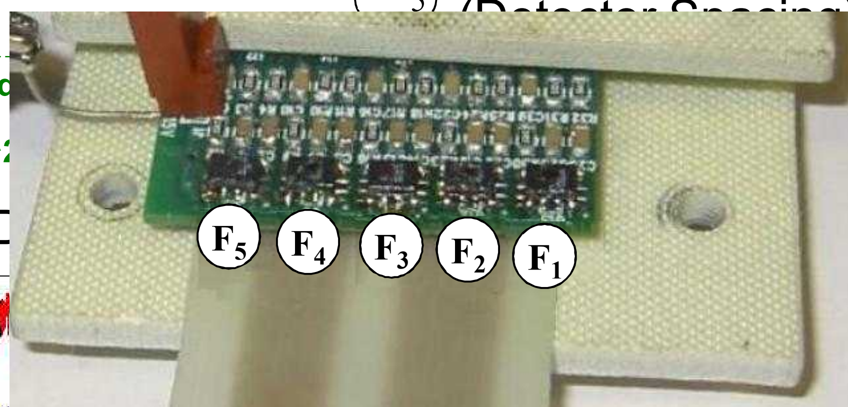
— I_2 Decoupled

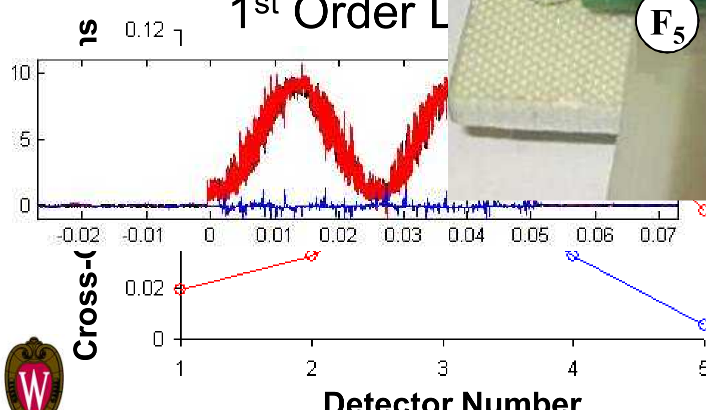
Coupling

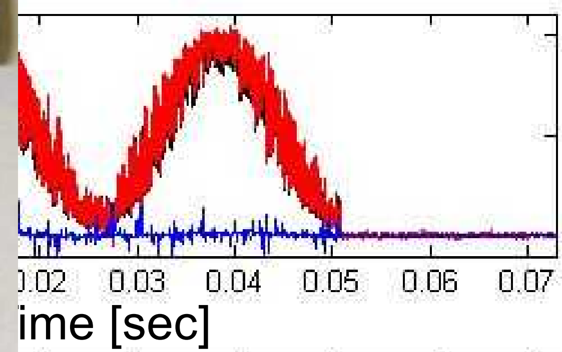
Field

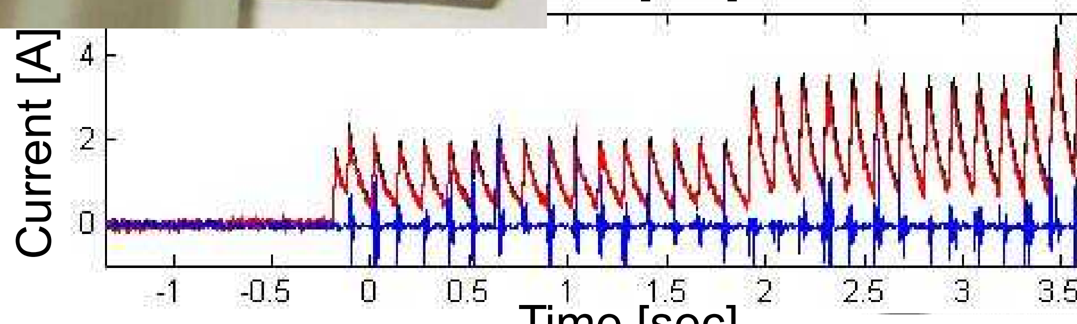
$f_d(x) = a$

1^{st} Order D









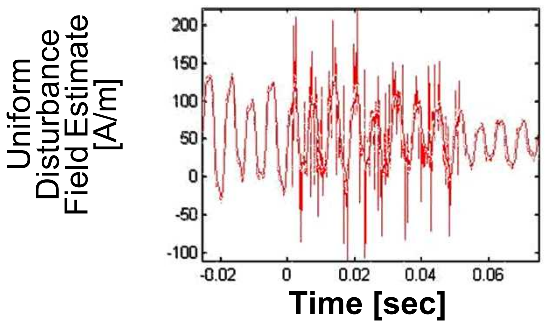
Polynomial Constants

$$f_d(x) = a_2x^2 + a_1x + a_0$$ ← **One-Dimensional**

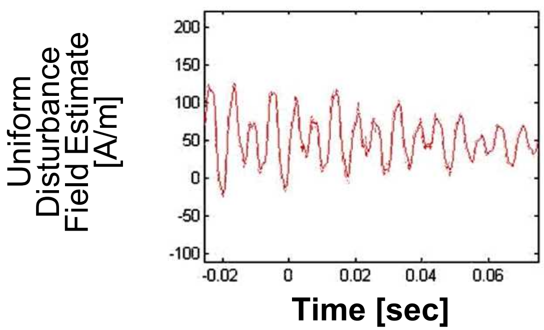
200 Hz
Low-Pass Filter

Zero Order DFD

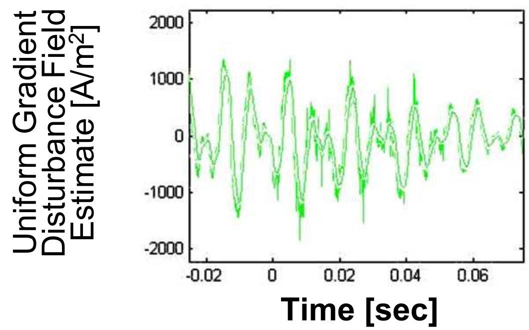
a_0



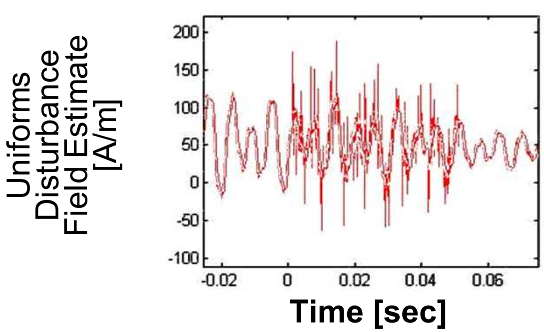
1st Order DFD

