

# 高周波ケーブルの特性計算近似式 APPROXIMATION CALCULATION OF ELECTRICAL PROPERTY ON HIGH FREQUENCY CABLE

$d_1$  : 内部導体の外径 (mm)  
 $d_2$  : 外部導体の内径 (mm)  
 $\rho_0$  : 標準軟銅の固有抵抗 ( $m\mu\Omega \cdot cm$ )  
 $\rho_1$  : 内部導体の固有抵抗 ( $m\mu\Omega \cdot cm$ )  
 $\rho_2$  : 外部導体の固有抵抗 ( $m\mu\Omega \cdot cm$ )  
 $f$  : 周波数 (MHz)  
 $\varepsilon$  : 合成誘電率  
 $\tan \delta$  : 合成誘電体力率

## 一次定数

高周波抵抗 :  $R (\Omega/\text{loop} \cdot \text{km}) = 2\sqrt{f(\text{MHz})} \left[ \frac{\sqrt{\rho_1}}{d_1} + \frac{\sqrt{\rho_2}}{d_2} \right]$   
 外部インダクタンス :  $Le (\text{mH}/\text{km}) = 0.21 \ln \frac{d_2}{d_1} = 0.4605 \log_{10} \frac{d_2}{d_1}$   
 内部インダクタンス :  $Li (\text{mH}/\text{km}) = \frac{10^{-3}}{\pi\sqrt{f(\text{MHz})}} \left[ \frac{\sqrt{\rho_1}}{d_1} + \frac{\sqrt{\rho_2}}{d_2} \right]$   
 インダクタンス :  $L (\text{mH}/\text{km}) = Le + Li \approx Le$   
 静電容量 :  $C (\text{pF}/\text{m}) = \frac{10^3 \varepsilon}{18 \ln \frac{d_2}{d_1}} = \frac{55.6 \varepsilon}{\ln \frac{d_2}{d_1}} = \frac{24.12 \varepsilon}{\log_{10} \frac{d_2}{d_1}}$   
 漏洩量 :  $G (\mu\text{S}/\text{km}) = 2\pi f (\text{MHz}) \cdot C (\text{nF}/\text{km}) \cdot \tan \delta \times 10^3$

## 二次定数

抵抗減衰定数 :  
 $\alpha_r (\text{np}/\text{km}) = \frac{1}{2} \frac{R (\Omega/\text{loop} \cdot \text{km})}{Z (\Omega)} = \frac{\sqrt{\varepsilon} f (\text{MHz})}{60} \frac{\left[ \frac{\sqrt{\rho_1}}{d_1} + \frac{\sqrt{\rho_2}}{d_2} \right]}{\ln \frac{d_2}{d_1}}$   
 $\alpha_r (\text{dB}/\text{km}) = 4.343 \frac{R (\Omega/\text{loop} \cdot \text{km})}{Z (\Omega)} = 0.0629 \sqrt{\varepsilon} f (\text{MHz}) \frac{\left[ \frac{\sqrt{\rho_1}}{d_1} + \frac{\sqrt{\rho_2}}{d_2} \right]}{\log_{10} \frac{d_2}{d_1}}$   
 漏洩減衰定数 :  $\alpha_g (\text{np}/\text{km}) = \frac{1}{2} G (\text{S}/\text{km}) \cdot Z (\Omega) = 10.47 f (\text{MHz}) \sqrt{\varepsilon} \tan \delta$   
 $\alpha_g (\text{dB}/\text{km}) = 4.343 G (\text{S}/\text{km}) \cdot Z (\Omega) = 90.9 f (\text{MHz}) \cdot \sqrt{\varepsilon} \tan \delta$   
 減衰定数 :  $\alpha = \alpha_r + \alpha_g$   
 位相定数 :  $\beta (\text{rad}/\text{km}) = 2\pi f (\text{MHz}) \sqrt{L (\text{H}/\text{km}) C (\text{F}/\text{km})}$   
 $= 2\pi f (\text{MHz}) \sqrt{L (\text{mH}/\text{km}) C (\text{nF}/\text{km})}$   
 $= \frac{2\pi}{\lambda (\text{km})} = \frac{20}{3} \pi f (\text{MHz}) \sqrt{\varepsilon}$   
 $\beta (\text{deg}/\text{km}) = 1200 f (\text{MHz}) \sqrt{\varepsilon}$

