Modeling and Analysis of the Effects of Electrical Contact Degradation on High-Speed Signal Transmission

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Abstract: Electrical contact failures may alter the signals that are being transmitted and is one of the major causes of system failure. In this letter, an equivalent model of the connector with a degraded contact surface is developed and its transmission characteristics are analyzed. The effects of electrical contact degradation on high-speed digital signal transmission are studied. And the experimental results verify the theoretical analysis. The results of this letter are helpful in developing a better understanding of high-speed connection devices, and provide a theoretical support to identify failure features in fault diagnosis.

Keywords: electrical connector, contact failure, equivalent model, high-speed signal

Classification: Microwave and millimeter wave devices, circuits, and systems

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1 Introduction

In recent years, the development of electronic communication technology drives an increasing demand on wider bandwidth of the interconnection component [1]. Being one of the essential parts in an interconnect system, electrical connector has become a bottleneck to increase the bandwidth and data rate of the system. Of particular interest are applications when the connectors are operated in harsh environments and the contact surface may degrade due to contaminants and corrosion [2-3].

For low data rates, the rise time is long, and the connector could be modeled as a “lumped parameter circuit”. Kondo, et al. [4] studied the relationship between contact resistance and fracture of oxide film for connector contacts. Dervos, et al. [5] studied the generation mechanisms of contact capacitance. As demonstrated in [6-7], the effects of capacitance and resistance were investigated. Rui et al. [8] proposed an equivalent circuit for coaxial connector with a degraded contact surface. But for high speed data, with the decreasing of the rise time, the transmission characteristics of the interconnect component is required to be studied, and the signal integrity of the interconnected component should be considered. Ryu, et al. [9] investigated a microwave model of an anisotropic conductive film flip-chip interconnection. Q. M. Shen et al. [10] simulated the impact of electrical contact resistance on signal transmission and provided an approach to solve the troublesome problem of electrical connector intermittent fault.

In this letter, the distributed parameters of the connector were considered, an equivalent transmission line model of the coaxial connector was developed and the transmission characteristics were analyzed. Furthermore, the effects of connector contact degradation on high speed digital signal transmission were theoretically
studied both in time domain and frequency domain. Finally, a series of experiments were performed to verify the theoretical analysis.

2 Theory analysis

A pair of coaxial connector consists of a pin and a receptacle. Both of the pin and receptacle are made up of inner conductor, dielectric layer and outer conductor. A typical coaxial connector junction interface is shown in Fig. 1. The left part presents the receptacle and the right part is the pin.

The signals propagate between the inner conductor and outer conductor in the connector. The coaxial connector could be analyzed as a transmission line model. The equivalent circuit parameters resistance \( R \), capacitance \( C \) and inductance \( L \) are not lumped together, but are uniformly distributed along the length of the connector. For a small line segment of length \( \Delta z \) metres,

\[
L = \frac{\mu}{2\pi} \ln \frac{b}{a} \quad \text{H/m}, \quad C = \frac{2\pi\varepsilon}{\ln \frac{b}{a}} \quad \text{F/m}, \quad R = \frac{R_\text{f}}{2\pi} \left( 1 + \frac{1}{b} \right) \quad \text{ohm/m} \quad \text{and} \quad G = \frac{2\pi\sigma}{\ln \frac{b}{a}} \quad \text{S/m},
\]

where \( \omega \) is the angular frequency of the transmission signals, \( a \) is the radius of the inner conductor, \( b \) is the radius of the outer conductor, \( u \) is the permeability of the dielectric layer, \( R_\text{f} = \text{Re}(1 + j \omega\delta) / (\sigma\delta) = \sqrt{\mu\sigma / (2\sigma)} \) is the surface resistance, \( \sigma \) and \( u_c \) are the conductivity and permeability of the conductor respectively, \( \delta_s \) is the skin depth, and the complex permittivity of the dielectric layer is \( \varepsilon = \varepsilon' + \varepsilon'' j \).

With the growth of corrosion at the contact surface between the pin and receptacle, a substantial capacitance \( C_f \) and contact resistance \( R_f \) will occur as the contact area becomes covered with a corrosion film. Based on the analysis above, the transmission line model of a coaxial connector considered in Fig. 2 can be formulated as described in the following paragraphs.

![Fig. 1. Schematic of a coaxial connector mating interface.](image1)

![Fig. 2. Interpolation of a degraded contact surface along the inner conductor of a coaxial connector pair.](image2)
As shown in Fig. 2, a coaxial connector pair in Fig. 1 can be modeled in three parts: the impedance model induced by the contact surface, and the other two coaxial parts (female connector and male connector). \( \gamma = \sqrt{(R + joL(G + joC)} \) is known as the propagation constant, and \( l_i \) is the length of section \( i \).

For contact surface in Fig. 1, assume the corrosion film covers the contact surface uniformly, the pin, corrosion film and receptacle constitute a small coaxial structure. Accordingly, an estimate of the capacitance and resistance can be made by using the following equations:

\[
C_f = \frac{2\pi\varepsilon_0\varepsilon_f L_f}{\ln((a_1+s)/a_2)}
\]

\[
R_f = \frac{s}{(\sigma_f 2\pi a_2 L_f)}
\]

where \( L_f \) is the length of the metal-film-metal contact, \( \varepsilon_f \), \( s \), and \( \sigma_f \) are the permittivity, thickness, and conductivity of the corrosion film, respectively. The impedance induced by the degraded contact surface could be calculated as

\[
Z_c = R_f/(1 + joC_f, R_f)
\]

For female connector and male connector sections in Fig. 2, the ABCD matrix of each section can then be expressed as shown in (3). [11]

\[
\begin{bmatrix}
A_i & B_i \\
C_i & D_i
\end{bmatrix} =
\begin{bmatrix}
\cosh(\gamma_i l_i) & \sinh(\gamma_i l_i)/Z_{0(i)} \\
\sinh(\gamma_i l_i)/Z_{0(i)} & \cosh(\gamma_i l_i)
\end{bmatrix}
\]

where \( i = 1,2 \). For a 50 Ohm system, \( Z_{0(1)}=Z_L=50 \) Ohm.