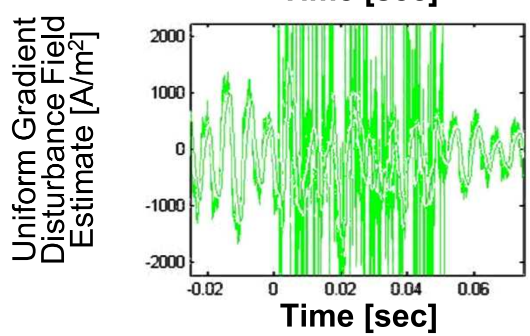


a_1

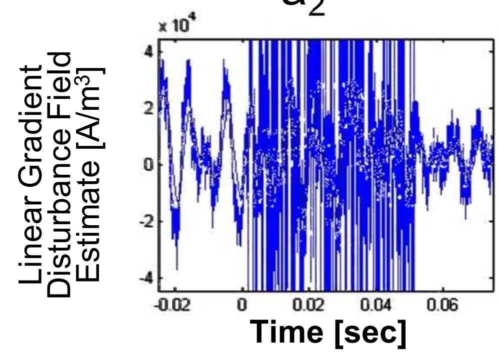


2nd Order DFD

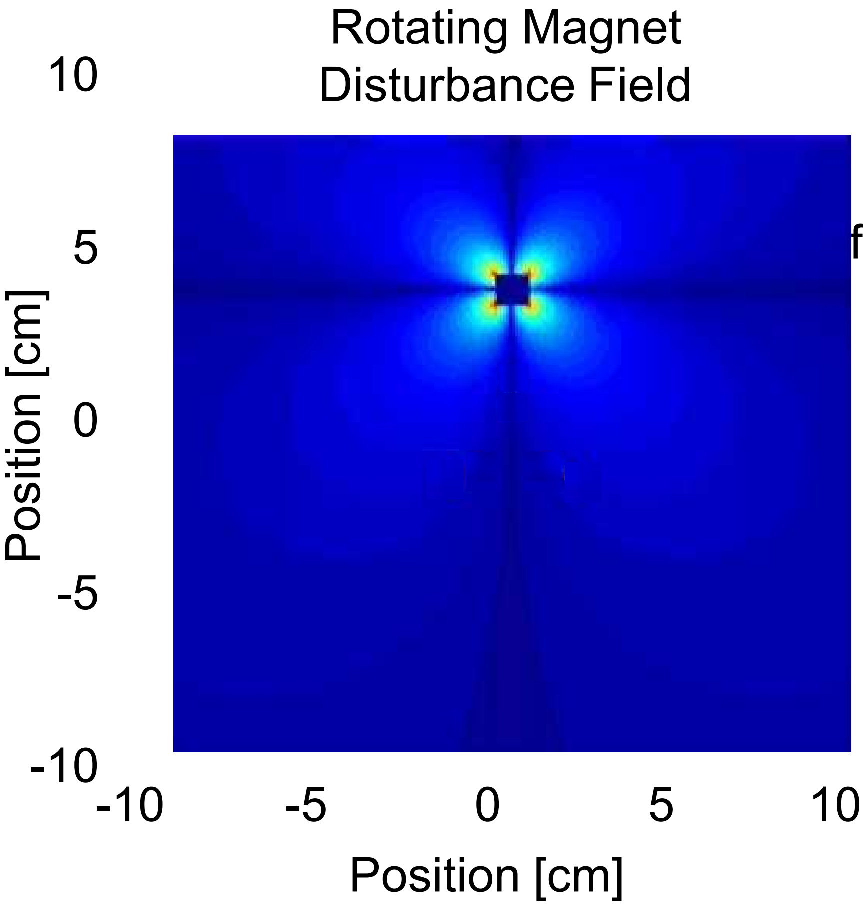




a_2



2-D DFD Simulation

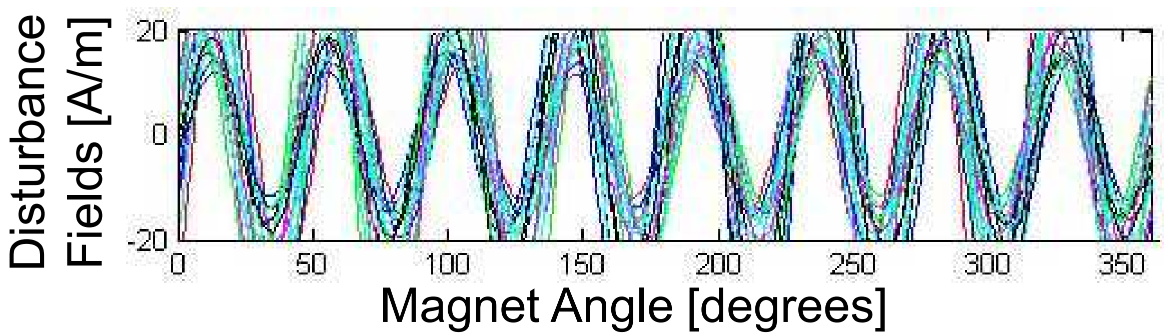


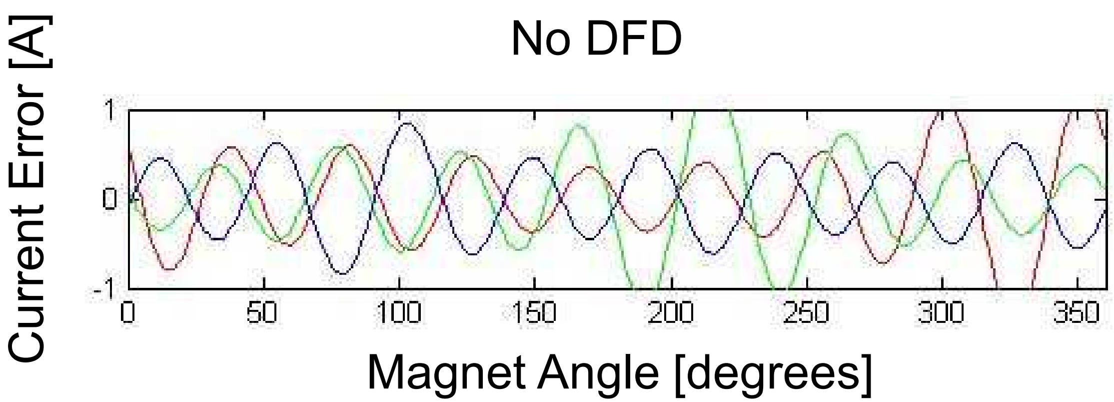
Zero Order DFD

- Conductor Locations
- Detector Locations

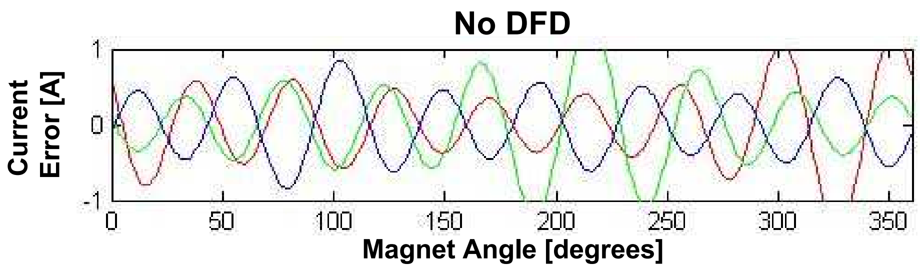
$$f_d(x,y) = a_0 + a_1x + a_2y + a_3x^2 + a_4y^2 + a_5xy + a_6x^3 + a_7y^3 + a_8x^2y + a_9xy^2 + a_{10}x^4 + a_{11}y^4 + a_{12}x^3y + a_{13}xy^3 + a_{14}x^2y^2$$

