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SERVO TOPOLOGY OF THE MARK II PROTOTYPE

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Abstract

The purpose of this report is to document the multi-input multi-output servo topology of the 1994 Mark II prototype. The design discussed uses a "feedaround servo topology" which couples the primary arm cavity, the mode cleaner, and the laser together; the control of the secondary cavity is decoupled from the other optical systems. Analysis is done to show the loop shapes used for keeping the primary arm cavity on resonance and for controlling the fluctuation of the light frequency injected into the primary cavity.

I. SERVO TOPOLOGY

The simplified servo topology of the current Mark II prototype with the feedaround path is shown in Figure 1. There are three feedback systems: the mode cleaner servo, the primary cavity servo system, and the secondary cavity servo system. The main role of the mode cleaner servo is to frequency stabilize the light leaving the mode cleaner cavity. This light is locked on resonance in the primary cavity and further frequency stabilized by the primary cavity servo system. The secondary cavity servo system then keeps the secondary cavity on resonance. A "feedaround path" from the primary cavity to the mode cleaner and the laser, couples the 3 optical systems together electronically.

In Figure 1, the frequency detection system using an RF-reflection technique is simply represented by a set of blocks consisting of a discriminator (a triangle with + and − inputs), a cavity pole filter, and a frequency voltage convertor. Here the frequency of the incident light is compared with the resonant frequency of the cavity (the resonant frequency of the cavity is linearly related to the cavity length); this signal is then optically filtered (roll-off occurs at cavity pole frequency) and then converted into voltages. This simple model is enough for steady state analysis of the system.

(1) Mode Cleaner Servo System

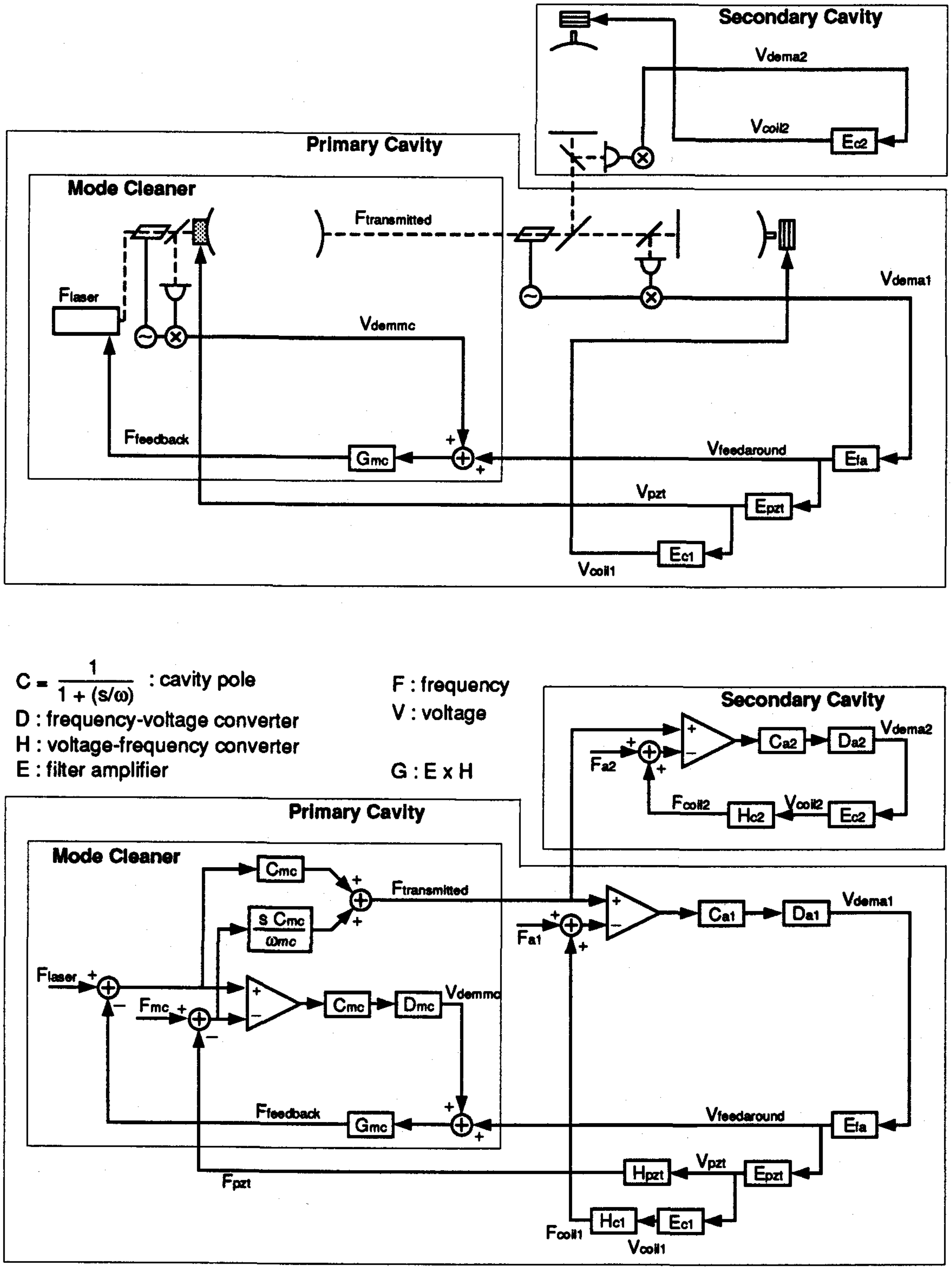
The frequency of the laser light (F_{laser}) is compared with the resonant frequency of the mode cleaner (F_{mc}), which is linearly related to the length of the mode cleaner cavity, and converted into the demodulation voltage (V_{demmc}) through the cavity pole filter (C_{mc}) and the frequency-voltage converter (D_{mc}). The demodulation voltage (V_{demmc}) is then filter-amplified and converted into frequency by G_{mc} and fed back to the laser frequency as $F_{feedback}$. In the actual system there are three feedback paths, rather than one, to the laser (the slow PZT, the fast PZT, and the Pockels cell path); for simplicity only one path is pictured in Figure 1. The frequency of the transmitted light ($F_{transmitted}$) consists of two components: the stabilized laser frequency low-pass-filtered by (C_{mc}), and the resonant frequency of the mode cleaner high-pass-filtered by ($s\ C_{mc}/\omega_{mc}$).

