LockedFP Block Diagram

```
<< Graphics`
```

Equation

ブロックダイアグラムを連立方程式であらわし, ν_4 を求めます.

$$\mathrm{Simplify}[\mathrm{Solve}[\{\nu_1 == \nu_0 - (\nu_2 * P_{MC} * H_{MC,PD} + N_{MC} + (\nu_3 * P_{IN} * H_{IN,PD} + N_{IN}) * C_{IN} * C_{FA}) * C_0 * (H_{PZT} * C_{PZT} + H_{EOM} * C_{EOM}),\ \nu_2 == \nu_1 - (\nu_{MC} - ((\nu_3 * P_{IN} * H_{IN,PD} + N_{IN}) * C_{IN} * C_{MC} + N_{MCEND}) * H_{MC,END}),\ \nu_3 == \nu_4 - \nu_{IN},\ \nu_4 == \nu_1 * P_{MC} + (\nu_{MC} - ((\nu_3 * P_{IN} * H_{IN,PD} + N_{IN}) * C_{IN} * C_{MC} + N_{MCEND}) * H_{MC,END}) * (1 - P_{MC})\},\ \{\nu_4\},\ \{\nu_1, \nu_2, \nu_3\}]]$$

General::spell1 : スペル間違いの可能性があります. 新規シンボル"END"はすでにあるシンボル"End"に似ています. 詳細

$$\{\{\nu_4 \to (\nu_{MC} - C_{IN} C_{MC} N_{IN} H_{MC,END} - N_{MCEND} H_{MC,END} + C_{IN} C_{MC} P_{IN} \nu_{IN} H_{IN,PD} H_{MC,END} + P_{MC} (\nu_0 - \nu_{MC} + (N_{MCEND} + C_{IN} C_{MC} (N_{IN} - P_{IN} \nu_{IN} H_{IN,PD})) H_{MC,END}) - C_0 (C_{EOM} H_{EOM} + C_{PZT} H_{PZT}) P_{MC} (N_{MC} + C_{FA} C_{IN} (N_{IN} - P_{IN} \nu_{IN} H_{IN,PD}) + (-\nu_{MC} + (N_{MCEND} + C_{IN} C_{MC} (N_{IN} - P_{IN} \nu_{IN} H_{IN,PD})) H_{MC,END}) H_{MC,PD})) / (1 - C_{IN} C_{MC} P_{IN} (-1 + P_{MC}) H_{IN,PD} H_{MC,END} + C_0 (C_{EOM} H_{EOM} + C_{PZT} H_{PZT}) P_{MC} (C_{FA} C_{IN} P_{IN} H_{IN,PD} + (1 + C_{IN} C_{MC} P_{IN} H_{IN,PD} H_{MC,END}) H_{MC,PD}))\}\}$$

$N_{MCEND,IN,MC}$ が無いとき、

$$T1 := (\nu_{MC} - C_{IN} C_{MC} N_{IN} H_{MC,END} + N_{MCEND} H_{MC,END} + C_{IN} C_{MC} P_{IN} \nu_{IN} H_{IN,PD} H_{MC,END} + P_{MC} (\nu_0 - \nu_{MC} - (N_{MCEND} + C_{IN} C_{MC} (-N_{IN} + P_{IN} \nu_{IN} H_{IN,PD})) H_{MC,END}) - C_0 (C_{EOM} H_{EOM} + C_{PZT} H_{PZT}) P_{MC} (N_{MC} + C_{FA} C_{IN} (N_{IN} - P_{IN} \nu_{IN} H_{IN,PD}) - (\nu_{MC} + (N_{MCEND} + C_{IN} C_{MC} (-N_{IN} + P_{IN} \nu_{IN} H_{IN,PD})) H_{MC,END}) H_{MC,PD})) / (1 - C_{IN} C_{MC} P_{IN} (-1 + P_{MC}) H_{IN,PD} H_{MC,END} + C_0 (C_{EOM} H_{EOM} + C_{PZT} H_{PZT}) P_{MC} (C_{FA} C_{IN} P_{IN} H_{IN,PD} + (1 + C_{IN} C_{MC} P_{IN} H_{IN,PD} H_{MC,END}) H_{MC,PD}))$$

$$T2 = \mathrm{Simplify}[T1 - \mathrm{Coefficient}[T1, N_{MCEND}] * N_{MCEND} - \mathrm{Coefficient}[T1, N_{IN}] * N_{IN} - \mathrm{Coefficient}[T1, N_{MC}] * N_{MC}]$$

$$(\nu_{MC} + C_{IN} C_{MC} P_{IN} \nu_{IN} H_{IN,PD} H_{MC,END} + P_{MC} (\nu_0 + \nu_{MC} (-1 + C_0 (C_{EOM} H_{EOM} + C_{PZT} H_{PZT}) H_{MC,PD}) + C_{IN} P_{IN} \nu_{IN} H_{IN,PD} (-C_{MC} H_{MC,END} + C_0 (C_{EOM} H_{EOM} + C_{PZT} H_{PZT}) (C_{FA} + C_{MC} H_{MC,END} H_{MC,PD})))) / (1 - C_{IN} C_{MC} P_{IN} (-1 + P_{MC}) H_{IN,PD} H_{MC,END} + C_0 (C_{EOM} H_{EOM} + C_{PZT} H_{PZT}) P_{MC} (C_{FA} C_{IN} P_{IN} H_{IN,PD} + (1 + C_{IN} C_{MC} P_{IN} H_{IN,PD} H_{MC,END}) H_{MC,PD}))$$

$$\mathrm{Simplify}[\mathrm{Coefficient}[T2, \nu_{IN}]]$$

$$(C_{IN} P_{IN} H_{IN,PD} (-C_{MC} (-1 + P_{MC}) H_{MC,END} + C_0 (C_{EOM} H_{EOM} + C_{PZT} H_{PZT}) P_{MC} (C_{FA} + C_{MC} H_{MC,END} H_{MC,PD}))) / (1 - C_{IN} C_{MC} P_{IN} (-1 + P_{MC}) H_{IN,PD} H_{MC,END} + C_0 (C_{EOM} H_{EOM} + C_{PZT} H_{PZT}) P_{MC} (C_{FA} C_{IN} P_{IN} H_{IN,PD} + (1 + C_{IN} C_{MC} P_{IN} H_{IN,PD} H_{MC,END}) H_{MC,PD}))$$

この式から, ν_4 はMCとPrimary Cavity Servoのループゲイン（後で説明）が大きくなれば ν_{IN} に近づくことが示せます.
（$P_{MC} = 1,\ 1 \ll C_{IN} C_{MC} P_{IN} H_{IN,PD} H_{MC,END}$ とした.）

```
Simplify[(C_IN P_IN H_IN,PD C_0 (C_EOM H_EOM + C_PZT H_PZT) P_MC (C_FA + C_MC H_MC,END H_MC,PD)) /
  (1 + C_0 (C_EOM H_EOM + C_PZT H_PZT) P_MC (C_FA C_IN P_IN H_IN,PD + C_IN C_MC P_IN H_IN,PD H_MC,END H_MC,PD))]
```

$$\frac{C_0\, C_{IN}\,(C_{EOM}\, H_{EOM} + C_{PZT}\, H_{PZT})\, P_{IN}\, P_{MC}\, H_{IN,PD}\,(C_{FA} + C_{MC}\, H_{MC,END}\, H_{MC,PD})}{1 + C_0\, C_{IN}\,(C_{EOM}\, H_{EOM} + C_{PZT}\, H_{PZT})\, P_{IN}\, P_{MC}\, H_{IN,PD}\,(C_{FA} + C_{MC}\, H_{MC,END}\, H_{MC,PD})}$$

しかし，当然のことながら，分子の中で，ν_{IN} を含む項よりも他のN_{IN}，N_{MC}，ν_{MC} を含む項が大きくては，
目標安定度であるν_{IN} を達成できません．そこで，ν_{IN} そのものと他の項の大きさを比較するために，他の項を求めます．

