

Design Considerations for the Characterization of Capacitors

Michael L. DeLibero

Case Western Reserve University

August, 2015

Acknowledgements

- Thesis Committe
- Dr. Merat
- Dr. Welsch
- Steven Ehret
- CWRU
- ARPA-E contract DE-AR000016

Outline

Background

Aim of Work

Instrumentation

Regression

Modeling

Conclusion

Future Work

Background

- In 2011, ARPA-E granted Dr. Welsch an award to develop Titanium-based capacitors.
- They promise to replace tantalum.
- Greater energy and power density.

Aim of Work

- Design instrumentation capable of testing a large number of titanium capacitors.
- Provide a numerical result to be able to characterize physical parameters in the capacitors.

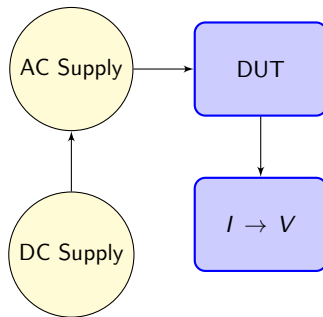
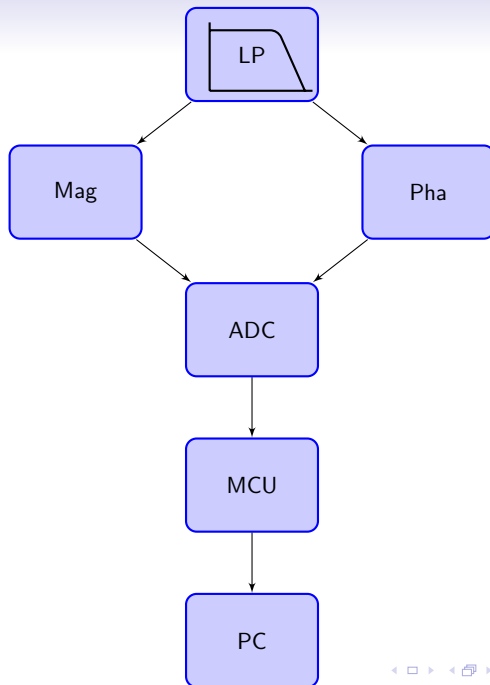
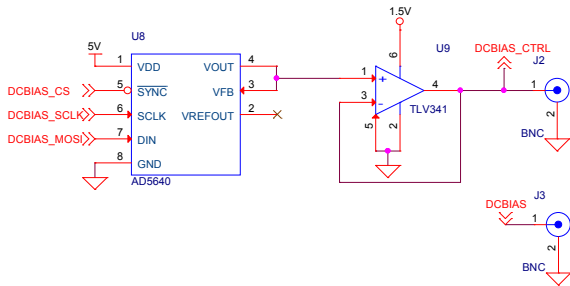
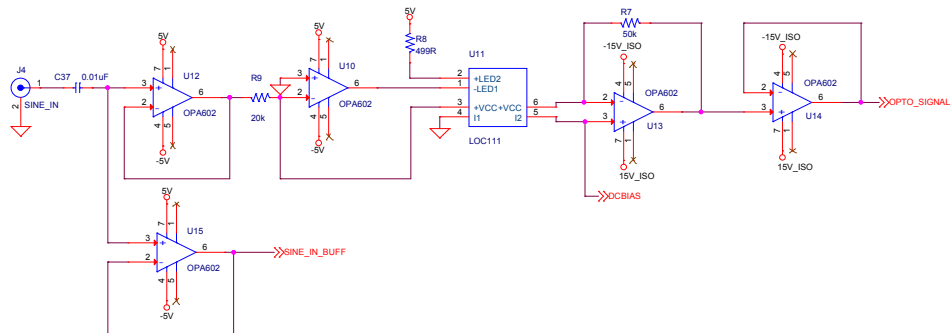
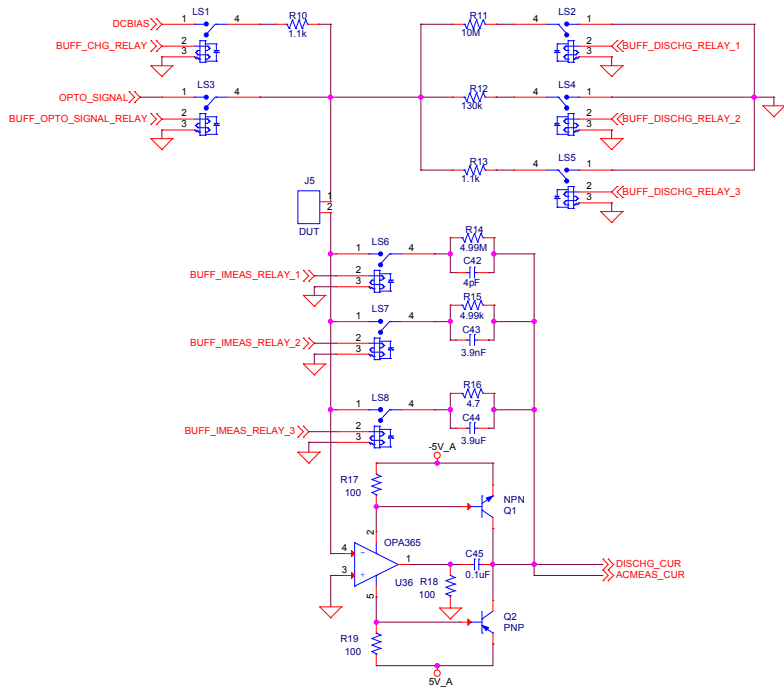


