ELECTROMAGNETIC SHIELDING EVALUATION OF CONDUCTIVE O-RINGS

Shinichiro Yamamoto†, Kenichi Hatakeyama†, Kenji Yamauchi†, Takeshi Yamada††
† Himeji Institute of Technology
E-mail: yamamoto.shinichiro@clnics.eng.himeji-tech.ac.jp
†† NOK Corporation
E-mail: yamada88@nok.co.jp

Abstract: A shielding evaluation method of conductive O-rings are proposed. With the sample holder proposed here shielding evaluation can be carried out at frequencies from 10kHz to 1GHz. Measured results for plane wave incidence are presented.

Key words: Conductive O-ring, Shielding effects

1. Introduction

Shielding design is one of the critical issues in high-speed, sensitive electric circuits and devices. There exist various kinds of materials for the shielding [1]. O-rings generally made from synthetic rubber are applied widely to seal mechanically moving parts for preventing oil, air, and dust-blow so far. Recently, since many electric circuits are integrated in machines, O-rings providing a simultaneous EMI gasket and hermetic/oil/pressure seal are required.

In order to meet the requirement, we developed conductive O-rings that are made from carbon impregnated rubbers in which short conductive fibers are dispersed.

Since the O-rings are fixed in narrow gaps between metallic surfaces in two ways called cylinder-fixing and plane-fixing [3], a test instrument with which shielding efficiency for both fixing types can be evaluated is necessary. Conventional techniques [1], [2] are, even with minor modifications, inadequate for this purpose. The authors proposed an elaborately designed coaxial-type sample holder that overcome this difficulty [3], [4]. In this paper, shielding characteristic of the O-rings are tested with this holder, and relationships between shielding effects, conductive additive content are discussed.

2. Sample Holder

2.1 O-rings and the Sample Holder

Figure 1 shows cylinder-fixing and plane-fixing types of O-rings. From a view point of electromagnetic wave propagation in the gaps, the cylinder-fixing and plane-fixing O-rings are considered to be gaskets inserted into a coaxial line and a parallel-plate radial line, respectively.

Fig.1 O-ring fixing types

The outer and inner diameter of the O-rings tested here are 25mm and 20mm, respectively. The ring thickness is 2.5mm. The rings are made from CR rubber in which short conductive fibers are dispersed randomly. The conductive filler amount is from 0 to 80phr, and relationship between the fillers and the shielding efficiency is investigated experimentally. Figure 2 illustrates the cross section view of the sample holder proposed here. The holder sizes of  a_2, a_3, b_3, L, d_1, d_2 are 3.5mm, 10mm, 12mm, 5mm, 9mm, 9mm for cylinder-fixing, and 3.5mm, 14mm,
18mm, 5mm, 2mm, 9mm for plane-fixing. Then the space distance where rings are inserted is 2mm in length while the ring is 2.5mm in thickness. Then the O-rings are compressed to 80% in thickness to obtain good electrical contact.

The both end lines of the holder are input/output sections whose characteristic impedance is 50 Ω. They are connected to Network Analyzer ports through 50 Ω coaxial cables to measure reflection and transmission coefficients. Figure 3 shows the photo of the holder assembled.

2.2 Reflection and Transmission Characteristics of the Holder

The sample holder is devised into 3 transmission lines, two parallel-plate radial lines and a coaxial line. Planes at both ends of each transmission line are designated p1, p2, ..., p8 as shown in Fig.4.

$V_{pm}$, $I_{pm}$ and $Z_{pm}$ ($m=1, 2, ..., 8$) are defined as the voltage across the m-th plane, the current flowing in the outer conductor of the m-th plane, and the input impedance at the m-th plane, respectively. Since the separation between the adjacent planes such as p1 and p2, p3 and p4, p5 and p6, p7 and p8 are much shorter than the wavelength, these adjacent planes are supposed to be electrically coincide, that is, $V_{p1} = V_{p2}$, $I_{p1} = I_{p2}$, ..., $V_{p7} = V_{p8}$, $I_{p7} = I_{p8}$.

Fields Between p2-p3, and p6-p7 Planes

Sections between p2-p3, and p6-p7 are considered to be radial lines where electromagnetic waves propagate toward radial directions. Field components are expressed with a cylindrical coordinate system. Since the gap distance here is very short compared to the wavelength, only $E_r$ and $H_\phi$ components can exist in the gap [5]. $E_r$ and $H_\phi$ are given as,

$$E_r = C_1 H_0^{(1)}(k\rho) \left( 1 + \frac{C_2 H_0^{(2)}(k\rho)}{C_1 H_0^{(1)}(k\rho)} \right)$$

(1)

$$H_\phi = -\frac{k}{j\omega \mu_0} C_1 H_1^{(1)}(k\rho) \left( 1 + \frac{C_2 H_1^{(2)}(k\rho)}{C_1 H_1^{(1)}(k\rho)} \right)$$