Numerator of ν_4

まず，求めたν_4 の分子のうち，ν_{IN} の係数を求めます．それをCoeffNuINとし，
それで他の項を割ることで，ν_{IN} と比較できます．
　まずν_{IN} の係数を求めます．

```
ν4 := T1
```

```
CoeffNuIN = Simplify[Coefficient[Numerator[ν4], νIN]]
```

$$C_{IN}\, P_{IN}\, H_{IN,PD}\,(-C_{MC}\,(-1 + P_{MC})\, H_{MC,END} + C_0\,(C_{EOM}\, H_{EOM} + C_{PZT}\, H_{PZT})\, P_{MC}\,(C_{FA} + C_{MC}\, H_{MC,END}\, H_{MC,PD}))$$

次にN_{IN} の係数を求めます．

```
Simplify[Coefficient[Numerator[ν4] / CoeffNuIN, N_IN]]
```

$$-\frac{1}{P_{IN}\, H_{IN,PD}}$$

```
Simplify[Coefficient[ν4, N_IN]]
```

$$-(C_{IN}\,(-C_{MC}\,(-1 + P_{MC})\, H_{MC,END} + C_0\,(C_{EOM}\, H_{EOM} + C_{PZT}\, H_{PZT})\, P_{MC}\,(C_{FA} + C_{MC}\, H_{MC,END}\, H_{MC,PD}))) / (1 - C_{IN}\, C_{MC}\, P_{IN}\,(-1 + P_{MC})\, H_{IN,PD}\, H_{MC,END} + C_0\,(C_{EOM}\, H_{EOM} + C_{PZT}\, H_{PZT})\, P_{MC}\,(C_{FA}\, C_{IN}\, P_{IN}\, H_{IN,PD} + (1 + C_{IN}\, C_{MC}\, P_{IN}\, H_{IN,PD}\, H_{MC,END})\, H_{MC,PD}))$$

次にN_{MC} の係数を求めます．

```
Simplify[Coefficient[Numerator[ν4] / CoeffNuIN, N_MC]]
```

$$-(C_0\,(C_{EOM}\, H_{EOM} + C_{PZT}\, H_{PZT})\, P_{MC}) / (C_{IN}\, P_{IN}\, H_{IN,PD}\,(-C_{MC}\,(-1 + P_{MC})\, H_{MC,END} + C_0\,(C_{EOM}\, H_{EOM} + C_{PZT}\, H_{PZT})\, P_{MC}\,(C_{FA} + C_{MC}\, H_{MC,END}\, H_{MC,PD})))$$

$\textbf{Simplify}[\textbf{Coefficient}[\nu_4,\ N_{MC}]]$

$$-(C_0\,(C_{EOM}\,H_{EOM} + C_{PZT}\,H_{PZT})\,P_{MC}) / (1 - C_{IN}\,C_{MC}\,P_{IN}\,(-1 + P_{MC})\,H_{IN,PD}\,H_{MC,END} + C_0\,(C_{EOM}\,H_{EOM} + C_{PZT}\,H_{PZT})\,P_{MC}\,(C_{FA}\,C_{IN}\,P_{IN}\,H_{IN,PD} + (1 + C_{IN}\,C_{MC}\,P_{IN}\,H_{IN,PD}\,H_{MC,END})\,H_{MC,PD}))$$

次にν_{MC} の係数を求めます.

$\textbf{Simplify}\left[\textbf{Coefficient}\left[\frac{\textbf{Numerator}[\nu_4]}{\textbf{CoeffNuIN}},\ \nu_{MC}\right]\right]$

$$(1 + P_{MC}\,(-1 + C_0\,(C_{EOM}\,H_{EOM} + C_{PZT}\,H_{PZT})\,H_{MC,PD})) / (C_{IN}\,P_{IN}\,H_{IN,PD}\,(-C_{MC}\,(-1 + P_{MC})\,H_{MC,END} + C_0\,(C_{EOM}\,H_{EOM} + C_{PZT}\,H_{PZT})\,P_{MC}\,(C_{FA} + C_{MC}\,H_{MC,END}\,H_{MC,PD})))$$

$\textbf{Simplify}[\textbf{Coefficient}[\nu_4,\ \nu_{MC}]]$

$$(1 + P_{MC}\,(-1 + C_0\,(C_{EOM}\,H_{EOM} + C_{PZT}\,H_{PZT})\,H_{MC,PD})) / (1 - C_{IN}\,C_{MC}\,P_{IN}\,(-1 + P_{MC})\,H_{IN,PD}\,H_{MC,END} + C_0\,(C_{EOM}\,H_{EOM} + C_{PZT}\,H_{PZT})\,P_{MC}\,(C_{FA}\,C_{IN}\,P_{IN}\,H_{IN,PD} + (1 + C_{IN}\,C_{MC}\,P_{IN}\,H_{IN,PD}\,H_{MC,END})\,H_{MC,PD}))$$

最後にN_{MCEND} の係数を求めます.

$\textbf{Simplify}\left[\textbf{Coefficient}\left[\frac{\textbf{Numerator}[\nu_4]}{\textbf{CoeffNuIN}},\ N_{MCEND}\right]\right]$

$$(H_{MC,END}\,(1 + P_{MC}\,(-1 + C_0\,(C_{EOM}\,H_{EOM} + C_{PZT}\,H_{PZT})\,H_{MC,PD}))) / (C_{IN}\,P_{IN}\,H_{IN,PD}\,(-C_{MC}\,(-1 + P_{MC})\,H_{MC,END} + C_0\,(C_{EOM}\,H_{EOM} + C_{PZT}\,H_{PZT})\,P_{MC}\,(C_{FA} + C_{MC}\,H_{MC,END}\,H_{MC,PD})))$$

$\textbf{Simplify}[\textbf{Coefficient}[\nu_4,\ N_{MCEND}]]$

$$(H_{MC,END}\,(1 + P_{MC}\,(-1 + C_0\,(C_{EOM}\,H_{EOM} + C_{PZT}\,H_{PZT})\,H_{MC,PD}))) / (1 - C_{IN}\,C_{MC}\,P_{IN}\,(-1 + P_{MC})\,H_{IN,PD}\,H_{MC,END} + C_0\,(C_{EOM}\,H_{EOM} + C_{PZT}\,H_{PZT})\,P_{MC}\,(C_{FA}\,C_{IN}\,P_{IN}\,H_{IN,PD} + (1 + C_{IN}\,C_{MC}\,P_{IN}\,H_{IN,PD}\,H_{MC,END})\,H_{MC,PD}))$$

Denominator of ν_1

$\textbf{Denominator}[\nu_4]$

$$1 - C_{IN}\,C_{MC}\,P_{IN}\,(-1 + P_{MC})\,H_{IN,PD}\,H_{MC,END} + C_0\,(C_{EOM}\,H_{EOM} + C_{PZT}\,H_{PZT})\,P_{MC}\,(C_{FA}\,C_{IN}\,P_{IN}\,H_{IN,PD} + (1 + C_{IN}\,C_{MC}\,P_{IN}\,H_{IN,PD}\,H_{MC,END})\,H_{MC,PD})$$

ちなみに, 分母は, $G_{MC} = C_0 * (C_{PZT} * H_{PZT} + C_{EOM} * H_{EOM}) * P_{MC} * H_{MC,PD}$,
$G_{IN} = C_{IN} * P_{IN} * H_{IN,PD} * \left(\frac{C_{FA}}{H_{MC,PD}} + P_{MC}\,C_{MC} * H_{MC,END}\right)$ とすると,
$1 + G_{MC}\,(P_{MC}\,C_{IN}\,P_{IN}\,H_{IN,PD} + G_{IN})$ となります. 普通, $G_{IN} >> P_{MC}\,C_{IN}\,P_{IN}\,H_{IN,PD}$ で,
$G_{MC} >> 1$, $G_{IN} >> 1$, ならば$1 + G_{MC}\,(G_{IN}) \to G_{MC}\,G_{IN}$ になる.