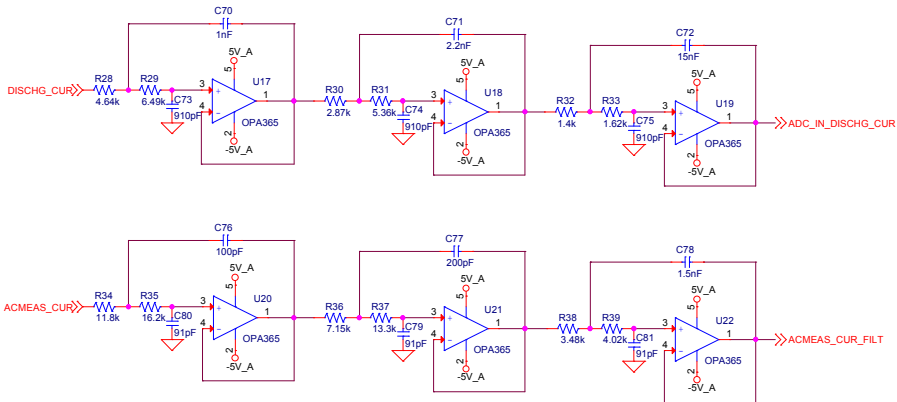
Figure: Circuit Flow Chart

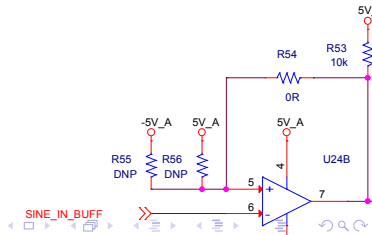
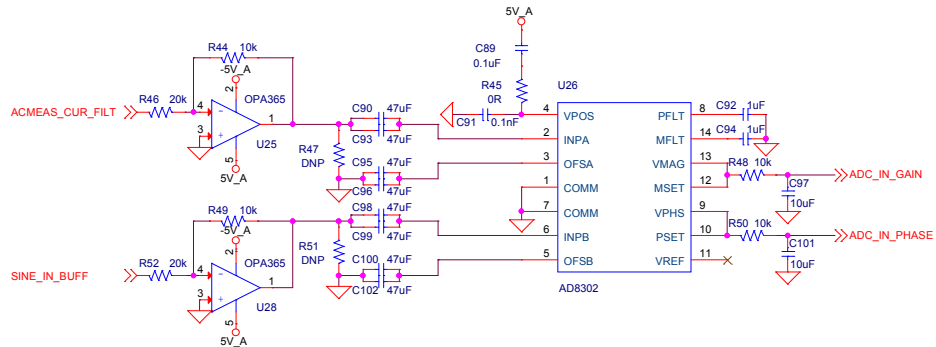
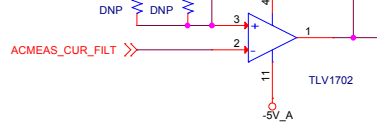