(2) Primary Cavity Servo System

The frequency of the transmitted light ($F_{transmitted}$) is compared with the resonant frequency of the primary cavity (F_{a1}) and is converted into the demodulation voltage (V_{dema1}) through the cavity pole filter (C_{a1}) and the frequency-voltage converter (D_{a1}). The demodulation voltage (V_{dema1}) is then filter-amplified by an electronic circuit (E_{fa}) and the feedaround voltage ($V_{feedaround}$) is injected into the demodulation voltage of the mode cleaner servo system (V_{demmc}). The feedaround voltage ($V_{feedaround}$) is again filter-amplified by another electronic circuit (E_{pzt}) and fed back to the mode cleaner PZT; the length of the mode cleaner, thus, the resonant frequency of it (F_{pzt}) is changed. The conversion ratio from the PZT voltage (V_{pzt}) to the equivalent frequency (F_{pzt}) is represented by H_{pzt}. The PZT voltage (V_{pzt}) is further filter-amplified by an electronic circuit (E_{c1}) and fed back to the magnet-coil system of the primary cavity; the length of the cavity, thus, the cavity's resonant frequency (F_{coil1}) is changed. The conversion ratio from the coil voltage (V_{coil1}) to the equivalent frequency (F_{coil1}) is represented by H_{c1}. The mode cleaner servo system can be considered as a super block with two inputs ($V_{feedaround}$ and F_{pzt}) and one output ($F_{transmitted}$) existing in the primary cavity servo loop.

(3) Secondary Cavity Servo System

The transmitted light, which is stabilized by the primary cavity servo, is compared with the resonant frequency of the secondary cavity (F_{a2}) and is converted into the demodulation voltage (V_{dema2}) through the cavity pole filter (C_{a2}) and the frequency-voltage converter (D_{a2}). The demodulation voltage (V_{dema2}) is then filter-amplified by an electronic circuit (E_{c2}) and fed back to the magnet-coil system of the secondary cavity; the length of the cavity, thus, the cavities resonant frequency (F_{coil2}) is changed. The conversion ratio from the coil voltage (V_{coil2}) to the equivalent frequency (F_{coil2}) is represented by H_{c2}. The coil voltage (V_{coil2}) is the final output of the interferometer and analyzed using an FFT.