Parameter1

CLIOの基本的なパラメ－タ－です.仮定を多く含みます.

```
(* Length *)
```
L_{MC} := 9.5
L_{IN} := 100
L_{Per} := 100
```
(* YAG Frequency and Frequency Noise *)
```
$\nu_{YAG} := 2.998 * 10^{8} / 1.064 * 10^{6};\ \nu_0 := 10^{4} * f^{-1}$

```
(* Cavity Poles *)
```
$$P_{MC} := \frac{4000}{4000 + f * i}$$
$$P_{IN} := \frac{250}{250 + f * i}$$
$$P_{Per} := \frac{250}{250 + f * i}$$

```
(* Isolated Seismic
  Noise : KAMIOKA seismic noise and f^-4 pendulum isolation are supposed. *)
```
$H_{MCPend} := 10^{-9} * f^{-4}$
$H_{INPend} := 10^{-9} * f^{-6}$
$H_{PerPend} := 10^{-9} * f^{-6}$

```
(* Corresponding Frequency Noise *)
```
$\nu_{MC} := (H_{MCPend} + 10^{-18}) / P_{IN} * L_{MC}^{-1} * \nu_{YAG};\ \nu_{IN} := H_{INPend} * L_{IN}^{-1} * \nu_{YAG}$

```
(* MC END Mirror Actuation Efficiency *)
```
$H_{MC,END} := (\nu_{YAG} / L_{MC}) * 4 * 10^{-6} * f^{-2}$

```
(* PerArm Near Mirror Actuation Efficiency *)
```
$H_{Per,NM} := (\nu_{YAG} / L_{Per}) * 2 * 10^{-7} * 1.1^{2} * f^{-2}$

```
(* Feedback Circuit Input Noise *)
```
$N_{IN} := 15 * 10^{-9}$
$N_{MC} := 15 * 10^{-9}$
$N_{MCEND} := 20 * 10^{-9}$

Feedback Circuit

Feedback Circuitの伝達関数です.

(* Photo Detecto Efficiency *)

$$H_{MC,PD} := 5 * 10^{-3}$$

$$H_{IN,PD} := 3 * 10^{-1}$$

$$H_{Per,PD} := 4.5 * 10^{-1}$$

(* MC *)

$$C_0 := 0.3 \;(* \frac{1*10^5 + f*i}{f*i} \text{ (* gain up @100 kHz *) } *)$$

$$C_{PZT} := 20 * \frac{20}{20 + f*i} * \left(\frac{3.3*10^3 + f*i}{333 + f*i}\right) * \frac{10^5}{10^5 + f*i} * e^{-i*2*\pi*f*\frac{25}{299792458}}$$

$$H_{PZT} := 1.5 * 10^6$$

$$C_{EOM} := \left(\frac{f*i}{500 + f*i} * \frac{10*10^3 + f*i}{10^3 + f*i} * \frac{1*10^6}{1*10^6 + f*i}\right) * \left(\frac{1*10^3}{1*10^3 + f*i} * \frac{3.2*10^3 + f*i}{3.2*10^3} * \frac{1.6}{0.5} * \frac{5*10^5 + f*i}{1.6*10^6 + f*i} * \frac{1.6}{0.5} * \frac{700*10^3}{700*10^3 + f*i}\right) * \left(250 * \frac{f*i}{10^3 + f*i} * \frac{10*10^3}{10*10^3 + f*i} * \frac{220*10^3 + f*i}{220*10^3} * \frac{306*10^3 + f*i}{306*10^3} * \frac{350*10^3}{350*10^3 + f*i}\right) * \frac{10^5}{10^5 + f*i} * e^{-i*2*\pi*f*\frac{25}{299792458}}$$

$$H_{EOM} := f*i*1*10^{-2}$$

(* Primary *)

$$C_{IN} := 3 * \frac{10^5}{10^5 + f*i} \text{ (* Normal Gain *)}$$

$$(* C_{IN} := 3 * \frac{10^5}{10^5 + f*i} * \frac{1*10^5 + f*i}{f*i} * \frac{3*10^4 + f*i}{f*i} * \frac{3*10^4 + f*i}{f*i} \text{ (* Gain up *) } *)$$

$$C_{FA} := \frac{f*i}{30 + f*i} * \frac{30*10^3 + f*i}{300*10^3 + f*i} * \frac{3*10^5}{3*10^4} * 1.1$$

$$C_{MC} := -1 * \frac{250 + f*i}{7.2*10^3 + f*i} * \frac{7.2*10^3}{2500} * \left(2 * \frac{3.3*10^3 + f*i}{16*10^3 + f*i} * \frac{16*10^3}{3.3*10^3}\right) * \frac{10^4}{10^4 + f*i} * \left(\frac{10^4}{10^4 * e^{-i\frac{\pi}{4}} + f*i} * \frac{10^4}{10^4 * e^{i\frac{\pi}{4}} + f*i}\right)$$

(* Secondary *)

$$C_{Per} := 1 * \frac{150 + f*i}{10^3 + f*i} * \frac{10^3}{150} * \frac{10^2 + f*i}{10^3 + f*i} * \left(\frac{10^4}{10^4 * e^{-i\frac{3\pi}{8}} + f*i} * \frac{10^4}{10^4 * e^{i\frac{\pi}{8}} + f*i} * \frac{10^4}{10^4 * e^{-i\frac{\pi}{8}} + f*i} * \frac{10^4}{10^4 * e^{i\frac{3\pi}{8}} + f*i}\right)^1 * (1/1)$$

$$G_{Per} := C_{Per} * P_{Per} * H_{Per,PD} * H_{Per,NM}$$

$$G_{MC} := C_0 * (C_{PZT} * H_{PZT} + C_{EOM} * H_{EOM}) * P_{MC} * H_{MC,PD}$$

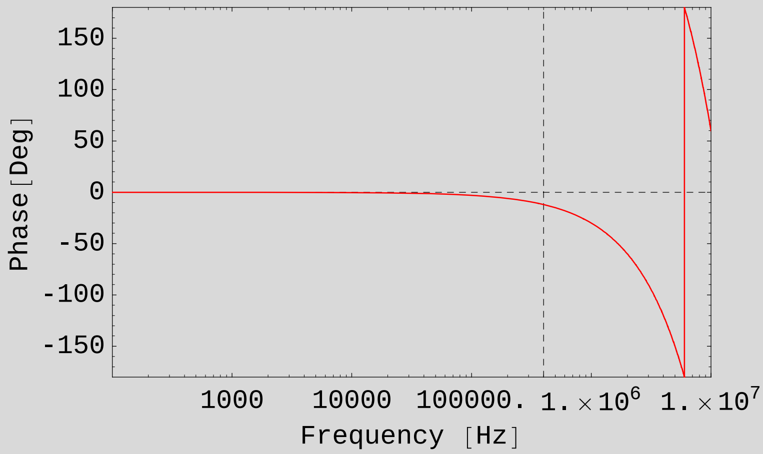
$$G_{IN} := C_{IN} * P_{IN} * H_{IN,PD} * \left(\frac{G_{MC}}{1 + G_{MC}} * \frac{C_{FA}}{H_{MC,PD}} + C_{MC} * H_{MC,END}\right)$$

(* Whitening *)

$$(* W := \frac{f*i}{100 + f*i} * \frac{f*i}{20 + f*i} * \frac{130}{130 + f*i} * 11 * 2.8 *)$$

$$W := \frac{f*i}{2.26 + f*i} * \frac{f*i}{91.11 + f*i} * \frac{f*i}{10.44 + f*i} * \frac{116}{116 + f*i} * 27.55$$

```
LogLinearPlot[{Arg[e^(-i*2*π*f* 25/299792458)] * 180/π}, {f, 10^2, 10^7},
 Frame → True, PlotRange -> {{10^2, 10^7}, {-180, 180}},
 PlotPoints → 1000, PlotStyle → {RGBColor[1, 0, 0]},
 GridLines -> {{{400000, {Dashing[{.01, .01}]}}}, {{0, {Dashing[{.01, .01}]}}}},
 FrameLabel → {"Frequency [Hz]", Phase[Deg]}]
```