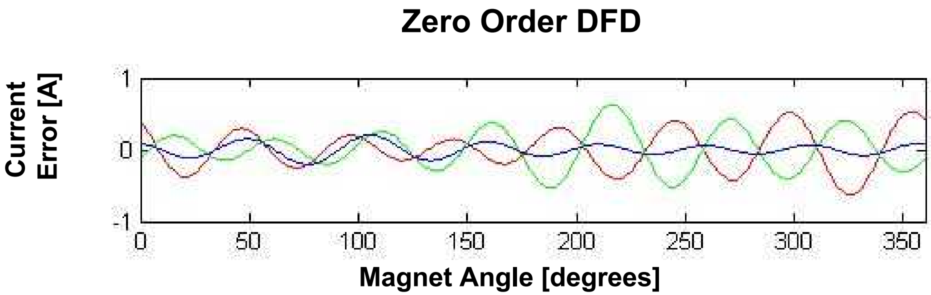
Current Errors without 2-D DFD



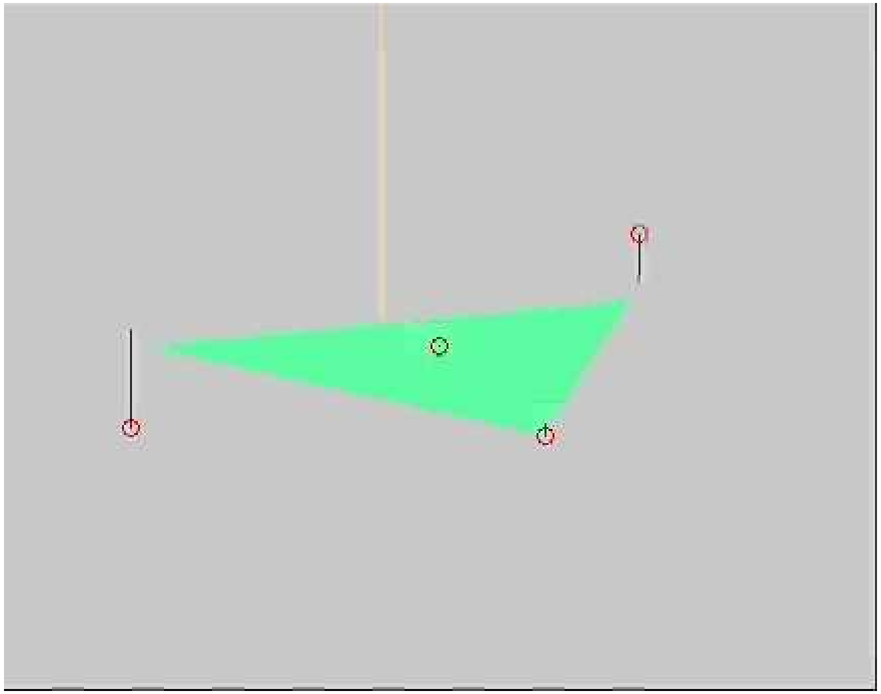


Zero Order 2-D DFD

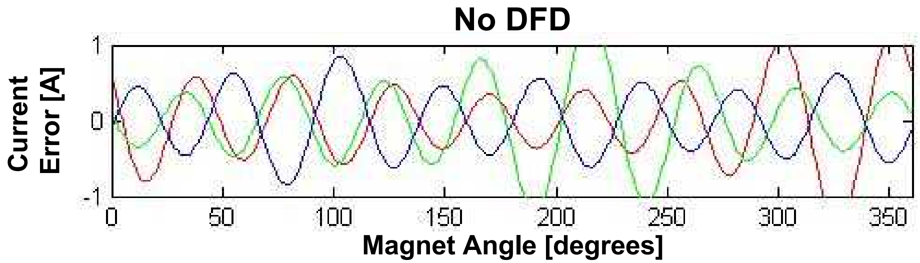


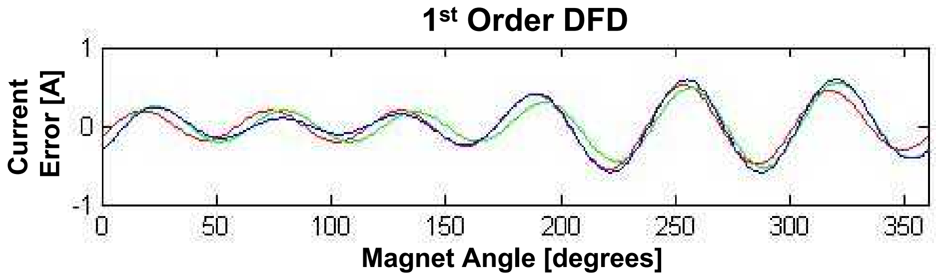


Disturbance Field Estimate

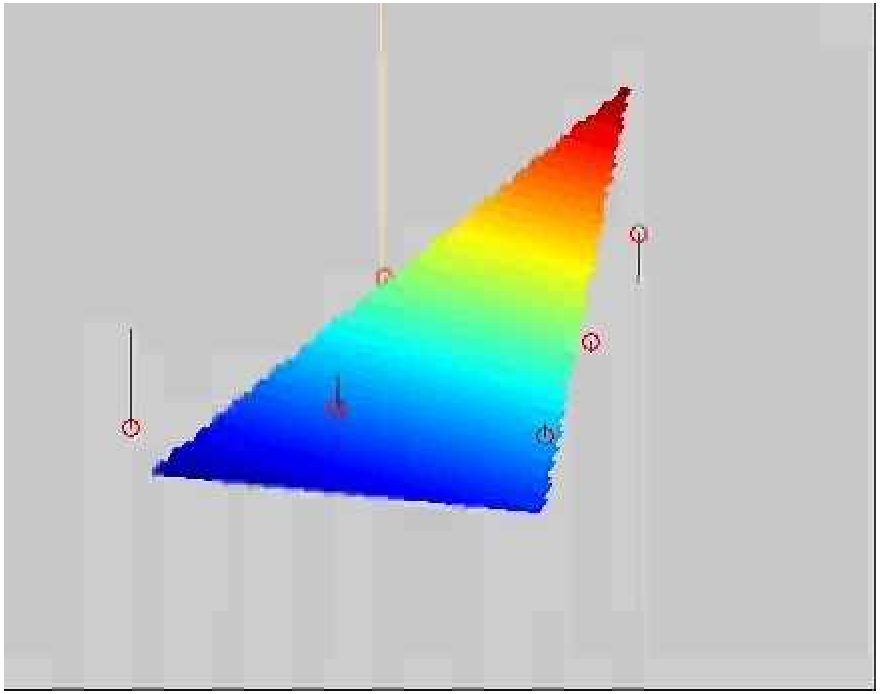


1st Order 2-D DFD



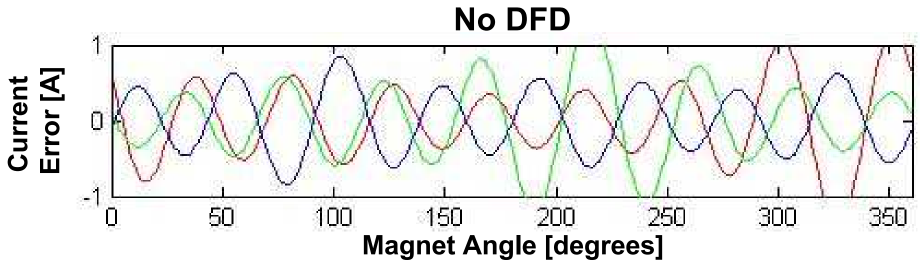


Disturbance Field Estimate

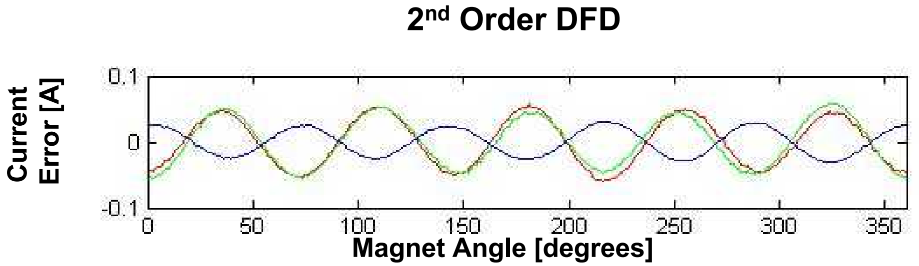


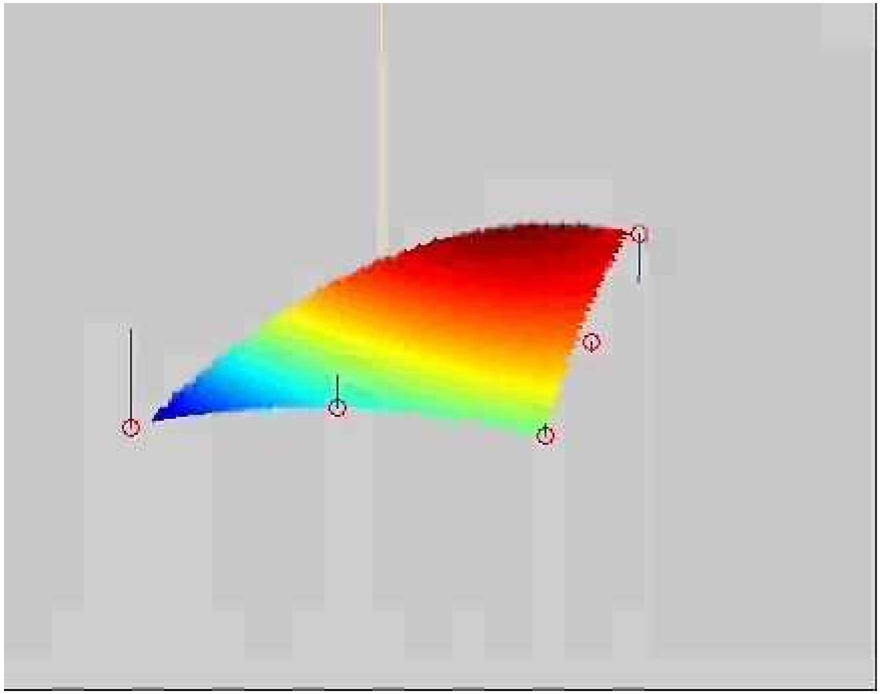
2^{nd} Order 2-D DFD