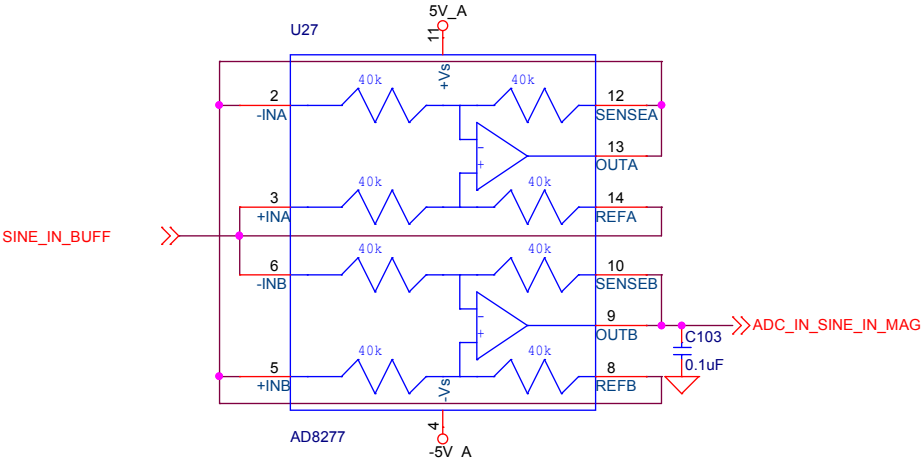




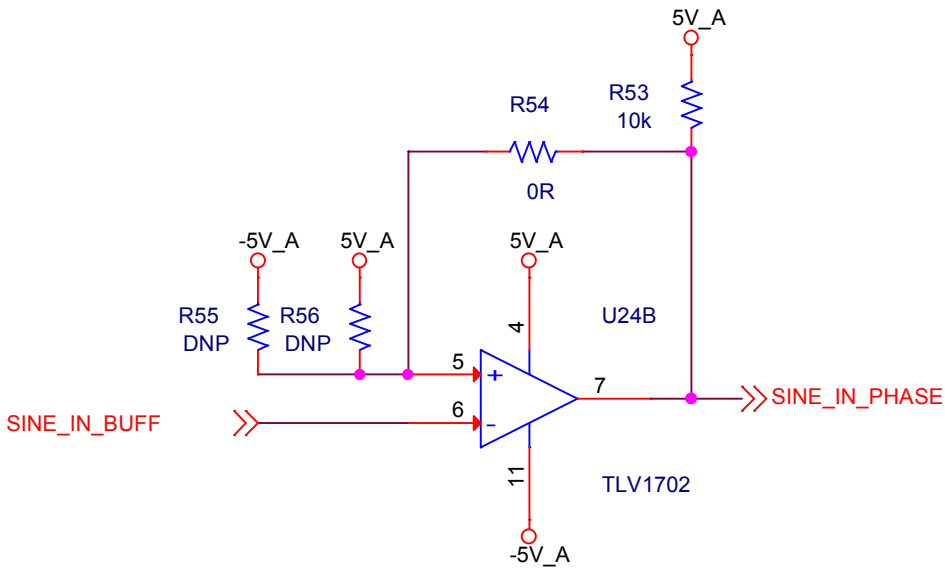








MAGNITUDE



PHASE

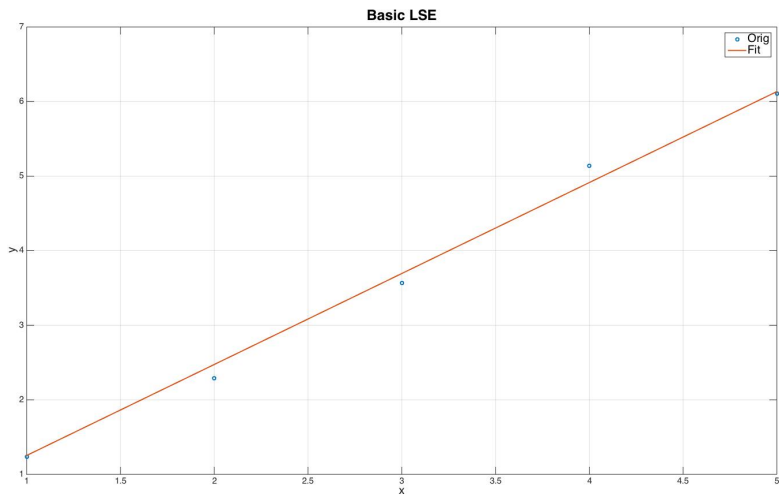


Figure: Basic LSE

Basic Regression

$$y = a_0 + a_1 x \quad (1)$$

$$E^2 = \sum_{i=1}^n (y_i - y)^2 \quad (2)$$

$$E^2 = \sum_{i=1}^n (y_i - (a_0 + a_1 x_i))^2 \quad (3)$$

$$\frac{\partial E^2}{\partial a_0} = 0 = \sum_{i=1}^n (-2y_i + 2a_0 + 2a_1 x_i) \quad (4)$$

$$\frac{\partial E^2}{\partial a_1} = 0 = \sum_{i=1}^n (-2y_i x_i + 2a_0 x_i + 2a_1 x_i^2) \quad (5)$$

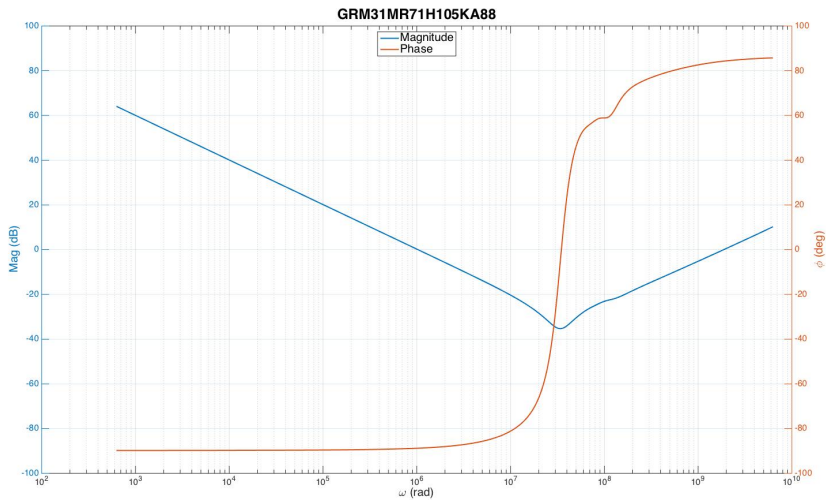


Figure: GRM31MR71H105KA88 Capacitor Data [3]