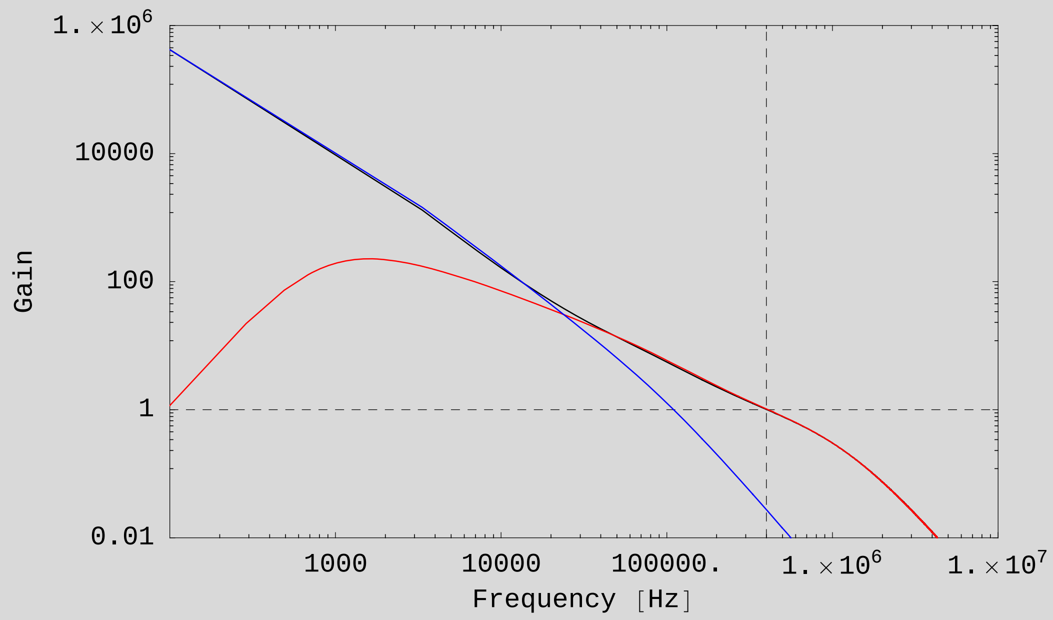
- Graphics -

■ MC Servo Loop Gain

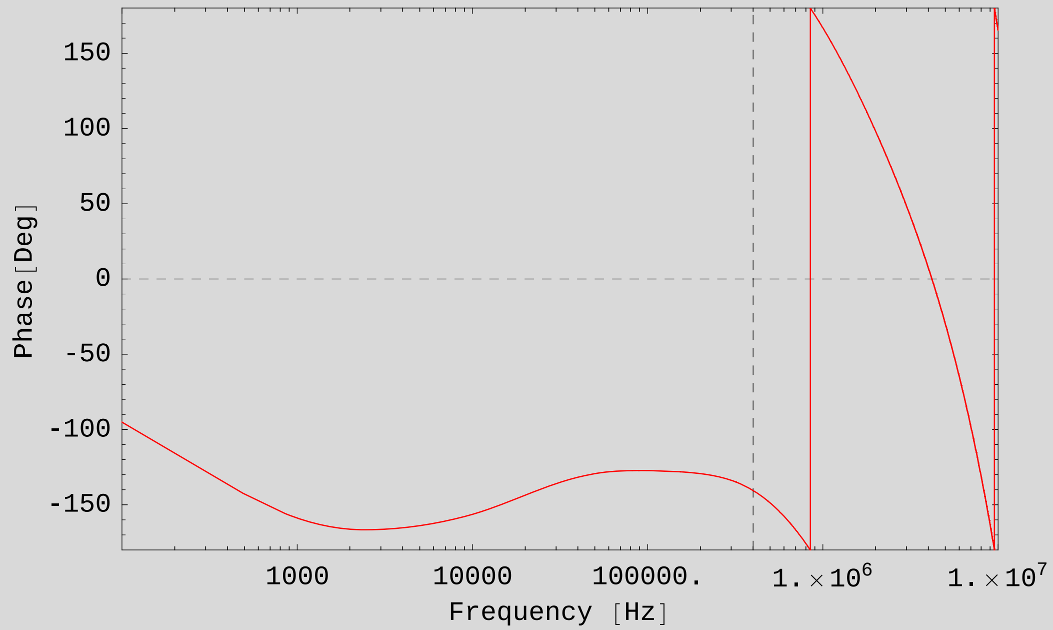
■ Normal gain

```
C0 := 1.5;
```

```
LogLogPlot[{Abs[C0 * (CPZT * HPZT + CEOM * HEOM) * PMC * HMC,PD],
  Abs[C0 * (CEOM * HEOM) * PMC * HMC,PD], Abs[C0 * (CPZT * HPZT) * PMC * HMC,PD]},
 {f, 10^2, 10^7}, Frame → True, PlotRange -> {{10^2, 10^7}, {10^-2, 10^6}},
 PlotPoints → 3000,
 PlotStyle → {RGBColor[0, 0, 0], RGBColor[1, 0, 0], RGBColor[0, 0, 1]},
 GridLines -> {{{400000, {Dashing[{.01, .01}]}}}, {{1, {Dashing[{.01, .01}]}}}},
 FrameLabel → {"Frequency [Hz]", Gain}]

LogLinearPlot[Arg[C0 * (CPZT * HPZT + CEOM * HEOM) * PMC * HMC,PD] * 180/π,
 {f, 10^2, 10^7}, Frame → True, PlotRange -> {{10^2, 10^7}, {-180, 180}},
 PlotPoints → 3000, PlotStyle → {RGBColor[1, 0, 0]},
 GridLines -> {{{400000, {Dashing[{.01, .01}]}}}, {{0, {Dashing[{.01, .01}]}}}},
 FrameLabel → {"Frequency [Hz]", Phase[Deg]}]
```