$C = \frac{1}{1 + (s/\omega)}$: cavity pole

D : frequency-voltage converter

H : voltage-frequency converter

E : filter amplifier

F : frequency

V : voltage

G : E x H

Figure 1. Schematic diagram (upper) and block diagram (lower) showing servo topology of the Mark II prototype

II. TRANSFER FUNCTIONS AND LOOP SHAPES

(1) Mode Cleaner Open Loop Transfer Function

The open loop transfer function of the mode cleaner servo loop (T_{mc}) is:

$$T_{mc} = -C_{mc}\, D_{mc}\, G_{mc}$$

This transfer function shows the degree to which the frequency noise injected into the mode cleaner is suppressed by the mode cleaner servo system. In practice, however, the limit is set by the length variation of the mode cleaner cavity.

In the Mark II prototype, this loop has a unity gain frequency of approximately 1 MHz with a phase margin of about 135°, just between 90° (smooth landing) and 180°(oscillation).

(2) Transfer Function from F_{pzt} to $F_{Transmitted}$

The PZT attached to one of the mode cleaner mirrors is used as an actuator for the primary cavity servo. If we make the assumption that the open loop gain of the mode cleaner servo loop (T_{mc}) is much larger than unity below the mode cleaner cavity pole frequency (ω_{mc}), then the transfer function ($T_{pzt(mc)}$) from the resonant frequency of the mode cleaner (F_{pzt}) to the frequency of the transmitted light ($F_{transmitted}$) is:

$$T_{pzt(mc)} \approx -C_{mc} - \frac{s\, C_{mc}}{\omega_{mc}} = -1$$

This assumption is valid in the Mark II prototype. The servo forces the laser frequency to follow the cavity length below the mode cleaner cavity pole frequency (ω_{mc}); the change in the cavity length directly affects the frequency of the transmitted light ($F_{transmitted}$) above the cavity pole frequency (ω_{mc}).

(3) Transfer function from $V_{feedaround}$ to $F_{transmitted}$

The transfer function ($T_{feedaround(mc)}$) from the feedaround injection ($V_{feedaround}$) to the frequency of the transmitted light ($F_{transmitted}$) is:

$$T_{feedaround(mc)} = \frac{-\,C_{mc}\, G_{mc}}{1 + C_{mc}\, D_{mc}\, G_{mc}}$$

This transfer function has a flat frequency dependence up to around the unity gain frequency of the mode cleaner servo and then falls off rapidly (see figure 2).

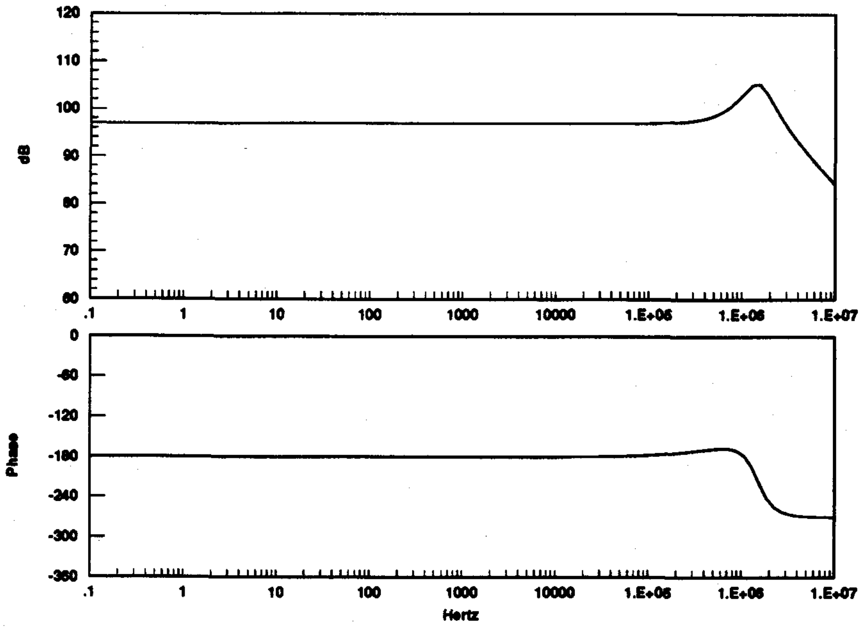


Figure 2. Transfer function from $V_{\text{feedaround}}$ to $F_{\text{transmitted}} = T_{\text{feedaround(mc)}}$

(4) Fringe Control Loop Gain for Primary Cavity Servo (Loop Gain Transfer Function When Loop is Broken at V_{demal}).