Disturbance Field Estimate

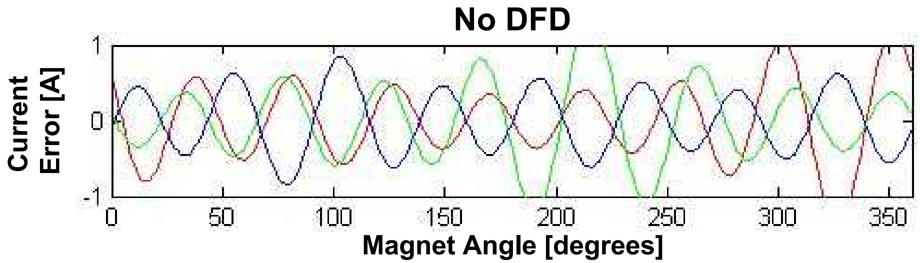


Vertical Scale → 10x Zoom

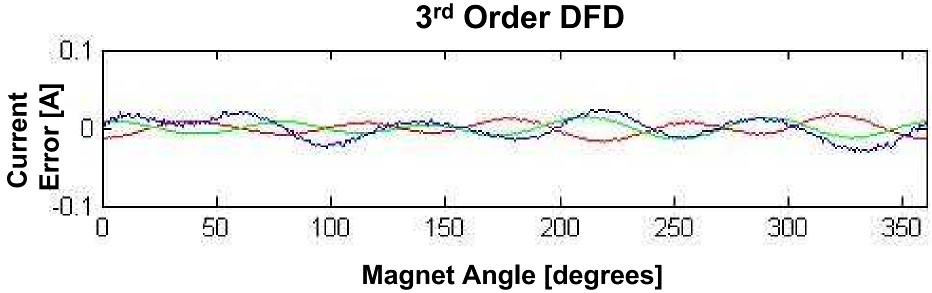




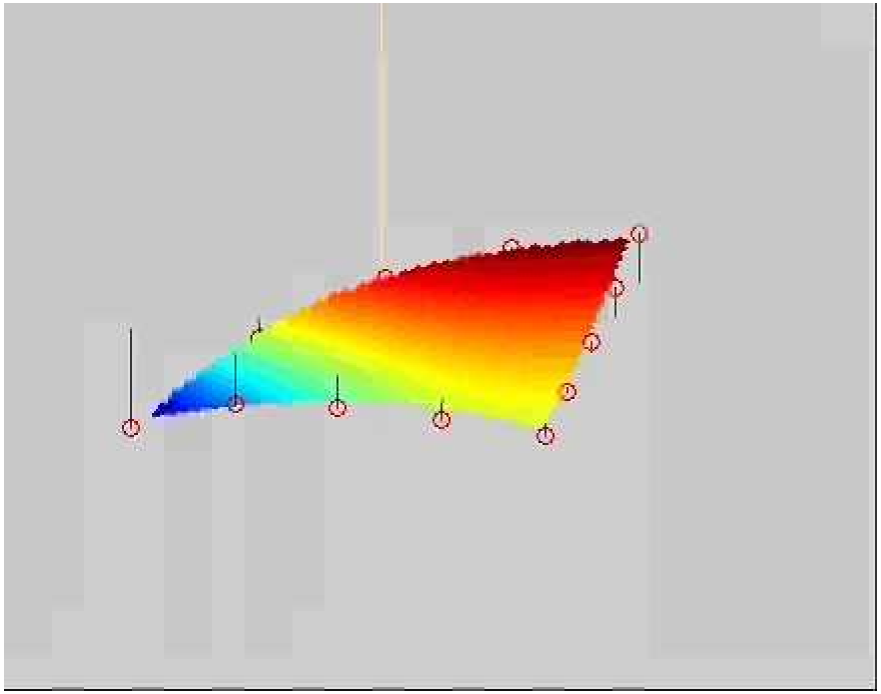
3^{rd} Order 2-D DFD



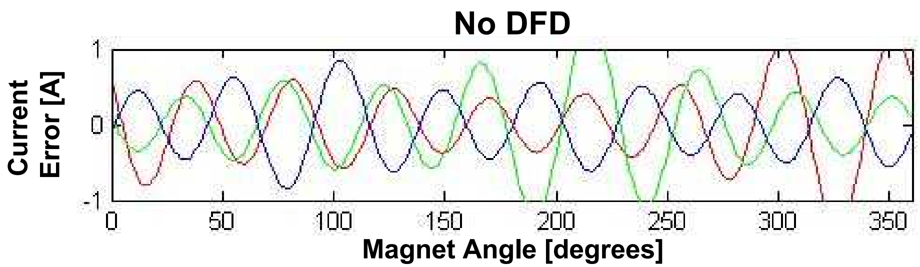
Vertical Scale → 10x Zoom



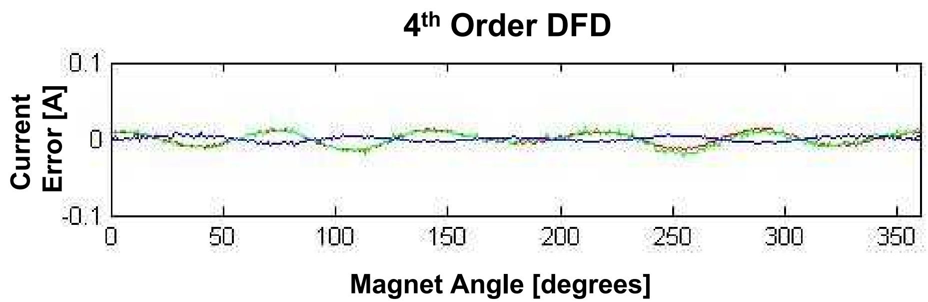
Disturbance Field Estimate



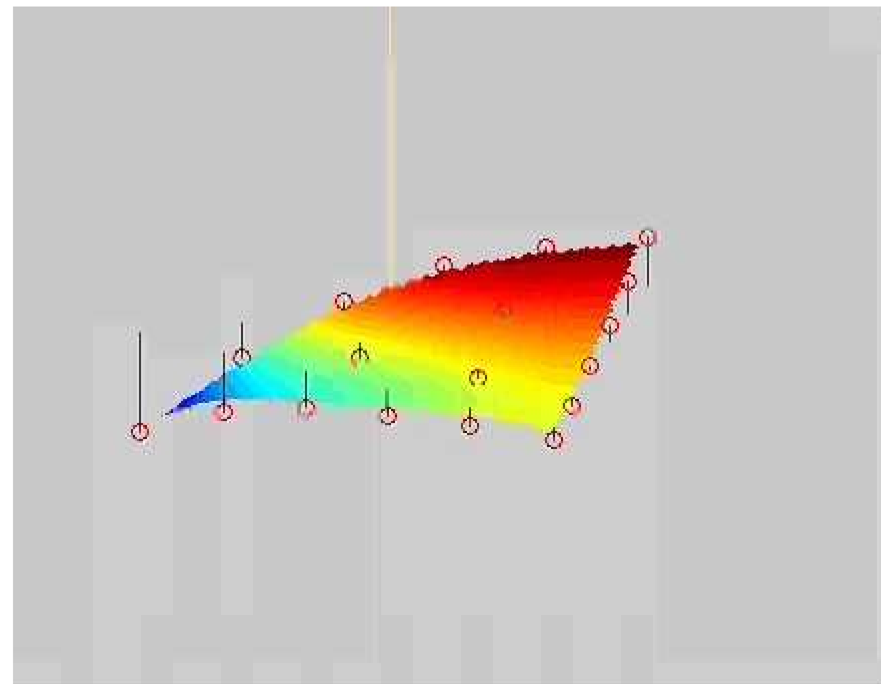
4^{th} Order 2-D DFD



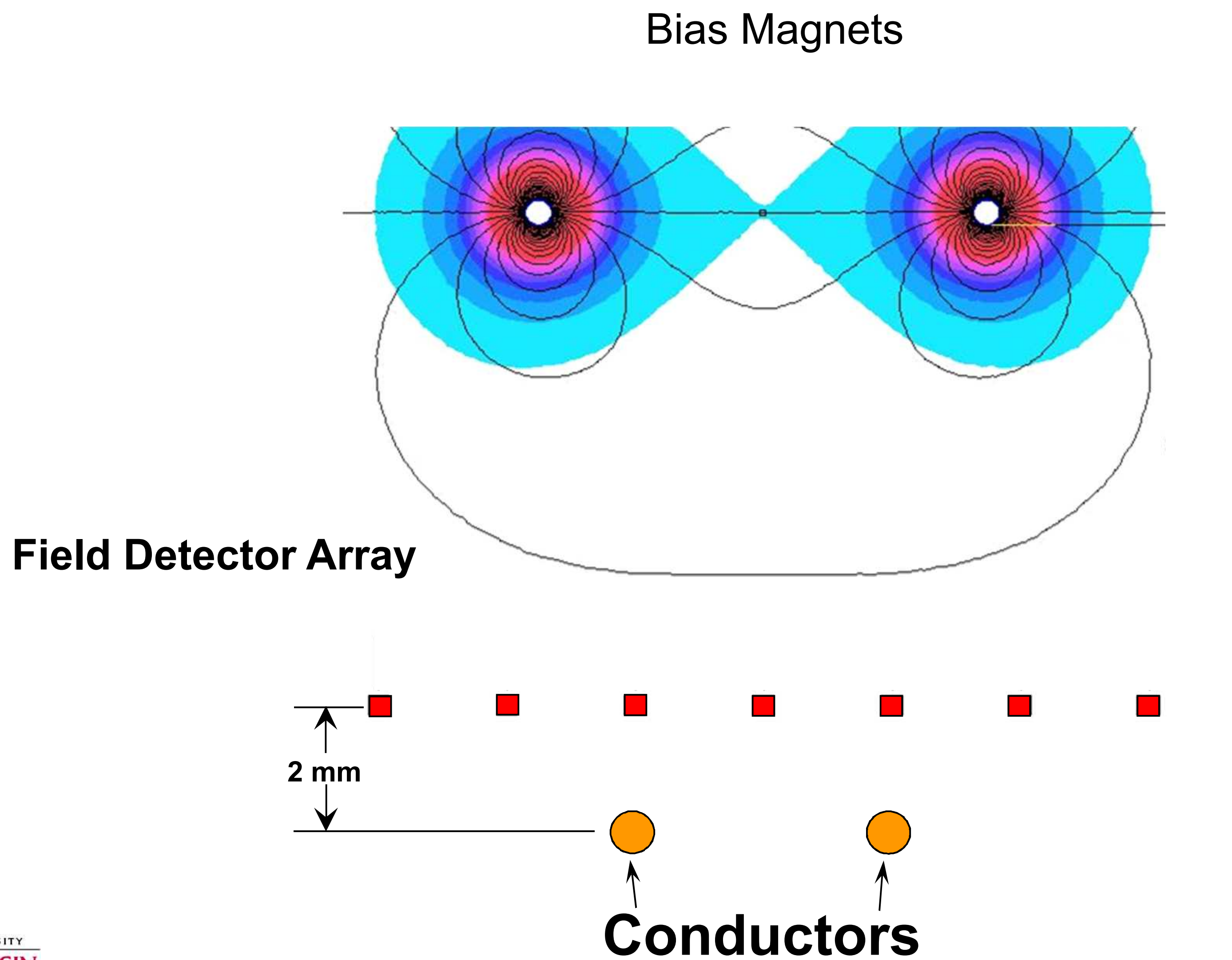
Vertical Scale → 10x Zoom