- Graphics -

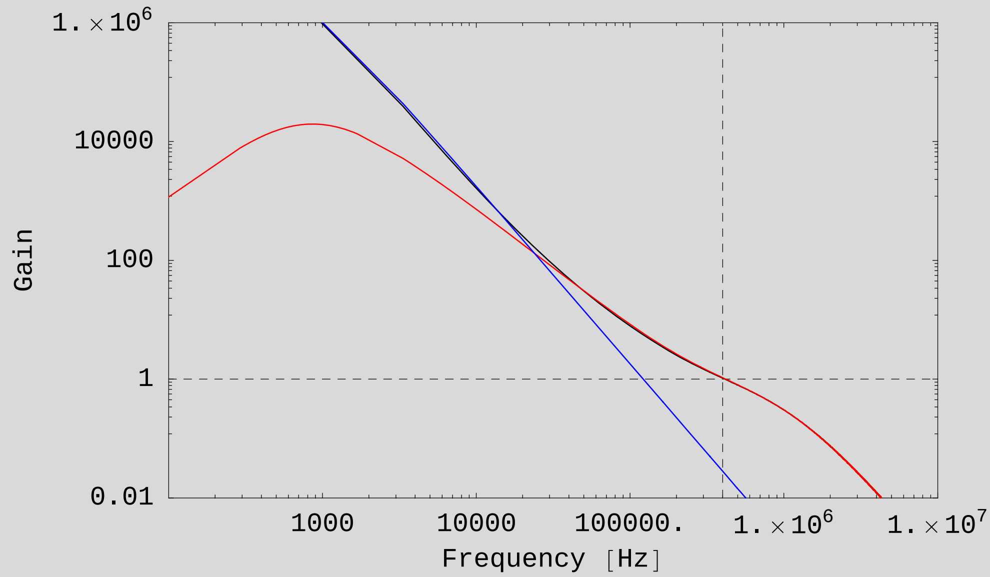


- Graphics -

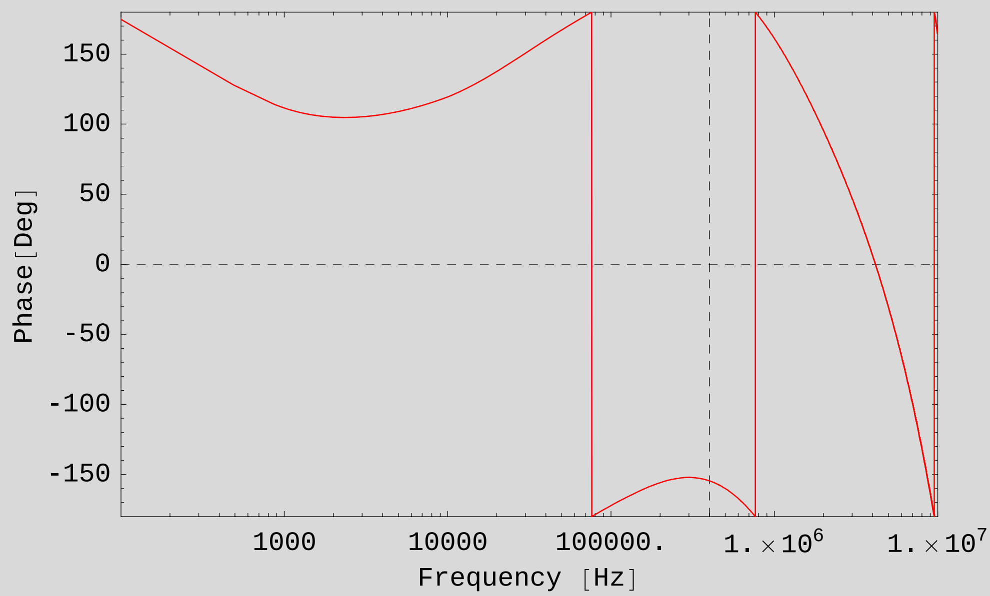
■ **Gain up**

$$C_0 := 1.5 * \frac{1 * 10^5 + f * i}{f * i}$$;(* gain up @100 kHz *)

```
LogLogPlot[{Abs[ C0 * (CPZT * HPZT + CEOM * HEOM) * PMC * HMC,PD],
  Abs[ C0 * (CEOM * HEOM) * PMC * HMC,PD], Abs[ C0 * (CPZT * HPZT) * PMC * HMC,PD]},
 {f, 10^2, 10^7}, Frame → True, PlotRange -> {{10^2, 10^7}, {10^-2, 10^6}},
 PlotPoints → 3000,
 PlotStyle → {RGBColor[0, 0, 0], RGBColor[1, 0, 0], RGBColor[0, 0, 1]},
 GridLines -> {{{400000, {Dashing[{.01, .01}]}}}, {{1, {Dashing[{.01, .01}]}}}},
 FrameLabel → {"Frequency [Hz]", Gain}]

LogLinearPlot[Arg[ C0 * (CPZT * HPZT + CEOM * HEOM) * PMC * HMC,PD] * 180/π,
 {f, 10^2, 10^7}, Frame → True, PlotRange -> {{10^2, 10^7}, {-180, 180}},
 PlotPoints → 3000, PlotStyle → {RGBColor[1, 0, 0]},
 GridLines -> {{{400000, {Dashing[{.01, .01}]}}}, {{0, {Dashing[{.01, .01}]}}}},
 FrameLabel → {"Frequency [Hz]", Phase[Deg]}]
```



- Graphics -



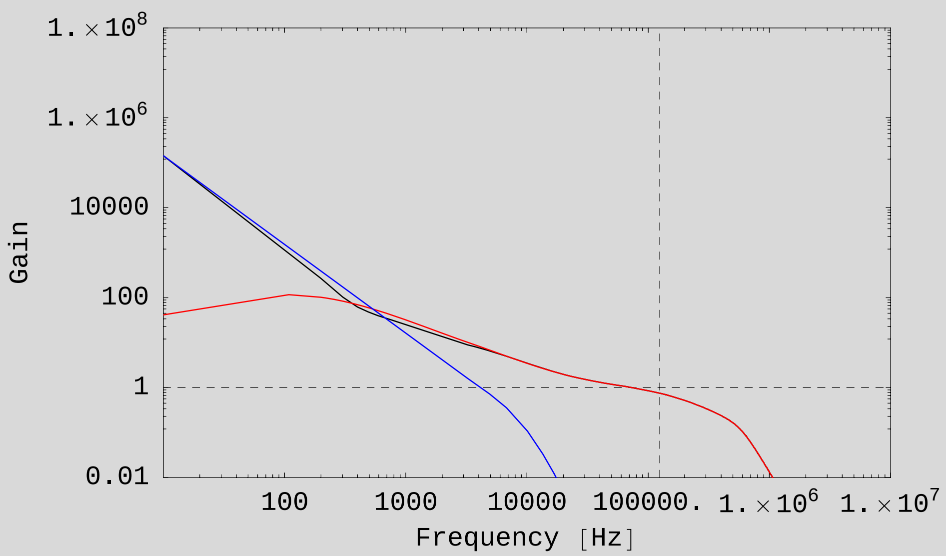
```
- Graphics -
```

Primary Cavity Servo Loop Gain

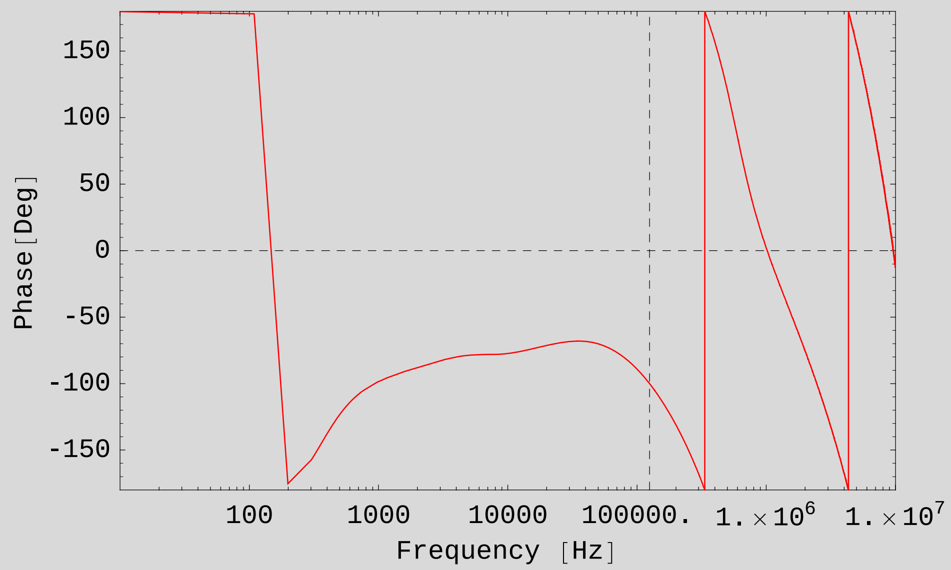
Normal gain

```
C0 := 1.5;
CIN := 2 * 10^5 / (10^5 + f * i);
```

```
LogLogPlot[{Abs[ CIN * (GMC / (1 + GMC) * CFA / HMC,PD + PMC * CMC * HMC,END) * PIN * HIN,PD],
  Abs[CIN * GMC / (1 + GMC) * CFA / HMC,PD * PIN * HIN,PD], Abs[CIN * CMC * HMC,END * PIN * HIN,PD]},
 {f, 10^1, 10^7}, Frame → True, PlotRange -> {{10^1, 10^7}, {10^-2, 10^8}},
 PlotPoints → 3000,
 PlotStyle → {RGBColor[0, 0, 0], RGBColor[1, 0, 0], RGBColor[0, 0, 1] },
 GridLines -> {{{125000, {Dashing[{.01, .01}]}}}, {{1, {Dashing[{.01, .01}]}}}},
 FrameLabel → {"Frequency [Hz]", Gain}]

LogLinearPlot[
 Arg[ CIN * (GMC / (1 + GMC) * CFA / HMC,PD + PMC * CMC * HMC,END) * PIN * HIN,PD] * 180/π,
 {f, 10^1, 10^7}, Frame → True, PlotRange -> {{10^1, 10^7}, {-180, 180}},
 PlotPoints → 3000, PlotStyle → {RGBColor[1, 0, 0]},
 GridLines -> {{{125000, {Dashing[{.01, .01}]}}}, {{0, {Dashing[{.01, .01}]}}}},
 FrameLabel → {"Frequency [Hz]", Phase[Deg]}]
```




```
- Graphics -
```