特性インピーダンス :

$$Z_{\infty} (\Omega) = \sqrt{\frac{L (\text{H}/\text{km})}{C (\text{F}/\text{km})}} = \frac{60}{\sqrt{\varepsilon}} \ln \frac{d_2}{d_1} = \frac{138 \cdot 1}{\sqrt{\varepsilon}} \log_{10} \frac{d_2}{d_1} = 60 k \ln \frac{d_2}{d_1}$$

$$= 138 \cdot 1 k \log_{10} \frac{d_2}{d_1} = \frac{10^4}{3} \frac{\sqrt{\varepsilon}}{C (\text{nF}/\text{km})}$$

100MHz以上の比較的低周波では

$$Z_0 = Z_{\infty} + \Delta Z_0 (1-j)$$

$$\Delta Z_0 = \frac{1.98}{\sqrt{\varepsilon} \sqrt{f}} \left( \frac{k_1}{d_1} + \frac{k_2}{d_2} \right), k_1^2 = \rho_1 / \rho_0, k_2^2 = \rho_2 / \rho_0$$

$d_1$  : Outside diameter of inner conductor (mm)  
 $d_2$  : Inner diameter of external conductor (mm)  
 $\rho_0$  : Intrinsic resistance of annealed copper ( $m\mu\Omega \cdot cm$ )  
 $\rho_1$  : Intrinsic resistance of inner conductor ( $m\mu\Omega \cdot cm$ )  
 $\rho_2$  : Intrinsic resistance of external conductor ( $m\mu\Omega \cdot cm$ )  
 $f$  : Frequency (MHz)  
 $\varepsilon$  : Total dielectric constant  
 $\tan \delta$  : Total dielectric loss factor

## PRIMARY CONSTANT

High frequency resistance :  $R (\Omega/\text{loop} \cdot \text{km}) = 2\sqrt{f(\text{MHz})} \left[ \frac{\sqrt{\rho_1}}{d_1} + \frac{\sqrt{\rho_2}}{d_2} \right]$   
 Outer inductance :  $Le (\text{mH}/\text{km}) = 0.21 \ln \frac{d_2}{d_1} = 0.4605 \log_{10} \frac{d_2}{d_1}$   
 Inner inductance :  $Li (\text{mH}/\text{km}) = \frac{10^{-3}}{\pi\sqrt{f(\text{MHz})}} \left[ \frac{\sqrt{\rho_1}}{d_1} + \frac{\sqrt{\rho_2}}{d_2} \right]$   
 Inductance :  $L (\text{mH}/\text{km}) = Le + Li \approx Le$   
 Capacitance :  $C (\text{pF}/\text{m}) = \frac{10^3 \varepsilon}{18 \ln \frac{d_2}{d_1}} = \frac{55.6 \varepsilon}{\ln \frac{d_2}{d_1}} = \frac{24.12 \varepsilon}{\log_{10} \frac{d_2}{d_1}}$   
 Amount of leakage :  $G (\mu\text{S}/\text{km}) = 2\pi f (\text{MHz}) \cdot C (\text{nF}/\text{km}) \cdot \tan \delta \times 10^3$