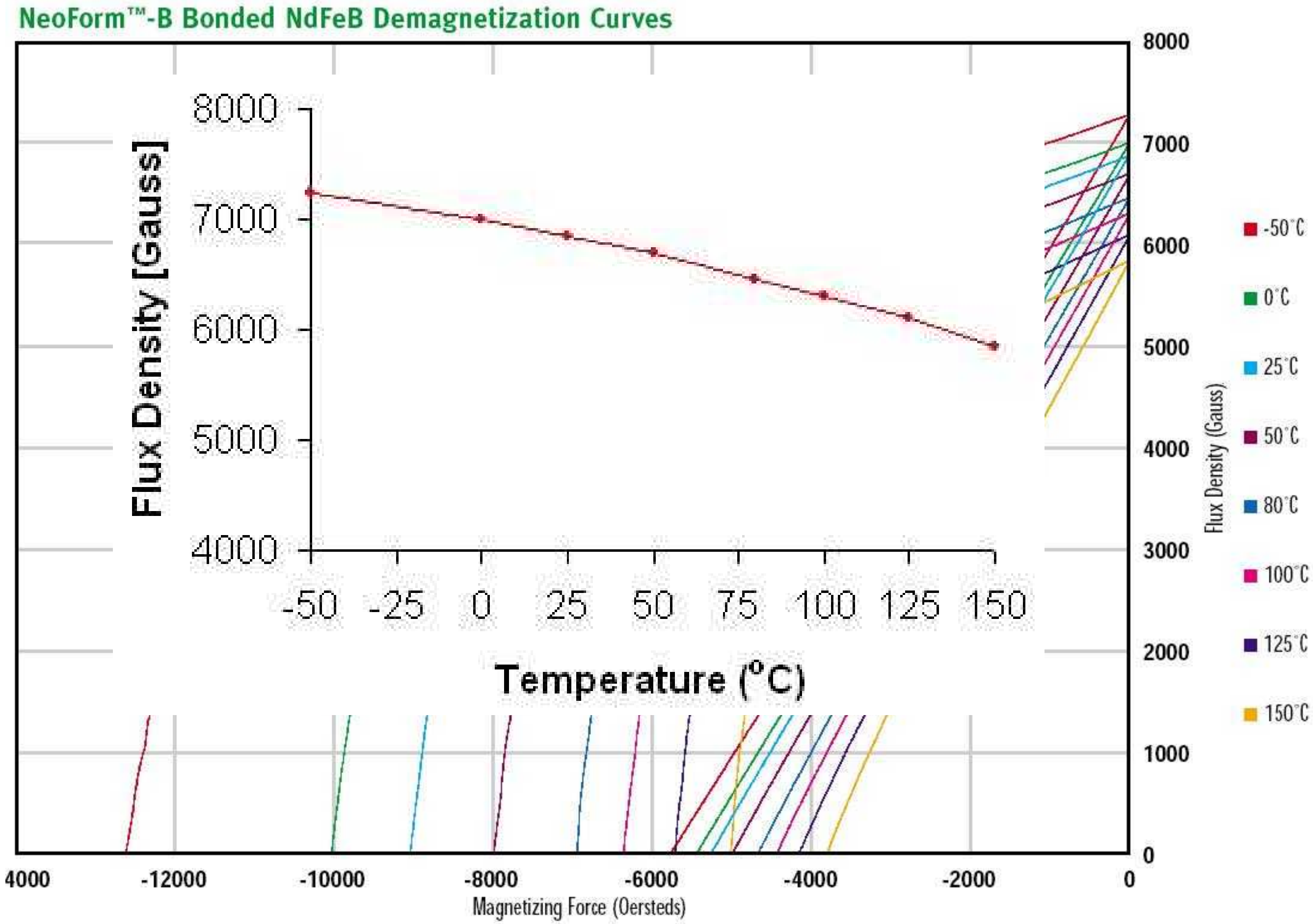
Disturbance Field Estimate



Bias Field Decoupling Simulation

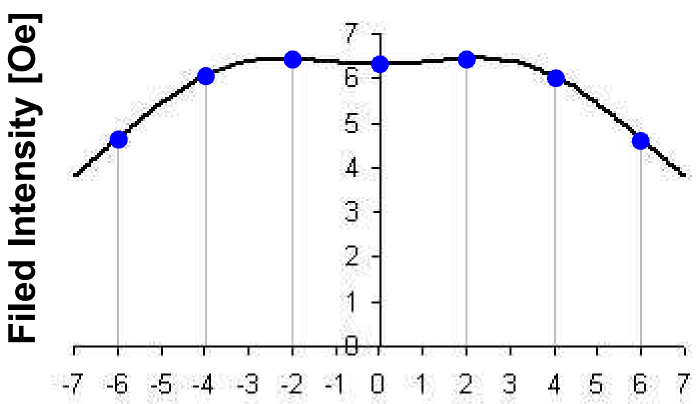


Temperature Dependence of Permanent Magnets



Bias Field Decoupling with DFD

Bias field is treated as a disturbance

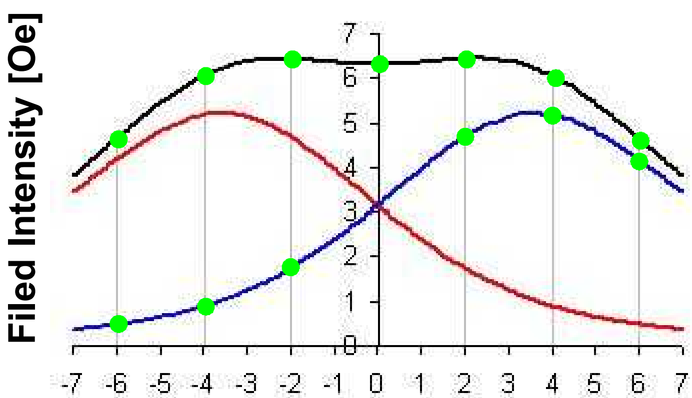


$$
\begin{array}{cc}
\text{Cross-Coupling} & \text{Polynomial Disturbance Field Estimate} \\
\end{array}
$$

$$
\begin{bmatrix}
A_{11} & A_{12} & 4.61 & x_0 & x_0^2 & x_0^3 & x_0^4 \\
A_{21} & A_{22} & 5.86 & x_1 & x_1^2 & x_1^3 & x_1^4 \\
A_{31} & A_{32} & 6.33 & x_2 & x_2^2 & x_2^3 & x_2^4 \\
A_{41} & A_{42} & 6.26 & x_3 & x_3^2 & x_3^3 & x_3^4 \\
A_{51} & A_{52} & 6.33 & x_4 & x_4^2 & x_4^3 & x_4^4 \\
A_{61} & A_{62} & 5.86 & x_5 & x_5^2 & x_5^3 & x_5^4 \\
A_{71} & A_{72} & 4.61 & x_6 & x_6^2 & x_6^3 & x_6^4
\end{bmatrix}
\begin{bmatrix}
I_1 \\ I_2 \\ \Delta_T \\ a_1 \\ a_2 \\ a_3 \\ a_4
\end{bmatrix}
=
\begin{bmatrix}
F_1 \\ F_2 \\ F_3 \\ F_4 \\ F_5 \\ F_6 \\ F_7
\end{bmatrix}
$$

