Probe Pin Wideband Electrical Circuit Model

Mohamed Eldessouki
SV TCL – An SV Probe Company
Overview

- Motivation and Objective
- Introduction
- Closed Form Circuit Model
- Probe Pin Measurements and Simulation
- Probe Pin Modeling and Verification
- Summary and Conclusion
Motivation

Customers are looking for Probe Head (PH) circuit model to be able to:

- Simulate and Predict Bandwidth (BW)
- Simulate and Predict Power Plane Input Impedance
- Reduce risk probe hardware not to meet test expectations

Objective

Develop Close Form Accurate Circuit Model
Verify Developed Model Using:
- Measured S-parameters
- Ansoft HFSS Simulation Tool (Field Analysis)
Introduction

Trio Probe & Spring Pin
Proximity and Skin Effect
Circuit Model Comparison
Transmission Line (TL) Model
Introduction

Probe Pin Structure

Probe tail

Ribbon area

Probe tip

Trio-probe

Top View

Current Flow

Pin Contact

Spring

Pin Contact

Spring Pin probe

Upper Plunger

Barrel

Lower Plunger
Introduction

Proximity and Skin Effect

Current density distribution in parallel wire. Unbalanced current distribution due to proximity effect.

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Rectangular cross-section

Low current density

Circular cross-section

High current density

Nested Probes

Side by Side Probes

Low Frequency

High Frequency

Proximity Effect

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Introduction

Fundamental Equations

\[ L = \frac{\mu}{I_0 I_0^*} \int_S \overline{H.H}^* dS \]

\[ C = \frac{\epsilon'}{V_0 V_0^*} \int_S \overline{E.E}^* dS \]

\[ R = \frac{R_s}{I_0 I_0^*} \int_{S_1+S_2} \overline{H.H}^* dl \]

\[ G = \frac{\omega \epsilon''}{V_0 V_0^*} \int_S \overline{E.E}^* dS \]

\[ \pi \text{ and } T \text{ Equivalent Circuit TL Model} \]
## Models Comparison

<table>
<thead>
<tr>
<th>Model</th>
<th>Advantages (Account for)</th>
<th>Disadvantages</th>
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<tr>
<td>Low Frequency</td>
<td>• Internal and External Inductance</td>
<td>• No Skin Effect</td>
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<tr>
<td></td>
<td>• Proximity effect</td>
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<td>High Frequency</td>
<td>• Skin Effect</td>
<td>• No Internal Inductance</td>
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<tr>
<td></td>
<td>• Internal Inductance</td>
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<tr>
<td>Wide Band</td>
<td>• Skin Effect</td>
<td>• No Proximity Effect on Resistance Calculation Only</td>
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<td></td>
<td>• Internal Inductance</td>
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<td>• Proximity Effect in Inductance Calculation</td>
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</tbody>
</table>
Closed Form Circuit Model

Models Comparison for Cylindrical Probe

\[
L = \frac{\mu_0}{\pi} \left[ \frac{1}{4} + \cosh^{-1} \left( \frac{D}{2a} \right) \right]
\]

\[
L_{\text{ext}} = \frac{\mu_0}{\pi} \cosh^{-1} \left( \frac{D}{2a} \right)
\]

\[L = \text{Im}(Z)\]

Where

\[
Z = 2Z_{\text{int}} + j\omega L_{\text{ext}}
\]

\[
L = \frac{R_s}{\pi a} \frac{\text{ber}(\zeta)\text{ber}'(\zeta) - j\text{bei}(\zeta)\text{bei}'(\zeta)}{\sqrt{2\omega \left( [\text{bei}'(\zeta)]^2 + [\text{ber}'(\zeta)]^2 \right)}} + \frac{\mu_0}{\pi} \cosh^{-1} \left( \frac{D}{2a} \right)
\]

\[
R = \frac{2}{\pi a^2 \sigma_c}
\]

\[
R = \frac{R_s}{\pi a} \frac{D/2a}{\sqrt{(D/2a)^2 - 1}}
\]

\[R = \text{Re}(Z)\]

\[
Z_{\text{int}} = \frac{R_s}{\sqrt{2\pi a}} \frac{\text{ber}(\zeta) + j\text{bei}(\zeta)}{\text{bei}'(\zeta) - j\text{ber}'(\zeta)}
\]