## SECONDARY CONSTANT

Attenuation constant by resistance :  
 $\alpha_r (\text{np}/\text{km}) = \frac{1}{2} \frac{R (\Omega/\text{loop} \cdot \text{km})}{Z (\Omega)} = \frac{\sqrt{\varepsilon} f (\text{MHz})}{60} \frac{\left[ \frac{\sqrt{\rho_1}}{d_1} + \frac{\sqrt{\rho_2}}{d_2} \right]}{\ln \frac{d_2}{d_1}}$   
 $\alpha_r (\text{dB}/\text{km}) = 4.343 \frac{R (\Omega/\text{loop} \cdot \text{km})}{Z (\Omega)} = 0.0629 \sqrt{\varepsilon} f (\text{MHz}) \frac{\left[ \frac{\sqrt{\rho_1}}{d_1} + \frac{\sqrt{\rho_2}}{d_2} \right]}{\log_{10} \frac{d_2}{d_1}}$   
 Attenuation constant by leakage :  
 $\alpha_g (\text{np}/\text{km}) = \frac{1}{2} G (\text{S}/\text{km}) \cdot Z (\Omega) = 10.47 f (\text{MHz}) \sqrt{\varepsilon} \tan \delta$   
 $\alpha_g (\text{dB}/\text{km}) = 4.343 G (\text{S}/\text{km}) \cdot Z (\Omega) = 90.9 f (\text{MHz}) \cdot \sqrt{\varepsilon} \tan \delta$   
 Attenuation constant :  $\alpha = \alpha_r + \alpha_g$   
 Phase constant :  $\beta (\text{rad}/\text{km}) = 2\pi f (\text{MHz}) \sqrt{L (\text{H}/\text{km}) C (\text{F}/\text{km})}$   
 $= 2\pi f (\text{MHz}) \sqrt{L (\text{mH}/\text{km}) C (\text{nF}/\text{km})}$   
 $= \frac{2\pi}{\lambda (\text{km})} = \frac{20}{3} \pi f (\text{MHz}) \sqrt{\varepsilon}$   
 $\beta (\text{deg}/\text{km}) = 1200 f (\text{MHz}) \sqrt{\varepsilon}$

Characteristic Impedance :

$$Z_{\infty} (\Omega) = \sqrt{\frac{L (\text{H}/\text{km})}{C (\text{F}/\text{km})}} = \frac{60}{\sqrt{\varepsilon}} \ln \frac{d_2}{d_1} = \frac{138 \cdot 1}{\sqrt{\varepsilon}} \log_{10} \frac{d_2}{d_1} = 60 k \ln \frac{d_2}{d_1}$$

$$= 138 \cdot 1 k \log_{10} \frac{d_2}{d_1} = \frac{10^4}{3} \frac{\sqrt{\varepsilon}}{C (\text{nF}/\text{km})}$$

In low frequency (>100MHz)

$$Z_0 = Z_{\infty} + \Delta Z_0 (1-j)$$

$$\Delta Z_0 = \frac{1.98}{\sqrt{\varepsilon} \sqrt{f}} \left( \frac{k_1}{d_1} + \frac{k_2}{d_2} \right), k_1^2 = \rho_1 / \rho_0, k_2^2 = \rho_2 / \rho_0$$

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## その他

合成誘電率：

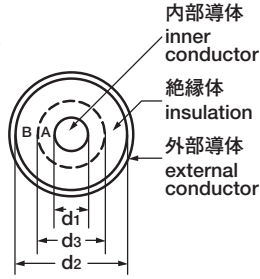
$$\varepsilon = \frac{\varepsilon_A \varepsilon_B P}{\varepsilon_A R + \varepsilon_B Q}, \quad \tan \delta = \frac{\varepsilon_A R \tan \delta_B Q \tan \delta_A}{\varepsilon_B R + \varepsilon_B Q}$$

Aを空気とすれば、 $\varepsilon_A=1$ 、 $\tan \delta_A=0$ となり

$$\varepsilon = \frac{\varepsilon_B P}{R + \varepsilon_B Q}, \quad \tan \delta = \frac{R \tan \delta_B}{R + \varepsilon_B Q}$$

ここに

$$P = \ln \frac{d_2}{d_1}, \quad Q = \ln \frac{d_3}{d_1}, \quad R = \ln \frac{d_2}{d_3}$$