The primary cavity servo has three paths: the feedaround path, the mode cleaner path, and the magnet-coil path. The open loop transfer function of each path ($T_{\text{feedaround(al)}}$, $T_{\text{pzt(al)}}$, and $T_{\text{magnetcoil(al)}}$, respectively) is:

$$\begin{aligned} T_{feedaround(a1)} &= C_{a1}\, D_{a1}\, E_{fa}\, T_{feedaround(mc)} \\ T_{pzt(a1)} &= C_{a1}\, D_{a1}\, E_{fa}\, E_{pzt}\, H_{pzt}\, T_{pzt(mc)} \\ &= -C_{a1}\, D_{a1}\, E_{fa}\, E_{pzt}\, H_{pzt} \\ T_{magnetcoil(a1)} &= -C_{a1}\, D_{a1}\, E_{fa}\, E_{pzt}\, E_{c1}\, H_{c1} \end{aligned}$$

This set of transfer functions is plotted in Figure 3. The total open loop transfer function (T_{a1} = loop gain when the closed loop is broken at V_{demal}) is:

$$T_{a1} = T_{feedaround(a1)} + T_{pzt(a1)} + T_{magnetcoil(a1)}$$

This transfer function shows the degree to which deviation of the operating point from the dark fringe is suppressed. It is evident from Figure 4 that at 1 Hertz the operating fringe should be attenuated by 180 db.

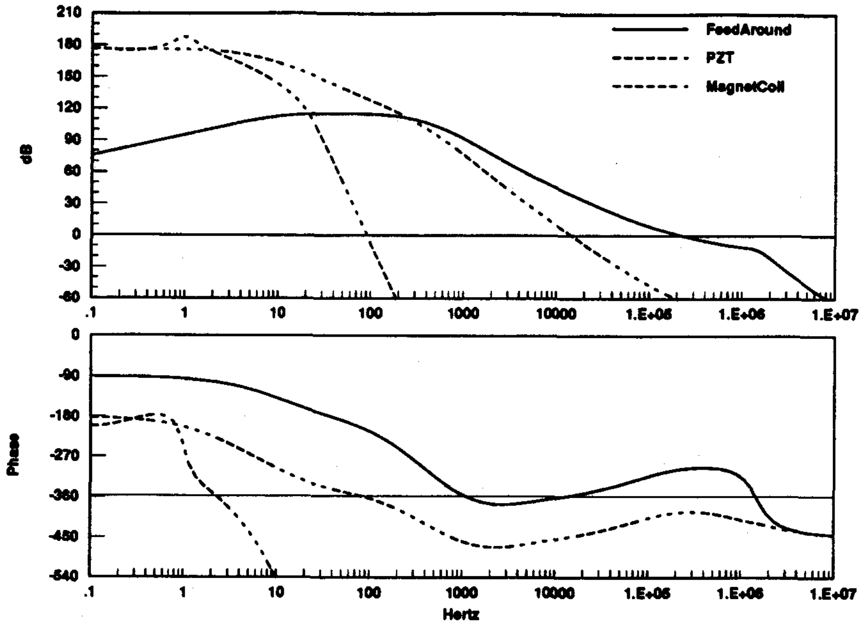


Figure 3. Transfer functions of the 3 different loops making up the length control of the primary cavity servo

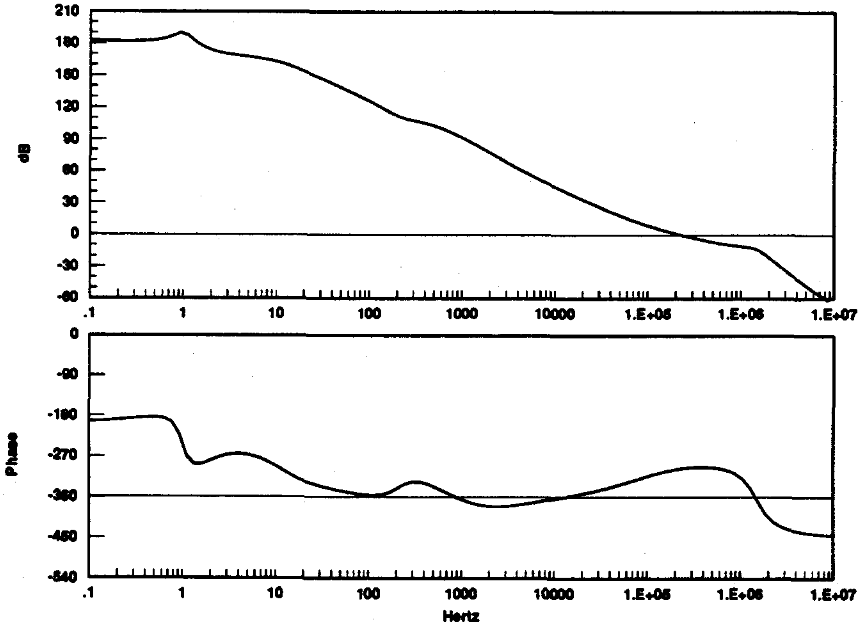


Figure 4. Effective Length Control Loop Gain for Primary Cavity Servo (Loop Gain Transfer Function When Loop is Broken at V_{demal})