(2)

where, $H_0^{(2)}$ and $H_0^{(2)}$ are the 1st and 2nd kinds of 0th order Hankel Functions, and $H_1^{(1)}$ and $H_1^{(2)}$ are the 1st and 2nd kinds of 1st order Hankel Functions, respectively. $k = \omega \sqrt{\varepsilon_0 \varepsilon_r \mu_0}$, $\omega = 2 \pi f$. $\mu_0$ is permeability of free space, and $C_1$ and $C_2$ are coefficients of the Hankel Functions. From Eqs.(1), (2), $V_{p7}$ and $I_{p7}$ are obtained as,

$$V_{p7} = -\frac{d_2}{2} E_{p7} \quad I_{p7} = 2\pi a_2 H_{4p7}$$

(3)

From Eqs.(1)-(3) at $\rho = a_3$, the input impedance $Z_{p7}$ at the p7 plane is given by $V_{p7} / I_{p7}$. With the same manner, $Z_{p6}$ is obtained at $\rho = a_3$.

When the O-ring for plane-fixing is measured, the ring is placed between p2 and p3. In this case, the ring is expressed as a ramped element of admittance $Y_\gamma$ as shown in Fig.5(a). $Z_{p2}$ in the figure can be obtained from $Z_{p3}$ and $Y_\gamma$.

$$Z_{p2} = \frac{1}{Y_\gamma + 1 / Z_{p3}}$$

(4)

In case there exist no sample in place, $Y_\gamma$ becomes 0.

Fields Between p4-p5 Plane

This section is considered to be a coaxial line. The relationships between $V_{p4}$, $I_{p4}$ and $V_{p5}$, $I_{p5}$ are given by the 2 port transmission line theory. When the O-ring is inserted between p4 and p5 as shown in Fig.5(b), the equations are given as,

$$\begin{pmatrix} V_{p4} \\ I_{p4} \end{pmatrix} = \begin{pmatrix} F_1 & F_3 \\ F_1 \end{pmatrix} \begin{pmatrix} V_{p5} \\ I_{p5} \end{pmatrix}$$

(5)

where,

$$\begin{pmatrix} F_{1,1} \\ F_{1,2} \end{pmatrix} = \begin{pmatrix} \cosh \gamma_{1,s} L_{1,s} & Z_{w1, w} \sinh \gamma_{1,s} L_{1,s} \\ \frac{1}{Z_{w1, w}} \sinh \gamma_{1,s} L_{1,s} & \cosh \gamma_{1,s} L_{1,s} \end{pmatrix}$$

(6)
Fig. 5 (a) Y1 of the plane-fixing O-ring  
(b) p4-p5 plane of the cylinder fixing O-ring

In Eq. (6), $F_1$ is $(F_1)$ or $(F_4)$, and accordingly $Z_{ac}$ is $Z_{ac1}$ or $Z_{ac2}$, $y_{ac1}$ is $y_{ac1}$ or $y_{ac2}$, $L_{ac1}$ is $L_1$ or $L_2$. Also, $Z_{ac1}$, $Z_{ac2}$, $y_{ac1}$, $y_{ac2}$ are given as,

$$Z_{ac1} = \frac{\xi_0}{2\pi} \ln \frac{b_1}{a_0}, \quad Z_{ac2} = \frac{Z_{pl1}}{\sqrt{\varepsilon_r}} \quad (7)$$

$$y_{ac1} = j \frac{2\pi}{\lambda_0}, \quad y_{ac2} = y_{ac1} \sqrt{\varepsilon_r} \quad (8)$$

where, $\lambda_0$ is wavelength in free space, $\varepsilon_r$ is a relative permittivity of the ring material, and $\xi_0$ is a intrinsic impedance in free space. The O-ring compressed in the gap is approximated to have a rectangular shape cross section whose area is the same as an original uncompressed circular shape. Then $L_1$ is 2.45mm, $Z_{pl1}$ and $Z_{pl2}$ are given as,

$$Z_{pl1} = V_{pl1}/I_{pl1}, \quad Z_{pl2} = V_{pl2}/I_{pl2} \quad (9)$$

In case there exist no sample in place, $L_0$ becomes 0.