伝播速度：

$$v \text{ (km/sec)} = \frac{2\pi f \text{ (MHz)}}{\beta \text{ (rad/km)}} = \frac{1}{\sqrt{L \text{ (H/km)} C \text{ (F/km)}}} = \frac{3 \times 10^5}{\sqrt{\varepsilon}}$$

波長：

$$\lambda \text{ (km)} = \frac{v \text{ (km/sec)}}{f \text{ (MHz)}} = \frac{2\pi}{\beta \text{ (rad/km)}} = \frac{0.3}{f \text{ (MHz)} \sqrt{\varepsilon}}$$

$$\text{波長短縮率} : k = \frac{1}{\sqrt{\varepsilon}}$$

等価導体層厚：

$$t \text{ (mm)} = \frac{5}{\pi} \sqrt{\frac{\rho \text{ (m}\mu\Omega \cdot \text{cm)}}{\mu \cdot f \text{ (MHz)}}} \times 10^{-3}$$

$$\text{Cu} : \rho = 1724 \dots \mu = 1 \dots t = 0.0661 / \sqrt{f \text{ (MHz)}}$$

$$\text{Al} : \rho = 2620 \dots \mu = 1 \dots t = 0.0809 / \sqrt{f \text{ (MHz)}}$$

$$\text{Sn} : \rho = 11400 \dots \mu = 1 \dots t = 0.170 / \sqrt{f \text{ (MHz)}}$$

$$\text{Pb} : \rho = 21900 \dots \mu = 1 \dots t = 0.236 / \sqrt{f \text{ (MHz)}}$$

$$\text{Fe} : \rho = 10000 \dots \mu = 100 \dots t = 0.0159 / \sqrt{f \text{ (MHz)}}$$

表皮作用による電流密度変化： $i_x = i_0 e^{-\frac{x}{t}}$

直流絶縁抵抗：

$$R\rho \text{ (}\Omega\text{-km)} = \frac{10^{-5} \rho}{2\pi} \ln \frac{d_2}{d_1} = 3.67 \times 10^{-6} \rho \log_{10} \frac{d_2}{d_1}$$

$\rho$ は絶縁体の比抵抗 ( $\Omega\text{-cm}$ )

## OTHERS

Total dielectric constant :

$$\varepsilon = \frac{\varepsilon_A \varepsilon_B P}{\varepsilon_A R + \varepsilon_B Q}, \quad \tan \delta = \frac{\varepsilon_A R \tan \delta_B Q \tan \delta_A}{\varepsilon_B R + \varepsilon_B Q}$$

Regard A as air,  $\varepsilon_A = 1$  and  $\tan \delta_A = 0$ ,

$$\varepsilon = \frac{\varepsilon_B P}{R + \varepsilon_B Q}, \quad \tan \delta = \frac{R \tan \delta_B}{R + \varepsilon_B Q}$$

$$P = \ln \frac{d_2}{d_1}, \quad Q = \ln \frac{d_3}{d_1}, \quad R = \ln \frac{d_2}{d_3}$$

Propagation velocity :

$$v \text{ (km/sec)} = \frac{2\pi f \text{ (MHz)}}{\beta \text{ (rad/km)}} = \frac{1}{\sqrt{L \text{ (H/km)} C \text{ (F/km)}}} = \frac{3 \times 10^5}{\sqrt{\varepsilon}}$$

Wavelength :

$$\lambda \text{ (km)} = \frac{v \text{ (km/sec)}}{f \text{ (MHz)}} = \frac{2\pi}{\beta \text{ (rad/km)}} = \frac{0.3}{f \text{ (MHz)} \sqrt{\varepsilon}}$$

$$\text{Contraction rate of wavelength} : k = \frac{1}{\sqrt{\varepsilon}}$$

Equivalent thickness of conductor :

$$t \text{ (mm)} = \frac{5}{\pi} \sqrt{\frac{\rho \text{ (m}\mu\Omega \cdot \text{cm)}}{\mu \cdot f \text{ (MHz)}}} \times 10^{-3}$$