$$G(s) = \frac{A_0 + A_1s + A_2s^2 + \dots + A_ns^n}{B_0 + B_1s + B_2s^2 + \dots + B_ms^m} [1][Eq. 3] \quad (6)$$

$$\lambda_h = \sum_{k=0}^m \omega_k^h [1][Eq. 15] \quad (7)$$

$$S_h = \sum_{k=0}^m \omega_k^h R_k [1][Eq. 16] \quad (8)$$

$$T_h = \sum_{k=0}^m \omega_k^h I_k [1][Eq. 17] \quad (9)$$

$$U_h = \sum_{k=0}^m \omega_k^h (R_k^2 + I_k^2) [1][Eq. 18] \quad (10)$$

$$M = \begin{bmatrix} \lambda_0 & 0 & -\lambda_2 & 0 & T_1 & S_2 \\ 0 & \lambda_2 & 0 & -\lambda_4 & -S_2 & T_3 \\ \lambda_2 & 0 & -\lambda_4 & 0 & T_3 & S_4 \\ 0 & \lambda_4 & 0 & -\lambda_6 & -S_4 & T_5 \\ T_1 & -S_2 & -T_3 & S_4 & U_2 & 0 \\ S_2 & T_3 & -S_4 & -T_5 & 0 & U_4 \end{bmatrix} \quad (11)$$