**Reflection and Transmission Coefficients**

$Z_{pl1}$ is given as,

$$Z_{pl1} = V_{pl1}/I_{pl1} = V_{pl2}/I_{pl2} = Z_{pl2} = 50 \, \Omega \quad (10)$$

From Eq. (1)-(3), Eq. (10) can be expressed as,

$$50 = j \frac{d_2}{2\pi a_2} \xi Q_{00} \left( 1 + \frac{C_2}{C_1} \frac{Q_{01}}{Q_{10}} \right) \quad (11)$$

$$Q_{00} = \frac{H_{00}^{(1)}(ka_2)}{H_{00}^{(2)}(ka_2)}, \quad Q_{01} = \frac{H_{01}^{(1)}(ka_2)}{H_{01}^{(2)}(ka_2)}, \quad Q_{11} = \frac{H_{10}^{(1)}(ka_2)}{H_{10}^{(2)}(ka_2)} \quad (12)$$

where, $\xi = \omega \mu_0 a / k$. By using $C_2/C_1$ value obtained from Eq. (11) and changing the $\rho$ value from $a_2$ to $a_3$, $Z_{pl}$ is obtained. According to the assumption stated in 2.2, $Z_{pl}$ equals $Z_{pl2}$. Then $Z_{pl}$ is given by Eq. (5). By continuing the same manner, we finally obtain $Z_{pl1}$, which leads to the reflection coefficient $\Gamma$ at p1. $\Gamma$ is given as,

$$\Gamma = \frac{Z_{pl1} - 50}{Z_{pl1} + 50} \quad (13)$$

As the input voltage $V_{in}$ at p1 plane equals $V_{pl1} / (1 + \Gamma)$, the transmission coefficient $T$ is given as,

$$T = \frac{V_{pl1}}{V_{in}} = \frac{V_{pl1}(1 + \Gamma)}{V_{pl1}} \quad (14)$$

The shielding effectiveness $S$ of the O-ring is given as $S = |\Gamma|$.

Figure 6 shows the calculated value from Eqs. (13), (14) of reflection and transmission coefficients of the holder for cylinder-fixing and plane-fixing types with no ring in place. The calculated results of the cylinder-fixing are agree well to that of the plane-fixing. Also, the measured results for each fixing type agree well to the calculated ones.

The reflection becomes smaller as frequency decreases. At frequencies below 1GHz, the transmission coefficients are almost 0dB ($|\Gamma|=1$), and the reflection coefficients are less than -10dB. We consider that the reliable values of shielding efficiency can be obtained with this holder at frequencies below to 1GHz.

**2.3 Shielding Effects of the O-ring**

When the O-ring material conductivity $\sigma_m$ is given, $Y_s$ in Eq. (4) and the relative permittivity $\varepsilon_r$ of the material in Eqs. (7), (8) are given as,

$$Y_s = \frac{2\pi}{\lambda_0} \frac{a_L \sigma_m}{d_1}, \quad \varepsilon_r = \frac{a_L \sigma_m}{\varepsilon_0} \quad (15)$$

where, $L_1$ is a ring thickness, 2.45mm. Figure 7 shows S values calculated by the use of $Y_s$ in Eq. (4) for plane-fixing, and from Eqs. (5)-(8) for cylinder-fixing. In the calculation, the material conductivity is $\sigma_m = 10$(S/m) and 100(S/m). From these examples calculated, we find that S values depend on the
material conductivity, and for the same value of the conductivity, both fixing types of O-rings give almost the same shielding effects at frequencies lower than 1GHz. Due to undesired reflections of the holder, the calculation at frequencies higher than 1GHz do not show reasonable values.

Fig.7 Shielding effects for both fixing types

3. Shielding Effects of the O-rings

Figures 8 shows the measured S values for cylinder-fixing and plane-fixing O-rings made from CR rubber. The conductive filler amounts are 0pfr, 60pfr, and 80pfr. The higher the filler amount, the larger the shielding effect. From the values for C1(conductive filler:0pfr), S values have frequency dependency, that is, at frequencies lower than around 1MHz S values are mostly the same, while they become greater as frequency increases at frequencies higher than 1MHz. In contrast, the frequency dependency is not appeared in the S values of C2(conductive filler:60pfr) and C3(conductive filler:80pfr). The O-rings containing conductive filler of 60pfr and 80pfr have shielding effects greater than 40dB.

The S values for the cylinder-fixing are mostly the same as those for the plane-fixing. As for C1 sample, S values for cylinder-fixing are greater than plane-fixing S values. The authors think that the conductive filler alignment generates the anisotropy in rubber conductivity that causes the shielding effect discrepancy between the plane- and the cylinder-fixing.

4. Conclusion

The shielding evaluation method of the conductive O-rings is introduced. By the use of the holder, the shielding effects for both the cylinder- and the plane-fixing can be measured from 10kHz to 1GHz.

The O-rings tested here are made from CR rubber in which conductive fillers are embedded as well as carbon particles. The conductive filler mixing makes shielding effects enhance up to around -40dB.

The rings without the conductive fillers show frequency dependence in S values, for example, C1 sample shows -10dB at frequencies lower than 1MHz and -30dB higher than 100MHz. However, the S values for C2, C3(O-rings made from CR rubber with filler content of 60pfr and 80pfr) are greater than 40dB and are almost kept constant over the range from 10kHz to 100MHz. To clear up the frequency dependency in shielding effect due to the filler content, further experimental investigations will be necessary.

References