$$\text{Cu} : \rho = 1724 \dots \mu = 1 \dots t = 0.0661 / \sqrt{f \text{ (MHz)}}$$

$$\text{Al} : \rho = 2620 \dots \mu = 1 \dots t = 0.0809 / \sqrt{f \text{ (MHz)}}$$

$$\text{Sn} : \rho = 11400 \dots \mu = 1 \dots t = 0.170 / \sqrt{f \text{ (MHz)}}$$

$$\text{Pb} : \rho = 21900 \dots \mu = 1 \dots t = 0.236 / \sqrt{f \text{ (MHz)}}$$

$$\text{Fe} : \rho = 10000 \dots \mu = 100 \dots t = 0.0159 / \sqrt{f \text{ (MHz)}}$$

Variation of current density due to skin effect :  $i_x = i_0 e^{-\frac{x}{t}}$

DC insulation resistance :

$$R\rho \text{ (}\Omega\text{-km)} = \frac{10^{-5} \rho}{2\pi} \ln \frac{d_2}{d_1} = 3.67 \times 10^{-6} \rho \log_{10} \frac{d_2}{d_1}$$

$\rho$  : Comparison resistance of insulation ( $\Omega\text{-cm}$ )

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## 金属の物理的性質 PHYSICAL PROPERTIES OF METAL MATERIALS

金属 METAL	体積固有抵抗 VOLUME RESISTANCE (20℃) ( $\mu\Omega \cdot \text{cm}$ )	体積固有抵抗 温度係数 TEMPERATURE FACTOR OF VOLUME RESISTANCE (20℃付近にて1℃につき)	熱起電力 THERMOELECTRO- MOTIVE FORCE (mV)	比重 SPECIFIC GRAVITY (20℃)	線熱膨張係数 THERMAL EXPANSION COEFFICIENT ( $\times 10^{-6}$ ) (20℃)	溶融点 MELTING POINT (℃)
銀 Ag	1.62	0.0038	+0.75	10.5	18.9	960.5
アルミニウム Al	2.62	0.0039	+0.38	2.70	23.0	660.0
金 Au	2.40	0.0034	+0.70	19.3	14.2	1,063.0
ビスマス Bi	115	0.004	-7.25	9.80	13.3	271.0
カルシウム Ca	4.60	—	—	1.55	25.0	810.0
カドミウム Cd	7.50	0.0038	+0.92	8.65	29.8	320.9
コバルト Co	9.70	—	-1.99	8.90	12.3	1,480.0
クロム Cr	2.60	—	—	7.10	8.20	1,615.0
銅 Cu	1.69	0.00393	+0.75	8.92	16.6	1,083.0
鉄 Fe	10.0	0.0050	+1.91	7.86	11.7	1,535.0
水銀 Hg	95.8	0.00089	—	13.55	—	-38.87
イリジウム Ir	6.00	—	+0.65	22.4	6.50	2,550.0
カリウム K	7.00	—	-0.94	0.36	83.0	62.3
リチウム Li	9.30	—	—	0.53	56.0	186.0
マグネシウム Mg	4.46	0.004	+0.42	1.74	25.6	651.0
モリブデン Mo	4.77	0.0033	+1.31	10.2	4.00	2,620.0
ナトリウム Na	4.60	—	-0.21	0.97	71.0	97.5
ニッケル Ni	6.90	0.006	-1.43	8.90	12.8	1,452.0
オスミウム Os	9.00	—	—	22.48	6.10	2,700.0
鉛 Pb	21.9	0.0039	+0.44	11.37	29.1	327.5
パラジウム Pd	10.8	0.0033	-0.78	12.0	11.8	1,555.0
白金 Pt	10.5	0.003	—	21.45	8.90	1,755.0
ルビジウム Rb	12.5	—	—	1.53	90.0	38.5
ロジウム Rh	5.10	—	-0.65	12.5	84.0	1,955.0
錫 Sn	11.4	0.0042	+0.45	7.35	20.0	231.85
ストロンチウム Sr	23.0	—	—	2.60	—	800.0
タンタル Ta	15.5	0.0031	+0.34	16.6	7.00	2,850.0
タングステン W	5.48	0.0045	+0.79	19.3	4.00	3,370.0
亜鉛 Zn	6.10	0.0037	+0.77	7.14	33.0	419.43