(5) Effective Frequency Stabilization Loop Gain for Primary Cavity Servo (Loop Gain Transfer Function When Loop is Broken at $F_{transmitted}$)

The effective frequency stabilization loop gain is different from the fringe control loop gain since the loop is broken at different points in the servo; the feedback to the test mass of the primary arm cavity is not responsible for stabilizing the frequency of the light. The frequency stabilization gain is represented by the open loop transfer function ($T_{frequency(a1)}$) from the frequency of the incident light into the primary cavity ($F_{transmitted}$) to the frequency of the mode cleaner transmitted light ($F_{transmitted}$):

$$T_{frequency(a1)} = \frac{T_{feedaround(a1)} + T_{pzt(a1)}}{1 - T_{magnetcoil(a1)}}$$

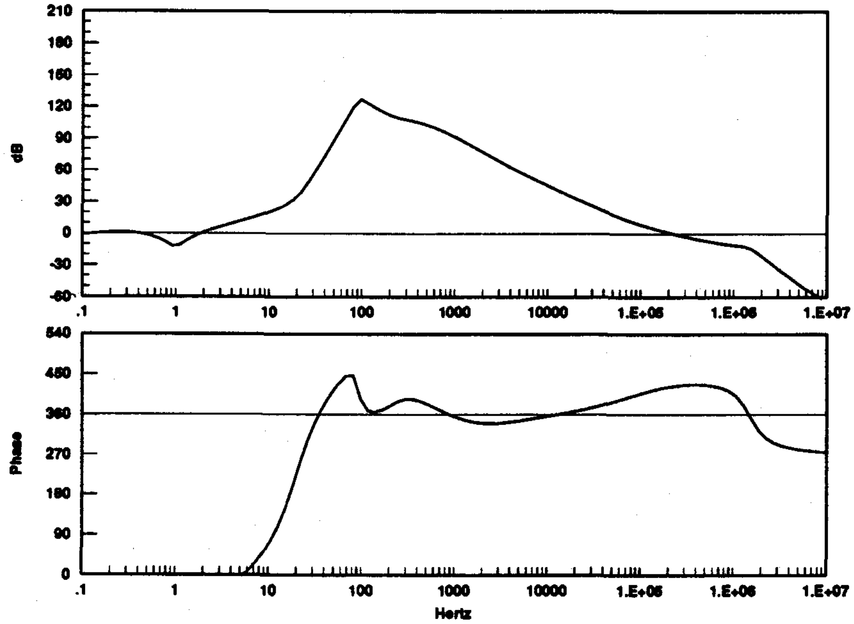


Figure 5. Effective Frequency Stabilization Loop Gain for Primary Cavity Servo (Loop Gain Transfer Function When Loop is Broken at $F_{transmitted}$)

This transfer function shows the degree to which the frequency noise injected into the primary arm cavity is suppressed. The frequency stabilization gain is the same as the fringe control gain above the frequency (around 100Hz) where the gain of the magnet/coil path ($T_{magnetcoil(a1)}$) is less than unity. The frequency stabilization gain is less than unity (no stabilization) where the magnet/coil path is dominant (less than around 1Hz).

III. SERVO MODEL

The servo models used for generating the plots in this report were built using the System Build package in MatrixX. Transfer functions of electronic components (i.e. amplifiers) were derived from corresponding circuit diagrams. The transfer functions for the optical systems were derived using either experimental data or simple models of Fabry-Perot cavities and the corresponding optical specifications. For simplicity, the complicated resonances of the PZTs and the notch filters for nulling their response were omitted.

The final model was also somewhat verified by experiment. We measured some important transfer functions in the real system, such as the closed loop transfer function of the primary cavity servo, which turned out to agree with the transfer functions obtained from the model.

The model is expected to be useful in various ways:

1. Can be used as an analysis tool to predict how electronic noise produced in different circuits turns into frequency noise.
2. Can be used as an analysis tool to predict the effect of spurious paths
3. Can be used as a tool for redesigning the primary cavity servo electronics.
4. Since the topology is very similar to the servo design for the triangular mode cleaner, with simple changes it can also be used as an analysis tool for the triangular mode cleaner.