

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)
 ρ_0 : 標準軟銅の固有抵抗 ($m\mu\Omega \cdot cm$)
 ρ_1 : 内部導体の固有抵抗 ($m\mu\Omega \cdot cm$)
 ρ_2 : 外部導体の固有抵抗 ($m\mu\Omega \cdot cm$)
 f : 周波数 (MHz)
 ε : 合成誘電率
 $\tan \delta$: 合成誘電体力率

d_1 : Outside diameter of inner conductor (mm)
 d_2 : Inner diameter of external conductor (mm)
 ρ_0 : Intrinsic resistance of annealed copper ($m\mu\Omega \cdot cm$)
 ρ_1 : Intrinsic resistance of inner conductor ($m\mu\Omega \cdot cm$)
 ρ_2 : Intrinsic resistance of external conductor ($m\mu\Omega \cdot cm$)
 f : Frequency (MHz)
 ε : Total dielectric constant
 $\tan \delta$: Total dielectric loss factor

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 : $Le (\text{mH}/\text{km}) = 0.2 \ln \frac{d_2}{d_1} = 0.4605 \log_{10} \frac{d_2}{d_1}$
 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 : $G (\mu\text{S}/\text{km}) = 2\pi f(\text{MHz}) \cdot C (\text{nF}/\text{km}) \cdot \tan \delta \times 10^3$

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 : $Le (\text{mH}/\text{km}) = 0.2 \ln \frac{d_2}{d_1} = 0.4605 \log_{10} \frac{d_2}{d_1}$
 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 : $G (\mu\text{S}/\text{km}) = 2\pi f(\text{MHz}) \cdot C (\text{nF}/\text{km}) \cdot \tan \delta \times 10^3$

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 :

$Z_0 (\Omega) = \sqrt{\frac{L (\text{H}/\text{km})}{C (\text{F}/\text{km})}} = \frac{60}{\sqrt{\varepsilon}} \ln \frac{d_2}{d_1} = \frac{138 \cdot 1}{\sqrt{\varepsilon}} \log_{10} \frac{d_2}{d_1} = 60k \ln \frac{d_2}{d_1}$
 $= 138 \cdot 1k \log_{10} \frac{d_2}{d_1} = \frac{10^4}{3} \frac{\sqrt{\varepsilon}}{C (\text{nF}/\text{km})}$

100MHz以上の比較的低周波では

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

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

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 :

$Z_0 (\Omega) = \sqrt{\frac{L (\text{H}/\text{km})}{C (\text{F}/\text{km})}} = \frac{60}{\sqrt{\varepsilon}} \ln \frac{d_2}{d_1} = \frac{138 \cdot 1}{\sqrt{\varepsilon}} \log_{10} \frac{d_2}{d_1} = 60k \ln \frac{d_2}{d_1}$
 $= 138 \cdot 1k \log_{10} \frac{d_2}{d_1} = \frac{10^4}{3} \frac{\sqrt{\varepsilon}}{C (\text{nF}/\text{km})}$

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 :

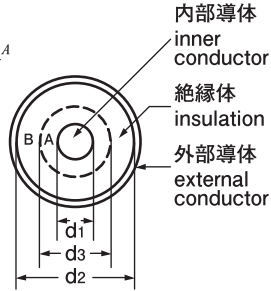
$$\varepsilon = \frac{\varepsilon_A \varepsilon_{BP}}{\varepsilon_{AR} + \varepsilon_{BQ}}, \quad \tan \delta = \frac{\varepsilon_{AR} \tan \delta_{BQ} \tan \delta_A}{\varepsilon_{BR} + \varepsilon_{BQ}}$$

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

$$\varepsilon = \frac{\varepsilon_{BP}}{R + \varepsilon_{BQ}}, \quad \tan \delta = \frac{R \tan \delta_B}{R + \varepsilon_{BQ}}$$

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 :

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

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

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

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

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

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

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

直流絶縁抵抗 :

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

ρ は絶縁体の比抵抗 ($\Omega\text{-cm}$)

OTHERS

Total dielectric constant :

$$\varepsilon = \frac{\varepsilon_A \varepsilon_{BP}}{\varepsilon_{AR} + \varepsilon_{BQ}}, \quad \tan \delta = \frac{\varepsilon_{AR} \tan \delta_{BQ} \tan \delta_A}{\varepsilon_{BR} + \varepsilon_{BQ}}$$

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

$$\varepsilon = \frac{\varepsilon_{BP}}{R + \varepsilon_{BQ}}, \quad \tan \delta = \frac{R \tan \delta_B}{R + \varepsilon_{BQ}}$$

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

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 :

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

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

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

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

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

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

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

DC insulation resistance :

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

ρ : 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°C) ($\mu\Omega \cdot \text{cm}$)	体積固有抵抗 温度係数 TEMPERATURE FACTOR OF VOLUME RESISTANCE (20°C付近にて1°Cにつき)	熱起電力 THERMOELECTRO- MOTIVE FORCE (mV)	比重 SPECIFIC GRAVITY (20°C)	線熱膨張係数 THERMAL EXPANSION COEFFICIENT ($\times 10^{-6}$) (20°C)	溶融点 MELTING POINT (°C)
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mium 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℃) ($\Omega \cdot \text{cm}$)	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^{15}	- 55 ~ 60
天然ゴム (シース用) NATURAL RUBBER (for jacket)	1.20 ~ 1.50	14 ~ 18	400 ~ 600	—	—	—	$10^8 \sim 10^{10}$	- 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	$10^{13} \sim 10^{14}$	- 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	$10^{14} \sim 10^{16}$	- 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	$10^{14} \sim 10^{15}$	- 80 ~ 180
ハイパロン HYPALON	1.40 ~ 1.70	8 ~ 12	200 ~ 350	5.50 ~ 7	3 ~ 5	20 ~ 30	$10^{13} \sim 10^{14}$	- 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	—	—	—	$10^{10} \sim 10^{12}$	- 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	$10^{12} \sim 10^{15}$	- 20 ~ 60
ポリエチレン POLYETHYLENE	0.92	13 ~ 17	500 ~ 550	2.30	0.03	35 ~ 45	$10^{17} \sim 10^{18}$	- 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	$10^{17} \sim 10^{18}$	- 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	$10^{17} \sim 10^{18}$	- 90 ~ 260
ナイロン NYLON	1.09 ~ 1.14	50 ~ 70	90 ~ 300	3.50	1 ~ 4	12 ~ 20	$10^{10} \sim 10^{14}$	- 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	$10^{12} \sim 10^{15}$	- 40 ~ 90

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