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## ゴム・プラスチックケーブル構成材料の物理的性質

### PHYSICAL PROPERTIES OF RUBBER&PLASTICS WHICH ARE USED FOR CABLES CONSTRUCTIVE MATERIALS

材 料 MATERIAL	比 重 SPECIFIC GRAVITY (20℃)	抗張力 TENSILE STRENGTH (MPa)	伸び ELONGATION (%)	比誘電率 DIELECTRIC CONSTANT (60~1 kHz) (20℃)	誘電正接 DIELECTRIC TANGENT (60~1 kHz) (20℃) (%)	破壊電圧 BREAKDOWN VOLTAGE (AC) (kV/mm)	体積固有 抵抗 VOLUME RESISTANCE (20℃) (Ω・cm)	連続使用 温度 CONTINUOUS WORKING TEMPERATURE (℃)
天然ゴム(絶縁用) NATURAL RUBBER (for insulation)	1.30~1.60	8~18	400~600	3~4.50	1.50~3	20~30	10 <sup>15</sup>	-55~60
天然ゴム(シース用) NATURAL RUBBER (for jacket)	1.20~1.50	14~18	400~600	—	—	—	10 <sup>8</sup> ~10 <sup>10</sup>	-55~60
SBR(スチレンブタジエンゴム) SBR (Styrene butadiene rubber)	1.30~1.60	4~8	400~650	3.50~4.50	2~5	20~30	10 <sup>13</sup> ~10 <sup>14</sup>	-50~75
ブチルゴム(絶縁用) BUTYL RUBBER (for insulation)	1.40~1.50	4~6	450~800	3~4.50	1~2.50	20~30	10 <sup>14</sup> ~10 <sup>16</sup>	-40~80
樹脂加硫ブチルゴム RESIN VULCANIZED BUTYL RUBBER	1.40~1.50	—	—	—	—	—	—	-40~100
珪素ゴム SILICONE RUBBER	1.20~1.70	4~6	200~400	3~5	2~4	15~20	10 <sup>14</sup> ~10 <sup>15</sup>	-80~180
ハイパーロン HYPALON	1.40~1.70	8~12	200~350	5.50~7	3~5	20~30	10 <sup>13</sup> ~10 <sup>14</sup>	-25~90
クロロプレンゴム(シース用) CHLOROPRENE RUBBER (for jacket)	1.40~1.60	12~16	400~600	—	—	—	10 <sup>10</sup> ~10 <sup>12</sup>	-40~70
ポリ塩化ビニル POLYVINYL CHLORIDE	1.20~1.50	13~25	200~400	5~7	8~15	20~40	10 <sup>12</sup> ~10 <sup>15</sup>	-20~60
ポリエチレン POLYETHYLENE	0.92	13~17	500~550	2.30	0.03	35~45	10 <sup>17</sup> ~10 <sup>18</sup>	-60~75
架橋ポリエチレン CROSS-LINKED POLYETHYLENE	0.92	14~20	400~520	2.30	0.03	35~45	10 <sup>17</sup> ~10 <sup>18</sup>	-60~100
ポリ四弗化エチレン (PTFE) POLYTETRAFLUOROETHYLENE (PTFE)	2.10~2.20	20~40	150~250	2.00	0.05	15~20	10 <sup>17</sup> ~10 <sup>18</sup>	-90~260
ナイロン NYLON	1.09~1.14	50~70	90~300	3.50	1~4	12~20	10 <sup>10</sup> ~10 <sup>14</sup>	-40~130
エチレンプロピレンゴム ETHYLENE PROPYLENE RUBBER	1.30~1.40	7~8	400~650	4~5	0.50~2	30~40	10 <sup>12</sup> ~10 <sup>15</sup>	-40~90

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