$$N = \begin{bmatrix} A_0 \\ A_1 \\ A_2 \\ A_3 \\ \vdots \\ B_1 \\ B_2 \\ B_3 \\ \vdots \end{bmatrix} \quad [1][Eq. 21b] \quad (12) \quad C = \begin{bmatrix} S_0 \\ T_1 \\ S_2 \\ T_3 \\ \vdots \\ 0 \\ U_2 \\ 0 \\ \vdots \end{bmatrix} \quad [1][Eq. 21c] \quad (13)$$

$$MN = C \quad [1][Eq. 20] \quad (14)$$

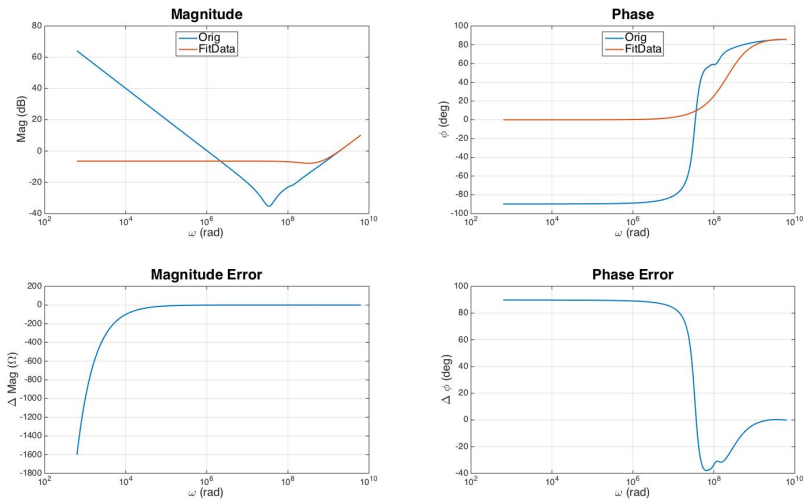


Figure: Levy's Technique

$$W_{kL} = \frac{1}{|Q(jw_k)_{L-1}|^2} [2] \quad (15)$$

$$E = \sum_{k=1}^n |\epsilon'_k|^2 W_{kL} [2][Eq. 7] \quad (16)$$

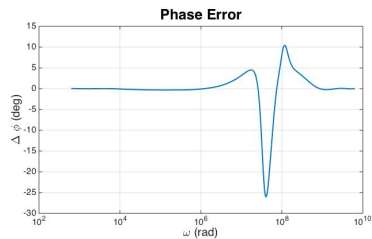
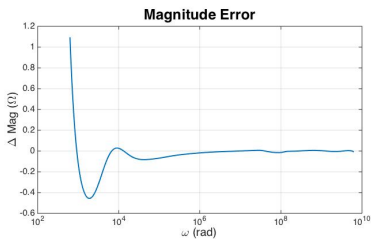
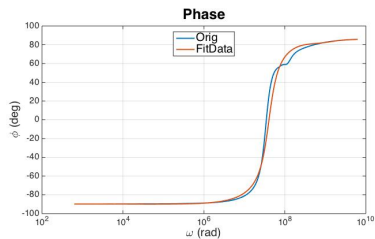
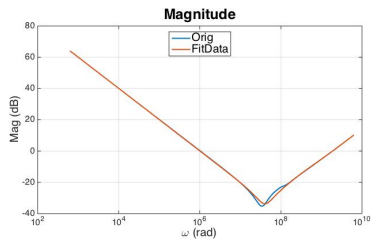