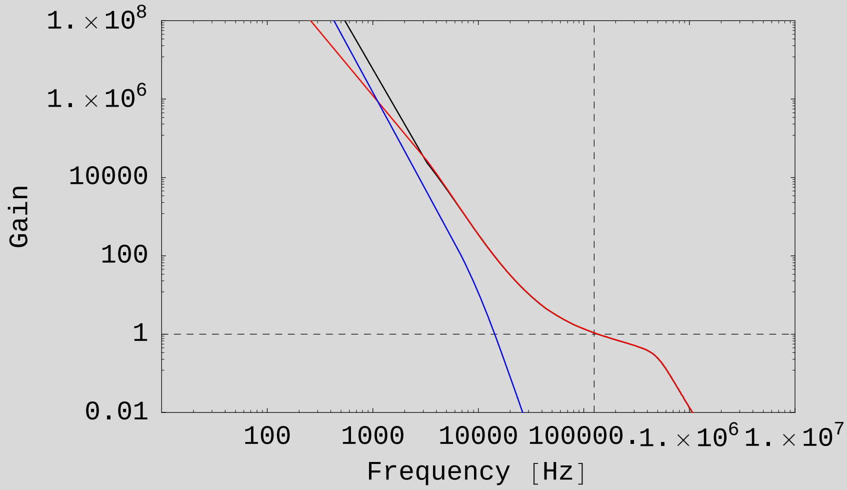
- Graphics -

■ Gain up

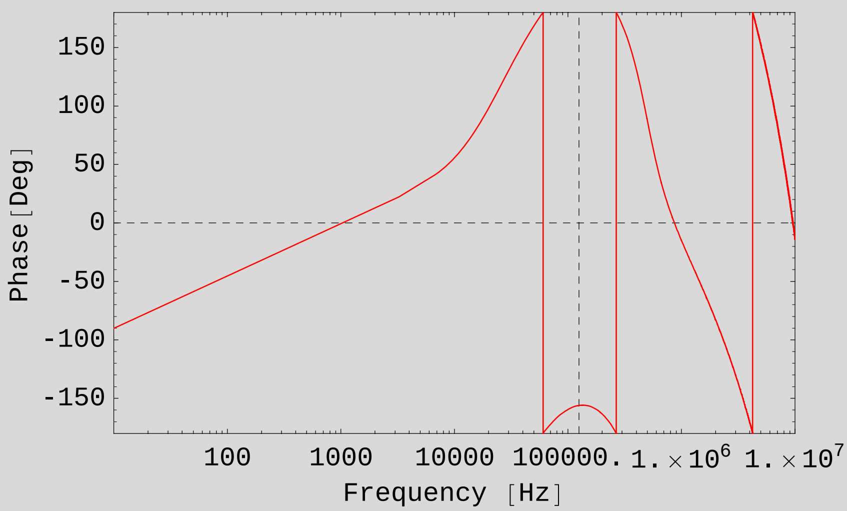
$$C_0 := 1.5 * \frac{1 * 10^5 + f * i}{f * i}; \text{(* MC Gain up@ 100 kHz *)}$$

$$C_{IN} := 2 * \frac{10^5}{10^5 + f * i} * \frac{1 * 10^5 + f * i}{f * i} * \frac{3 * 10^4 + f * i}{f * i} * \frac{3 * 10^4 + f * i}{f * i}; \text{(* Gain up *)}$$

```
LogLogPlot[{Abs[ C_IN * (G_MC / (1 + G_MC) * C_FA / H_MC,PD + P_MC * C_MC * H_MC,END) * P_IN * H_IN,PD],
  Abs[C_IN * G_MC / (1 + G_MC) * C_FA / H_MC,PD * P_IN * H_IN,PD], Abs[C_IN * C_MC * H_MC,END * P_IN * H_IN,PD]},
 {f, 10^1, 10^7}, Frame → True, PlotRange -> {{10^1, 10^7}, {10^-2, 10^8}},
 PlotPoints → 3000,
 PlotStyle → {RGBColor[0, 0, 0], RGBColor[1, 0, 0], RGBColor[0, 0, 1] },
 GridLines -> {{{125000, {Dashing[{.01, .01}]}}}, {{1, {Dashing[{.01, .01}]}}}},
 FrameLabel → {"Frequency [Hz]", Gain}]

LogLinearPlot[
 Arg[ C_IN * (G_MC / (1 + G_MC) * C_FA / H_MC,PD + P_MC * C_MC * H_MC,END) * P_IN * H_IN,PD] * 180/π,
 {f, 10^1, 10^7}, Frame → True, PlotRange -> {{10^1, 10^7}, {-180, 180}},
 PlotPoints → 3000, PlotStyle → {RGBColor[1, 0, 0]},
 GridLines -> {{{125000, {Dashing[{.01, .01}]}}}, {{0, {Dashing[{.01, .01}]}}}},
 FrameLabel → {"Frequency [Hz]", Phase[Deg]}]
```