Where

\[
\zeta = \frac{2Z_{\text{int}}}{Z_{\text{int}}^2 + \omega^2}
\]

\[
\text{ber}(\zeta) = \frac{\text{Re}(Z)}{\sqrt{\text{Re}(Z)^2 - \text{Im}(Z)^2}}
\]

\[
\text{bei}(\zeta) = \frac{\text{Im}(Z)}{\sqrt{\text{Re}(Z)^2 - \text{Im}(Z)^2}}
\]

Low Frequency

High Frequency

Wide Band
Closed Form Circuit Model

Inductance Comparison for Cylindrical Probe

Calculated based on spring pin dimensions

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Resistance Comparison for Cylindrical Probe

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Calculated based on spring pin dimensions

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Wide band

$$R = \frac{2}{\pi a^2 \sigma_c}$$

Low Frequency

$$R = \frac{R_s}{\pi a} \frac{D/2a}{\sqrt{(D/2a)^2 - 1}}$$

D=1mm

a=155μm

D=400μm

a=155μm

Wide band

High frequency

$$R = \frac{R_s}{\pi a} \frac{ber(\zeta)bei'(\zeta) - jbei(\zeta)ber'(\zeta)}{\sqrt{2[bei'(\zeta)]^2 + [ber'(\zeta)]^2}}$$

Low Frequency

$$caR = \sigma \pi$$

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Models Development for Rectangular Probe

**Loop Inductance calculation**

\[ L_{loop} = 2L_{self} - 2M \]

**Internal Inductance calculation** \( L_{int} \)

\[ L_{int} = \frac{\mu_0}{8\pi} \left( \frac{t}{8} + \frac{w}{8} \right) \]

\[ w >> t \]

**Find the external inductance** \( L_{ext} = L_{loop} - L_{int} \)

**Add frequency dependent internal inductance**

\[ L_{loop} = L_{ext} + L_{int}(f) \]

**Calculate wideband R & L**

\[ Z_{int}(f) = \frac{R_s}{\sqrt{2\pi a}} \frac{ber(\zeta) + jbei(\zeta)}{bei'(\zeta) - jber'(\zeta)} \]

\[ R = \text{Re}(Z) \quad L = \text{Im}(Z) \]

Where

\[ Z = 2L_{int} + j\omega L_{ext} \]

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Internal Inductance Correction Factor for Stamped Probe

Nested Probe

\[ L_{\text{int}} = \frac{\mu_0}{8\pi} \sqrt{1 - \left( \frac{t}{w} - 1 \right)^2} \]

Side by side Probe

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Inductance Comparison for Stamped Probe

Calculated based on 3mil Trio-probe dimensions

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Low Frequency model

High Frequency model

Wideband model

\[ L = 2 \text{Im}(Z_{in}) / \omega + \frac{\mu_0}{\pi} \left[ \ln \left( \frac{d}{w+t} \right) + \frac{3}{2} \right] - \frac{\mu_0}{4\pi} \]

\[ t = \begin{align*} 10 &\mu m \\ 39 &\mu m \\ 90 &\mu m \\ 100 &\mu m \end{align*} \]

\[ w = \begin{align*} 39 &\mu m \\ 50 &\mu m \\ 90 &\mu m \\ 100 &\mu m \end{align*} \]

\[ d = \begin{align*} 125 &\mu m \\ 300 &\mu m \\ 500 &\mu m \end{align*} \]
Closed Form Circuit Model

Resistance Comparison for Stamped Probe

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Calculated based on 3mil Trio-probe dimensions

(d = 130μm, w = 125μm)

\[
R = \frac{2}{wt\sigma_c}
\]

Wide band

Low Frequency

Wide band

Low Frequency

Proximity effect error

Error due to Geometry approximation

\[ a_e = \frac{(w + t)}{\pi} \]