Figure: LSE + Iteration

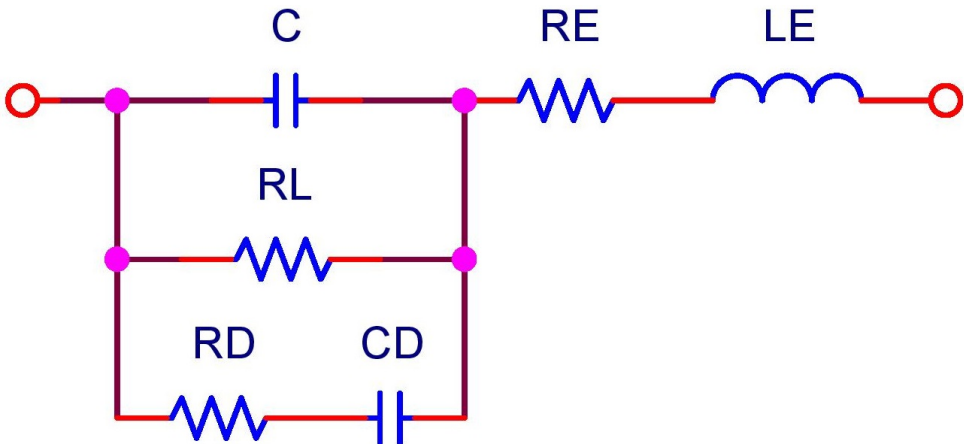


Figure: 6 Term Model

$$\bar{Z}(s) = \frac{(R_E + R_L) + (L_E + C_D R_D R_E + C_D R_D R_L + C R_E R_L + C_D R_E R_L)s}{1 + (C_D R_D + C R_L + C_D R_L)s + C C_D R_D R_L s^2} + \frac{(C_D L_E R_D + C L_E R_L + C_D L_E R_L + C C_D R_D R_E R_L)s^2 + C C_D L_E R_D R_L s^3}{1 + (C_D R_D + C R_L + C_D R_L)s + C C_D R_D R_L s^2} \quad (17)$$

$$\bar{Z}(s) = \frac{a_0 + a_1 s + a_2 s^2 + a_3 s^3}{b_0 + b_1 s + b_2 s^2} \quad (18)$$

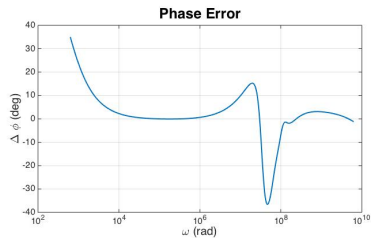
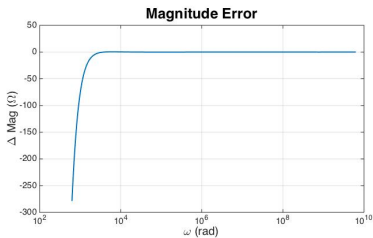
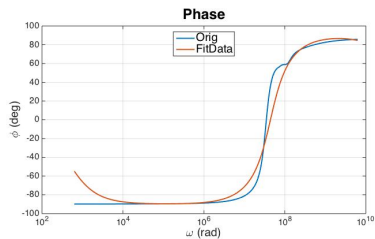
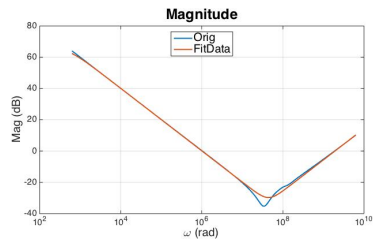


Figure: 6 Term Model: Bad Initilization

$$\begin{aligned}a_0 &= 5.9991E^{+03} \\a_1 &= 1.7934E^{-04} \\a_2 &= 3.3158E^{-12} \\a_3 &= 6.8295E^{-22} \\b_0 &= 1.0000 \\b_1 &= 5.9057E^{-03} \\b_2 &= 1.4067E^{-12}\end{aligned}\quad (19)$$

$$\begin{aligned}C &= -8.2563E^{-10} \\R_E &= 3.1886E^{-01} \\L_E &= 4.8551E^{-10} \\R_L &= 4.8551E^{-10} \\C_D &= 9.8536E^{-07} \\R_D &= -2.8824E^{-01}\end{aligned}\quad (20)$$

$$\begin{aligned}a_0 &= 1 \\a_1 &= 1 \\a_2 &= 1 \\a_3 &= 1 \\b_0 &= 1 \\b_1 &= 0 \\b_2 &= 0\end{aligned}\quad (21)$$

$$\begin{aligned}C &= INF \\R_E &= INF \\L_E &= INF \\R_L &= IND \\C_D &= IND \\R_D &= IND\end{aligned}\quad (22)$$

$$\begin{aligned}a_0 &= 2 \\a_1 &= 5 \\a_2 &= 4 \\a_3 &= 1 \\b_0 &= 1 \\b_1 &= 3 \\b_2 &= 1\end{aligned}\quad (23)$$

$$\begin{aligned}C &= 1 \\R_E &= 1 \\L_E &= 1 \\R_L &= 1 \\C_D &= 1 \\R_D &= 1\end{aligned}\quad (24)$$