The ABCD matrix of the contact surface could be calculated as shown in (4).

\[
\begin{bmatrix}
A_f & B_f \\
C_f & D_f
\end{bmatrix} =
\begin{bmatrix} 1 & Z_c \end{bmatrix}
\]

The model for the complete connector is the cascade of these three sections. Accordingly, the equivalent ABCD matrix of the connector is shown in Eq. (5).

\[
\begin{bmatrix}
A_{eq} & B_{eq} \\
C_{eq} & D_{eq}
\end{bmatrix} =
\begin{bmatrix}
A_i & B_i \\
C_i & D_i
\end{bmatrix}
\begin{bmatrix}
A_f & B_f \\
C_f & D_f
\end{bmatrix}
\]

Accordingly, the transfer function can be calculated as

\[
T = V_2/V_1 = Z_L/(A_{eq}Z_L+B_{eq})
\]

The transfer function of a SMA (SubMiniature version A) coaxial connector corroded for 2 hours is estimated as an example. Based on the SEM (scanning electron microscope) analysis, it is found that the corrosion film is mainly composed of nickel oxide, and the average thickness of the film could be measured as \( s=8.2 \) um. According to reference [12], the relative permittivity of the nickel oxide is \( \varepsilon_r \approx 11 \). The resistance could be measured by a microhmmeter, and the result is \( R_f=12 \) Ohm. Accordingly, the amplitude and phase of the transfer function could be calculated as shown in Fig. 3(a) and Fig. 3(b).

Assume the input signal \( v(t) \) is a square signal with a frequency of \( m \), a rise time of \( \tau \), the high level is \( x \), low level is zero, and the duty ratio is 50%. Accordingly, the cutoff frequency \( F \) could be calculated as \( F = 0.35/\tau \). The input signal can be displayed in the form of Fourier expansion:

\[
v(t) = \frac{4x}{\pi} \left[ \sin 2\pi ft + \frac{1}{3} \sin 6\pi ft + ... + \frac{1}{n} \sin 2n\pi ft + ... \right] + \frac{x}{2}
\]

where \( f = 0.5m \) , and \( nf = F = 0.35/\tau \) .Thus, the number of harmonics is \( n = 0.7/(m\tau) \) . The input signal in frequency domain is \( V(\omega) = \mathcal{F}(v(t)) \), where \( \mathcal{F} \) represents the Fourier transform.
The output signal in frequency domain is calculated as $V_2(\omega) = V_1(\omega)T(\omega)$, and the output signal in time domain is $v_2(t) = \mathcal{F}^{-1}(V_1(\omega)T(\omega))$.

If the signal frequency is 1 Gbps, the high level $x=200$ mV and the rise time is $\tau=100$ ps, the number of harmonics could be calculated as $n=7$. The input and output signals in time domain are shown in Fig. 4(a). And the input and output signal in frequency domain are shown in Fig. 4(b).

In time domain, due to the capacitive characteristics of the degraded contact surface, the degraded connector presents a charge-discharge behavior in the system. As the connector and load are in series in the circuit, the input voltage is the sum of the voltage on the connector and the voltage on the load. When the connector is charging, the voltage on it will increase, and the output voltage will decrease. In contrary, when the connector is discharging, the output voltage will increase. Accordingly, the results in Fig. 4(a) can be explained.

In frequency domain, the input signal is the sum of a series of signals in different frequency. When the input signals transfer through the degraded connector to the load, the capacitive contact surface will attenuate the low frequency signals, as shown in Fig. 4(b). Furthermore, the higher of the capacitance value of the connector, the smaller attenuation of the output signal harmonics will be.

3 Experiment and discussion
A series of experiments are performed to further discuss the effects of the degraded
connector on high-speed signals. SMA coaxial connectors are chosen as the samples considered in this study. Both of an un-degraded connector and a connector corroded for 2 hours are tested. In this letter, an Agilent network analyzer E5071C was used to measure the eye diagrams of the connectors. The data rate is set to 1 Gbps, the rise time is set to 100 ps, the high level of the input signal is 200 mV, and the low level is 0. Fig. 5 and Fig. 6 show the eye diagrams for un-degraded and degraded connector, respectively.

![Fig. 5. Eye diagram for an un-degraded connector.](image1)

![Fig. 6. Eye diagram for a degraded connector.](image2)

In Fig. 5, the measured rise time and fall time is 100 ps, the jitter p-p is 3.125 ps, and the signal-to-noise ratio is 2.123 k. These results indicate the connector works well. Inspection of Fig. 6 shows the eye diagram for a degraded connector. Obviously, the transfer performance is degraded. The rise time and fall time is 80 ps, the jitter p-p is 6.25 ps, which is larger than 3.125 ps (the value of un-degraded connector). And the signal-to-noise ratio is reduced to 10.33. These results are accordance with the theoretical analysis before.

4 Conclusion

In this letter, the effects of connector contact degradation on digital signal transmission performance have been analyzed. An equivalent model of the connector with a degraded contact surface is developed based on the transmission line theory. And its transmission characteristics in the transmit path are analyzed. The experimental results verify the theoretical analysis. It is found that the connector degradation will lead to distortion of the input waveform and cause voltage noise and jitter. The results of this letter are helpful in developing a better understanding of possible failure modes and in identifying failure features in fault diagnosis for digital systems.