Calculated based on 3mil Trio-probe dimensions

(d = 1mm, w = 125μm)

\[
R = \frac{R_z}{(w+t)} \frac{\pi d/2(w+t)}{\sqrt{\left(\frac{\pi d}{2(w+t)}\right)^2 - 1}}
\]

Wide band

High frequency

Low frequency

High frequency

\[ \pi \]
Closed Form Circuit Model

Capacitance Calculation for Stamped Probe

Nested Probe

\[ C = C_{pp} + C_{\text{fringe}} = \frac{w\varepsilon}{d} + \frac{\pi\varepsilon}{\cosh^{-1}(d/t)} \]

Side by side Probe

\[ C = \frac{\pi\varepsilon}{\cosh^{-1}\left((d - w + t)/t\right)} \]

Equivalence diagram:

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Circuit Model

 Probe tail
 Stamp section
 Probe tip

Port1
Z1

Port2
Z2

Z3

Upper Plunger

Barrel

Lower Plunger

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Measurements & Simulation

Measurement Setup
Measurements & Simulation

Ansoft HFSS Simulation

Structure and Boundary conditions.
Measurements & Simulation

Insertion and Return Loss Magnitude

 HFSS Simulation Measurements

 HFSS Simulation Measurements

 HFSS Simulation Measurements
Measurements & Simulation

Insertion and Return Loss Magnitude

HFSS Simulation Measurements

HFSS Simulation Measurements

HFSS Simulation Measurements

Insertion Loss S11 (dB)

Insertion Loss S21 (dB)

Insertion Loss S12 (dB)

Return Loss S22 (dB)
Measurements & Simulation

Insertion and Return Loss Phase

- HFSS Simulation Measurements
- HFSS Simulation Measurements
- HFSS Simulation Measurements
Circuit Model & Model Verification

Lumped Circuit $\pi$ Model

Upper Plunger

Barrel

Lower Plunger
Circuit Model & Model Verification

Circuit Model Parameters (Total L & C)

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Circuit Model & Model Verification

Circuit Model Parameters (total R & G)

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Circuit Model & Model Verification

TL Circuit Model S-Parameters

- **Return Loss S11 (dB)**
  - HFSS Simulation
  - Measurements
  - TL Model

- **Insertion Loss S12 (dB)**
  - HFSS Simulation
  - Measurements
  - TL Model

- **Return Loss S22 (dB)**
  - HFSS Simulation
  - Measurements
  - TL Model
Circuit Model & Model Verification

TL Circuit Model S-Parameters

- **Return Loss Phase S11 (degree)**
  - HFSS Simulation
  - Measurements
  - TL Model
  - Frequency range: 0 to 20 GHz

- **Insertion Loss Phase S12 (degree)**
  - HFSS Simulation
  - Measurements
  - TL Model
  - Frequency range: 0 to 20 GHz

- **Insertion Loss Phase S21 (degree)**
  - HFSS Simulation
  - Measurements
  - TL Model
  - Frequency range: 0 to 20 GHz

- **Return Loss Phase S22 (degree)**
  - HFSS Simulation
  - Measurements
  - TL Model
  - Frequency range: 0 to 20 GHz
Circuit Model & Model Verification

Measurements vs. Model Magnitude & Phase

Error in insertion loss $<S_{21}$ & $<S_{12}$ (degree)

Error in insertion loss $|S_{21}|$ & $|S_{12}|$ (dB)
Lumped and TL circuit models had been developed using close form Wideband solution.

Two models were developed. One for circular cross section and one for rectangular cross section.

Models had been analyzed for 400um probe spacing.

Results show a good match with maximum magnitude error of 0.5dB and phase error of 12 degree at high frequency.
CONCLUSION

- Using a closed form model, minimize simulation time and cost.
- Closed form model can be used for quick product feasibility.
- Model can be integrated with other probe card components to obtain a full performance prior to manufacturing to minimize risks and design optimization time delays.
- TL model provides better results compared with lumped circuit model, where distribution effect takes place.
References