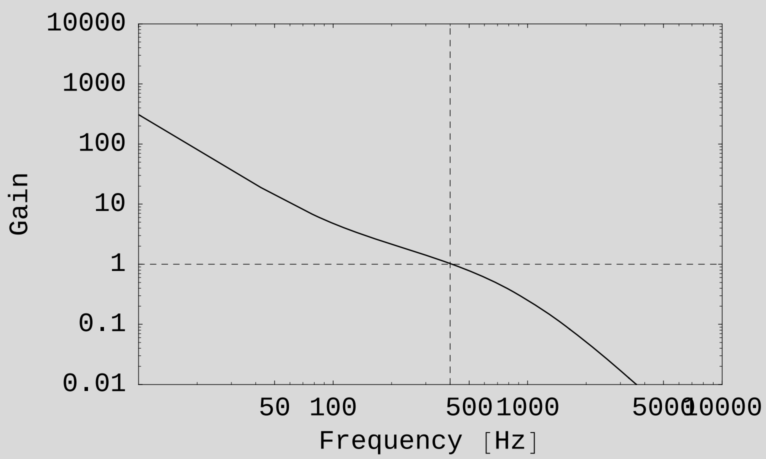
- Graphics -



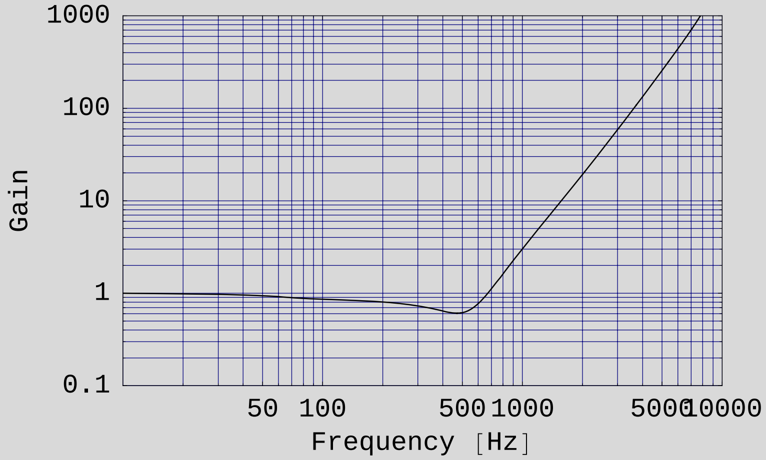
- Graphics -

Secondary Cavity Servo Loop Gain

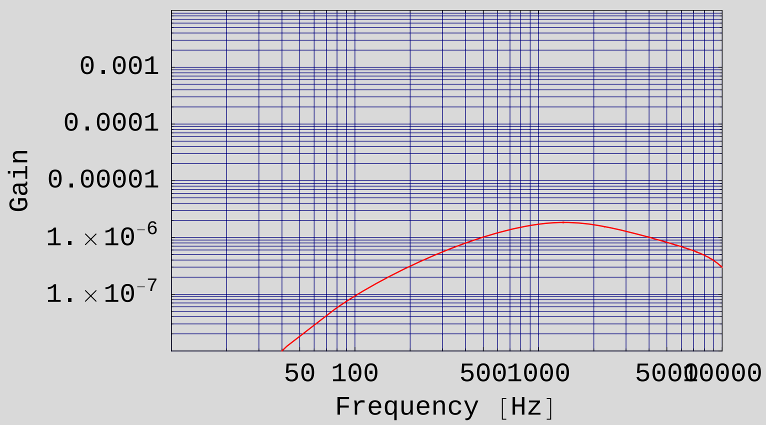
```
LogLogPlot[{Abs[GPer]}, {f, 10^1, 10^4},
 Frame → True, PlotRange -> {{10^1, 10^4}, {10^-2, 10^4}},
 PlotPoints → 300, PlotStyle → RGBColor[0, 0, 0],
 GridLines -> {{{400, {Dashing[{.01, .01}]}}}, {{1, {Dashing[{.01, .01}]}}}},
 FrameLabel → {"Frequency [Hz]", Gain}]

LogLogPlot[{Abs[(1 - GPer) / (GPer)]}, {f, 10^1, 10^4}, Frame → True,
 PlotRange → {{10^1, 10^4}, {10^-1, 10^3}}, PlotPoints → 300,
 PlotStyle → RGBColor[0, 0, 0], GridLines → Automatic,
 FrameLabel → {"Frequency [Hz]", Gain}]

(* Noise from PD *)
GPPDper = LogLogPlot[{Abs[W * (2 * 10^-7) * CPer / (1 + GPer)]},
  {f, 10^1, 10^4}, Frame → True, PlotRange → {{10^1, 10^4}, {10^-8, 10^-2}},
  PlotPoints → 300, PlotStyle → RGBColor[1, 0, 0], GridLines → Automatic,
  FrameLabel → {"Frequency [Hz]", Gain}]

(* Noise from Coil Driver *)
GPCoilNoise = LogLogPlot[{Abs[W * (2 * 10^-7) * GPer / (1 + GPer)]},
  {f, 10^1, 10^4}, Frame → True, PlotRange → {{10^1, 10^4}, {10^-8, 10^-2}},
  PlotPoints → 300, PlotStyle → RGBColor[0, 0, 1], GridLines → Automatic,
  FrameLabel → {"Frequency [Hz]", Gain}]

(* Noise from PD and Coil Driver *)
LogLogPlot[
 {√(Abs[W * (2 * 10^-7) * GPer / (1 + GPer)]^2 + Abs[W * (2 * 10^-7) * CPer / (1 + GPer)]^2)},
 {f, 10^1, 10^4}, Frame → True, PlotRange → {{10^1, 10^4}, {10^-8, 10^-2}},
 PlotPoints → 300, PlotStyle → RGBColor[0, 0, 1], GridLines → Automatic,
 FrameLabel → {"Frequency [Hz]", Gain}]
```



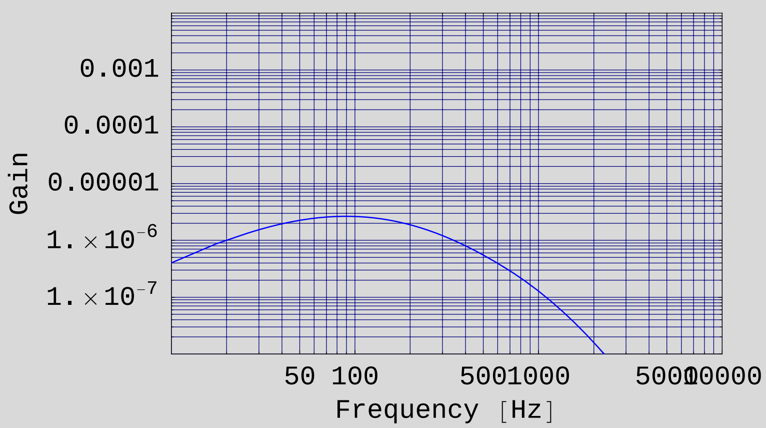
- Graphics -



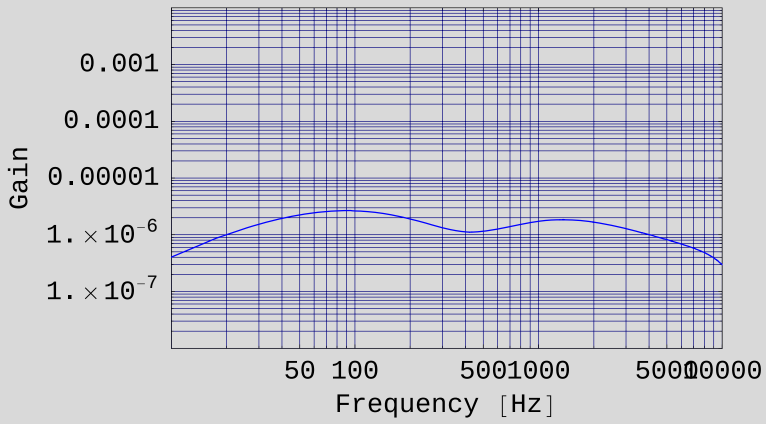
- Graphics -



- Graphics -



- Graphics -



- Graphics -

Noise Contributions

■ Noise Contributions(Lock Acquire Gain)

N_{IN}, N_{MC}, ν_{MC}, と目標感度ν_{IN} との比較.黄色：ν_{IN}, 黒色：N_{IN}, 赤色：N_{MC}, ピンク色：ν_{MC}.式から明らかなように,
N_{MC} やν_{MC} は, G_{IN} を大きくとってやれば, 簡単に下げられることがわかります.

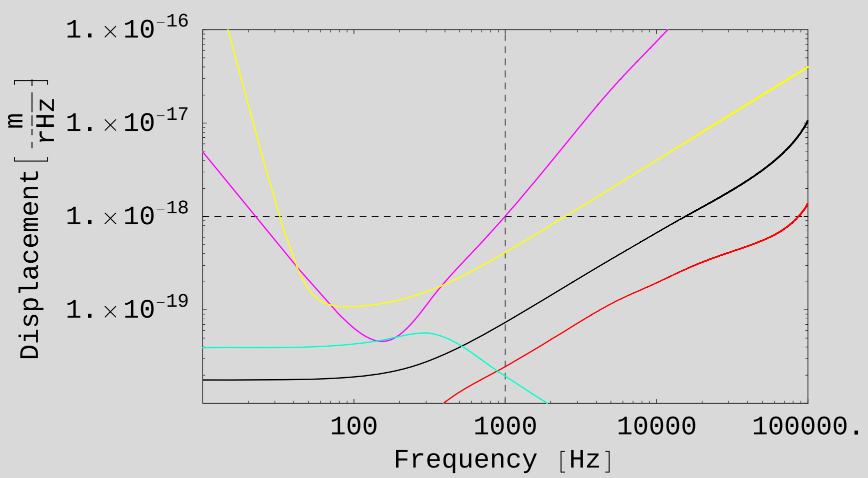
しかし, N_{IN} は, $H_{IN,PD}$ をあげるか, N_{IN} 自身を下げるしかありません.
N_{IN} を入力換算雑音とすると, N_{IN} はPrimary Cavity Servo回路の初段のゲイン (C_{IN}) を上げられる設計にすれば,
普通数nV / rHzにはすることができますが, そのためには, 式

$$G_{IN} = C_{IN} * P_{IN} * H_{IN,PD} * \left(\frac{G_{MC}}{1+G_{MC}} * \frac{C_{FA}}{H_{MC,PD}} + P_{MC} * C_{MC} * H_{MC,END}\right)$$

からわかるように, $H_{MC,PD}$ を大きくしてやらないといけません.つまり, MC用のPDに光をたくさん入れるか,
変調を大きくするかです .2006 年5月18日までは, MC用の変調が小さかったので,
それを改善しました.もっと大きくしてもかまわないかもしれません.これで,
回路の入力換算雑音としてのN_{IN} はこれで落とせます.
しかしPD自身の, 入力光がないときにすでにある雑音はこれでは減らせませんので, 現状だと,
数十nV / rHzの雑音が残ります.こうなると, もう, $H_{IN,PD}$ を大きくすることでしか下げられません.しかし,
G_{IN} を一定に保つ制限があると, $H_{IN,PD}$ を大きくすることと,
Primary Cavity Servo回路の初段のゲイン (C_{IN}) を上げることは, トレ - ドオフの関係になるので,
入力換算雑音を大きくしない程度に, C_{IN} を設定せねばなりません.結局それを解消するには,
G_{IN} のUGFをあげてル - プゲインをあげなければなりません.そうなると,
結局G_{MC} のUGFもあげていかねばなりません.こうなると, かなりしんどい領域に入ります.

```
C0 := 0.3;
CIN := 3 * 10^5/(10^5 + f * i) ;(* Normal Gain *)
```