Bias Magnet Coupling

Bias Field Decoupling with DFD



— Total bias field

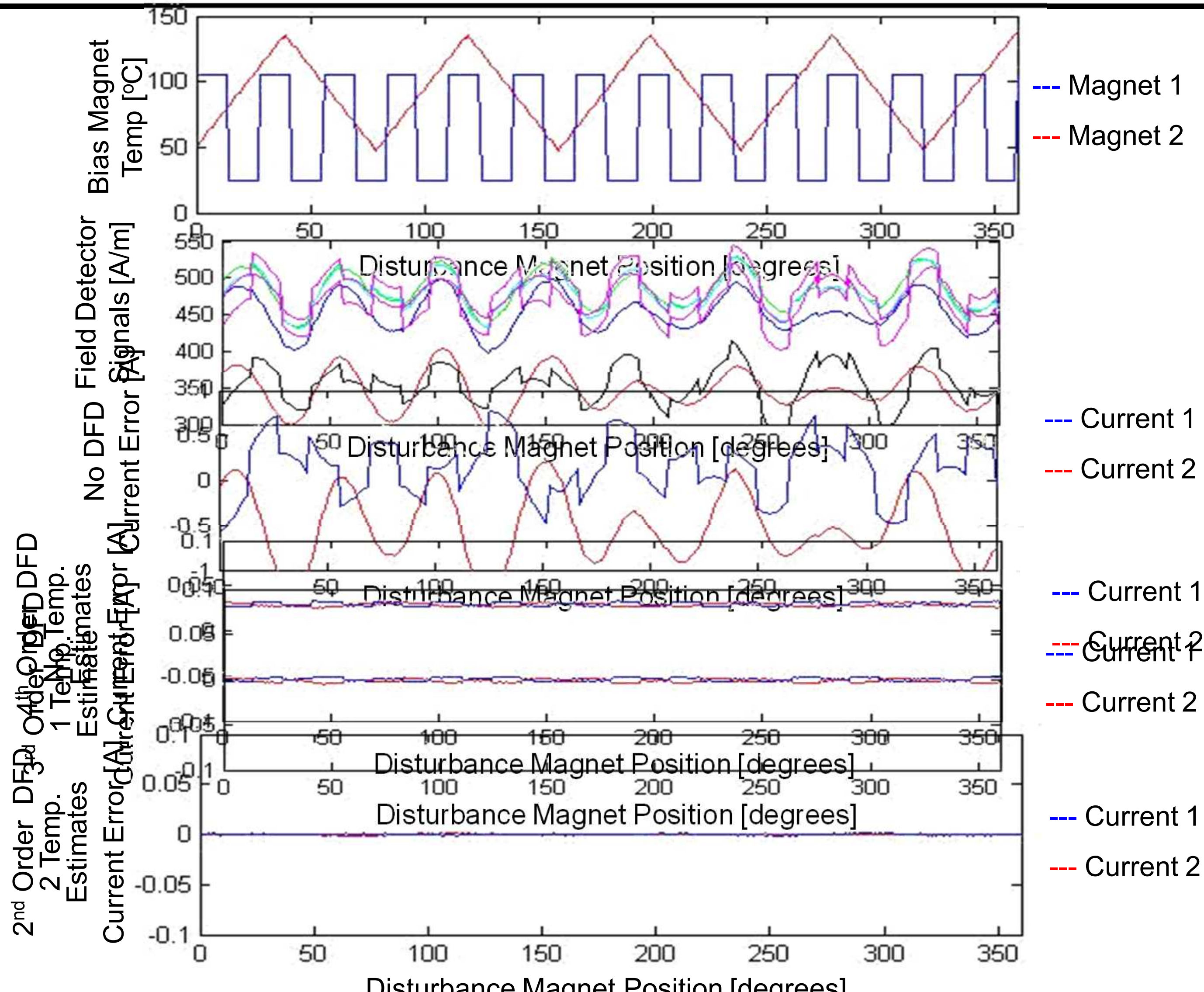
— Magnet 1

— Magnet 2

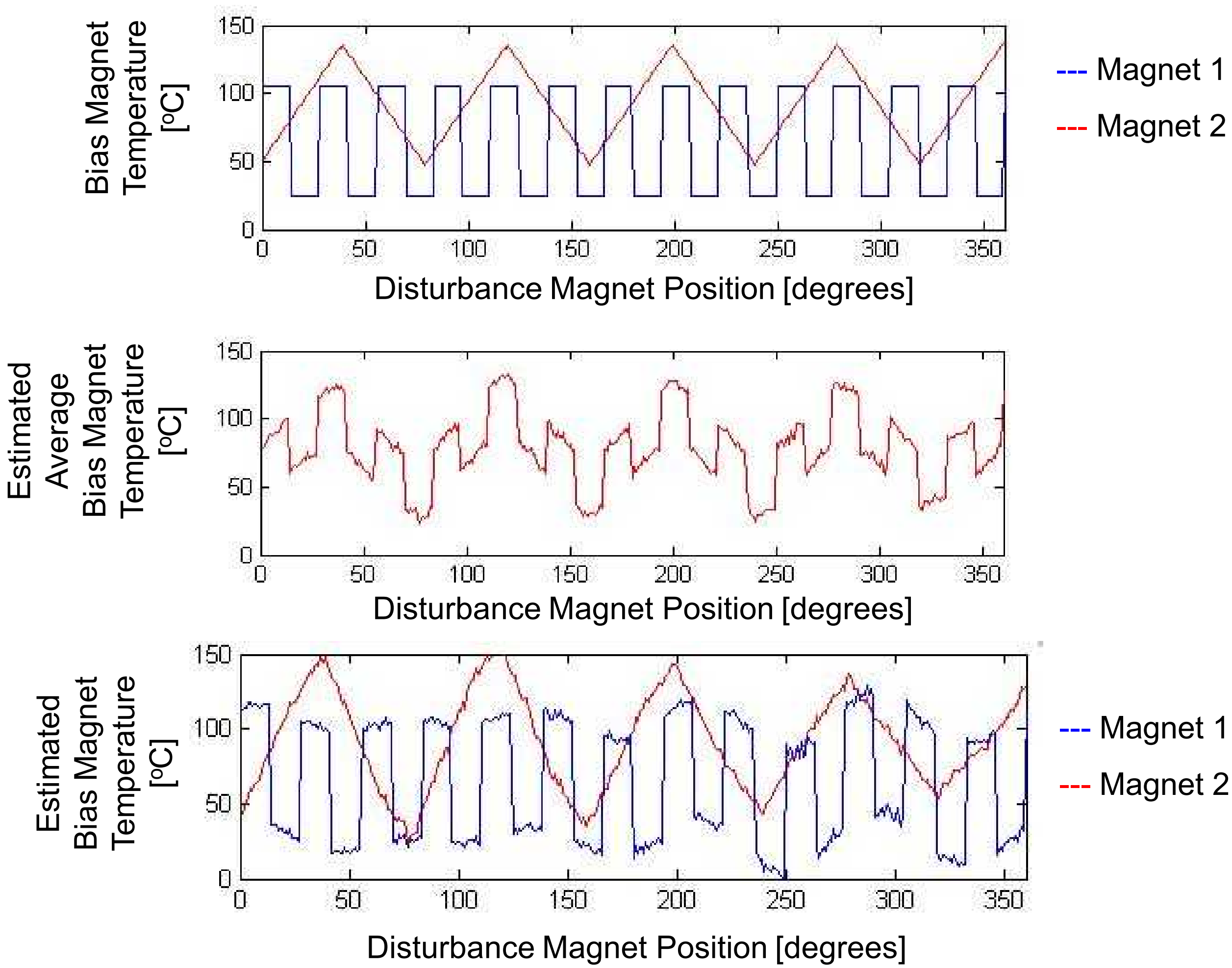
Cross-Coupling | Polynomial Disturbance Field Estimate | Bias Magnet Coupling

$$\begin{bmatrix} A_{11} & A_{12} & 4.61 & 1 & x_0 & x_0^2 & x_0^3 \\ A_{21} & A_{22} & 5.86 & 1 & x_1 & x_1^2 & x_1^3 \\ A_{31} & A_{32} & 6.35 & 1 & x_2 & x_2^2 & x_2^3 \\ A_{41} & A_{42} & 6.26 & 1 & x_3 & x_3^2 & x_3^3 \\ A_{51} & A_{52} & 6.83 & 1 & x_4 & x_4^2 & x_4^3 \\ A_{61} & A_{62} & 5.86 & 1 & x_5 & x_5^2 & x_5^3 \\ A_{71} & A_{72} & 4.61 & 1 & x_6 & x_6^2 & x_6^3 \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ \Delta_{T1} \\ a_0 \\ a_1 \\ a_2 \\ a_3 \end{bmatrix} = \begin{bmatrix} F_1 \\ F_2 \\ F_3 \\ F_4 \\ F_5 \\ F_6 \\ F_7 \end{bmatrix}$$

Disturbance Rejection



Magnet Temp. Estimation



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Conclusions

- Cross-coupled fields from neighboring conductors can be actively decoupled without using magnetic shielding.
- Unknown disturbance fields can also be decoupled using extra field detectors
- The order of DTD used depends on the magnitude of spatial field gradient anticipated in the net disturbance field.
- The temperature dependence of the biasing magnet(s) can be decoupled using DFD, without measuring the magnet's temperature.
- DFD can be used to estimate the magnet temperature, effectively turning the magnet into a temperature sensor.