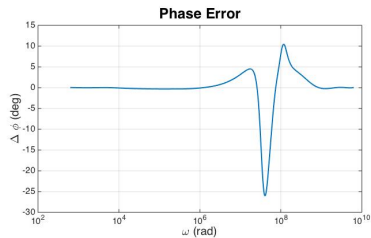
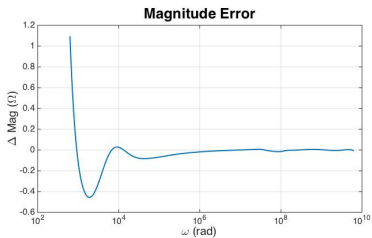
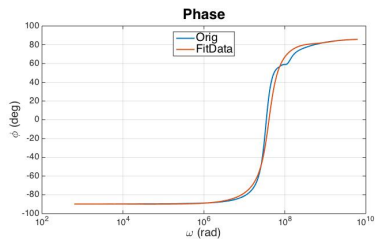
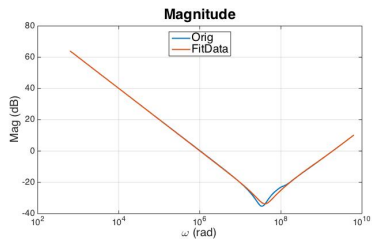


Figure: 6 Term Model: Good Initilization

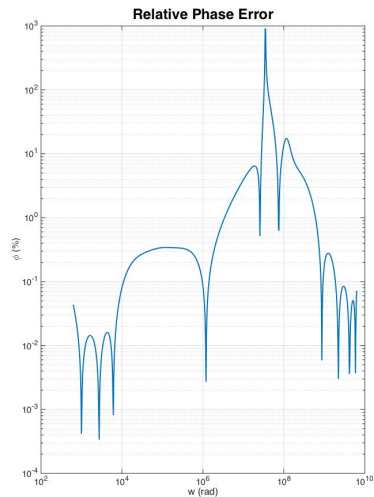
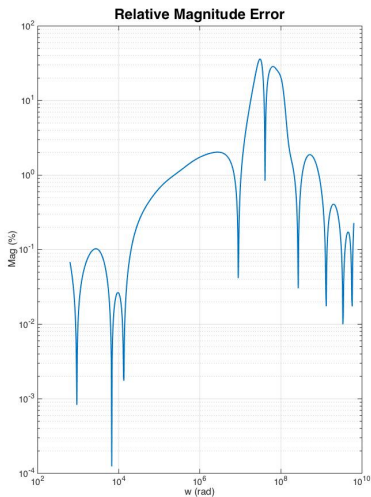


Figure: 6 Term Model: Relative Error

Conclusion

Measurement Range:

- DC bias range $0 \rightarrow 500\text{V}$.
- Frequency Range of $100\text{Hz} \rightarrow 100\text{kHz}$.

Regression Accuracy:

- Accurate outside of resonance.
- 2Ω and 2° .
- $< 5\%$.

Future Work

- Build the circuit and validate against the stated capabilities and accuracy.
- Increase the available frequency range for the measurement circuitry.
- Add additional fail-safe protection to the circuit.
- Update the regression technique for better accuracy.
- Evaluate the accuracy of the six term model.



E. C. Levy.

Complex-curve fitting.

Automatic Control, IRE Transactions on, AC-4(1):37–44,
1959.



C. K. Sanathanan and J. Koerner.

Transfer function synthesis as a ratio of two complex
polynomials.

Automatic Control, IEEE Transactions on, 8(1):56–58, Jan
1963.



Sim surfing.

[http://ds.murata.co.jp/software/simsurfing/en-us/
index.html?intcid5=com_xxx_xxx_cm_nv_xxx](http://ds.murata.co.jp/software/simsurfing/en-us/index.html?intcid5=com_xxx_xxx_cm_nv_xxx).