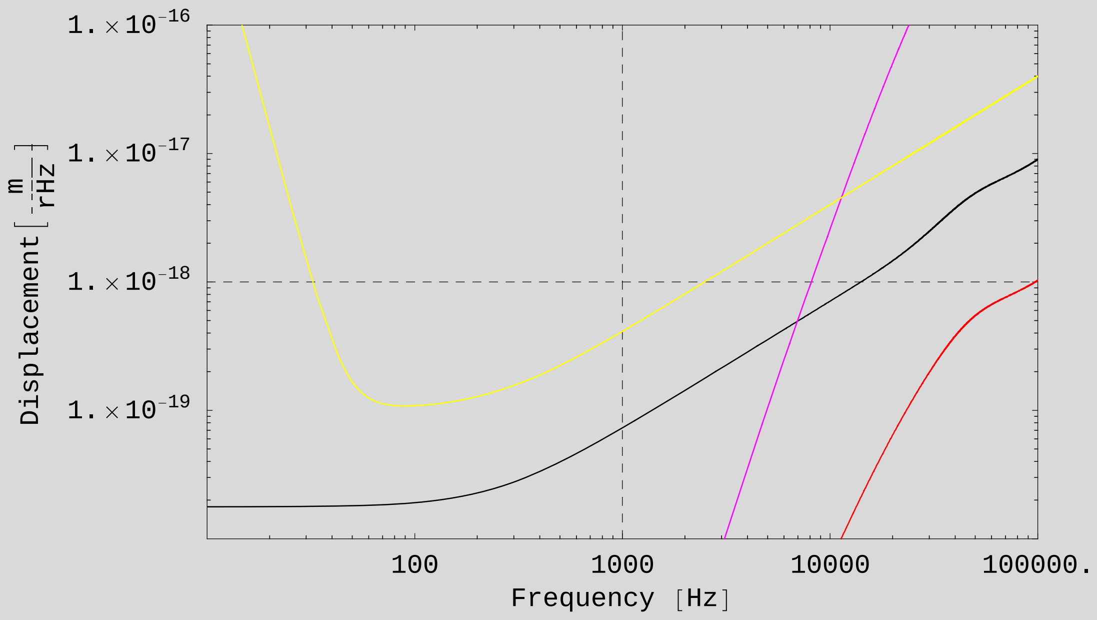
```
LogLogPlot[{LIN/νYAG * Abs[NIN *
    (-(CIN (-CMC (-1 + PMC) HMC,END + C0 (CEOM HEOM + CPZT HPZT) PMC (CFA + CMC HMC,END HMC,PD))) /
      (1 - CIN CMC PIN (-1 + PMC) HIN,PD HMC,END + C0 (CEOM HEOM + CPZT HPZT)
         PMC (CFA CIN PIN HIN,PD + (1 + CIN CMC PIN HIN,PD HMC,END) HMC,PD)))],
  LIN/νYAG * Abs[NMC * (-(C0 (CEOM HEOM + CPZT HPZT) PMC) / (1 - CIN CMC PIN (-1 + PMC)
         HIN,PD HMC,END + C0 (CEOM HEOM + CPZT HPZT) PMC
         (CFA CIN PIN HIN,PD + (1 + CIN CMC PIN HIN,PD HMC,END) HMC,PD)))],
  LIN/νYAG * Abs[νMC * ((1 + PMC (-1 + C0 (CEOM HEOM + CPZT HPZT) HMC,PD)) /
      (1 - CIN CMC PIN (-1 + PMC) HIN,PD HMC,END + C0 (CEOM HEOM + CPZT HPZT)
         PMC (CFA CIN PIN HIN,PD + (1 + CIN CMC PIN HIN,PD HMC,END) HMC,PD)))],
  LIN/νYAG * Abs[NMCEND * ((HMC,END (1 + PMC (-1 + C0 (CEOM HEOM + CPZT HPZT) HMC,PD))) /
      (1 - CIN CMC PIN (-1 + PMC) HIN,PD HMC,END + C0 (CEOM HEOM + CPZT HPZT)
         PMC (CFA CIN PIN HIN,PD + (1 + CIN CMC PIN HIN,PD HMC,END) HMC,PD)))],
  Abs[(HINPend + 10^-19) / PIN]}, {f, 10^1, 10^5}, Frame →
  True,
 PlotRange ->
  {{10^1, 10^5},
   {10^-20, 10^-16}},
 PlotPoints → 3000, PlotStyle →
  {RGBColor[0, 0, 0],
   RGBColor[1, 0, 0],
   RGBColor[1, 0, 1],
   RGBColor[0, 1, 0.8], RGBColor[1, 1, 0]},
 GridLines -> {{{1000, {Dashing[{.01, .01}]}}},
   {{1 * 10^-18, {Dashing[{.01, .01}]}}}},
 FrameLabel → {"Frequency [Hz]", Displacement [m/rHz]}]
```



- Graphics -

■ Noise Contributions(After GainUP)

```
C_0 := 0.3 * (1 * 10^5 + f * i)/(f * i);(* Gain @ 100 kHz *)
C_IN := 3 * 10^5/(10^5 + f * i) * (3 * 10^4 + f * i)/(f * i) * (3 * 10^4 + f * i)/(f * i) * (3 * 10^4 + f * i)/(f * i);
(* Gain @ 30 kHz and 30 kHz and 30 kHz *)
(*G_MC=C_0 *(C_PZT*H_PZT+C_EOM *H_EOM)*P_MC *H_MC,PD;
 G_IN=C_IN *P_IN *H_IN,PD*(C_FA/H_MC,PD +P_MC*C_MC *H_MC,END);*)

LogLogPlot[{L_IN/ν_YAG * Abs[N_IN *
      (-(C_IN (-C_MC (-1 + P_MC) H_MC,END + C_0 (C_EOM H_EOM + C_PZT H_PZT) P_MC (C_FA + C_MC H_MC,END H_MC,PD)))) /
        (1 - C_IN C_MC P_IN (-1 + P_MC) H_IN,PD H_MC,END + C_0 (C_EOM H_EOM + C_PZT H_PZT)
           P_MC (C_FA C_IN P_IN H_IN,PD + (1 + C_IN C_MC P_IN H_IN,PD H_MC,END) H_MC,PD)))],
   L_IN/ν_YAG * Abs[N_MC * (-(C_0 (C_EOM H_EOM + C_PZT H_PZT) P_MC) / (1 - C_IN C_MC P_IN (-1 + P_MC)
           H_IN,PD H_MC,END + C_0 (C_EOM H_EOM + C_PZT H_PZT) P_MC
           (C_FA C_IN P_IN H_IN,PD + (1 + C_IN C_MC P_IN H_IN,PD H_MC,END) H_MC,PD)))],
   L_IN/ν_YAG * Abs[ν_MC * ((1 + P_MC (-1 + C_0 (C_EOM H_EOM + C_PZT H_PZT) H_MC,PD)) /
        (1 - C_IN C_MC P_IN (-1 + P_MC) H_IN,PD H_MC,END + C_0 (C_EOM H_EOM + C_PZT H_PZT)
          P_MC (C_FA C_IN P_IN H_IN,PD + (1 + C_IN C_MC P_IN H_IN,PD H_MC,END) H_MC,PD)))],
   L_IN/ν_YAG * Abs[N_MCEND * ((H_MC,END (1 + P_MC (-1 + C_0 (C_EOM H_EOM + C_PZT H_PZT) H_MC,PD))) /
        (1 - C_IN C_MC P_IN (-1 + P_MC) H_IN,PD H_MC,END + C_0 (C_EOM H_EOM + C_PZT H_PZT)
          P_MC (C_FA C_IN P_IN H_IN,PD + (1 + C_IN C_MC P_IN H_IN,PD H_MC,END) H_MC,PD)))],
   Abs[(H_INPend + 10^-19) / P_IN]}, {f, 10^1, 10^5}, Frame →
   True,
  PlotRange ->
   {{10^1, 10^5},
    {10^-20, 10^-16}},
  PlotPoints → 3000, PlotStyle →
   {RGBColor[0, 0, 0],
    RGBColor[1, 0, 0],
    RGBColor[1, 0, 1],
    RGBColor[0, 1, 0.8], RGBColor[1, 1, 0]},
  GridLines -> {{{1000, {Dashing[{.01, .01}]}}},
    {{1 * 10^-18, {Dashing[{.01, .01}]}}}},
  FrameLabel → {"Frequency [Hz]", Displacement [m/rHz]}]
```


1. × 10^-16
1. × 10^-17
1. × 10^-18
1. × 10^-19
Displacement [m/√Hz]
100
1000
10000
100000.
Frequency [Hz]

- Graphics -