Circuit Design Clinic
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Mixed-Technology Laser System, Part 3

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The August 2006 Circuit Design Clinic continued coverage of some problems with a medical laser design. In this third part, the design problem of stabilizing the whole laser loop is undertaken.

Problem:

Design the dynamic compensation of a Nd YAG laser power control loop, to achieve a stable loop within the static error (accuracy) requirements.

Solution:

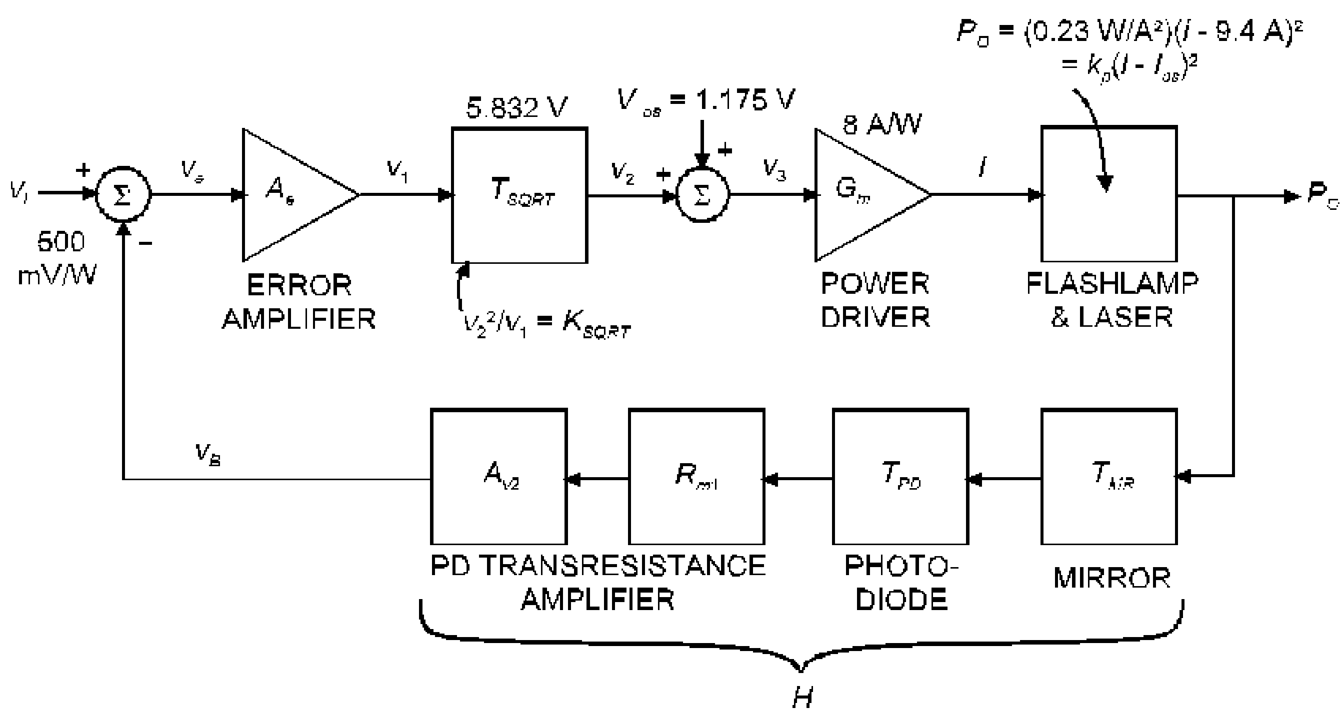
The control loop dynamic-response requirements were a 20 Hz maximum pulse rate and a 50 ms minimum pulse duration. Then for a chosen transition (rise and fall) time of less than 5 ms, incremental bandwidth would need to be:

$$f_{bw} \cong \frac{0.35}{5\,\text{ms}} = 70\,\text{Hz}$$

The single-pole time constant associated with this bandwidth must be:

$$\tau < \frac{5\,\text{ms}}{2.2} = 2.27\,\text{ms}$$

The loop is repeated in block-diagram (system-level) form below, redrawn in more detail than the original notebook copy.



The static loop gain, required for *static* stability (that is, no drift) and accuracy, conflicts with dynamic stability. The higher the loop gain is made, the harder it is to keep the feedback loop from oscillating. Reducing loop gain tends to stabilize the feedback loop, but it also causes the low-frequency error to increase. In the original loop without T_{SQRT}, the variation in loop gain from zero-scale (zs) to full-scale (fs) caused error to be excessive at zs and instability at fs. The square-root circuit resulted in a constant gain over the output power range.

This design exercise goes around the loop, characterizing the transfer functions of the various blocks (subsystems) before determining whether the loop is stable, and by how much.

Forward Path Operating-Point Analysis

The forward path of the loop, or G, has the nonlinear flashlamp-laser block. Its incremental (small-signal) gain can be found by differentiating the expression for power, $P_O(i)$. At the zs of 0.1 W out, dP_O/di is 0.30 W/A, but at the fs output of 5 W, it increases by over seven times, to 2.15 W/A. A 7-to-1 loop-gain variation makes feedback design difficult! A square-root circuit was inserted upstream from the flashlamp-laser to compensate its nonlinearity.

The block diagram of the forward path has a summing block inserted between the square-root circuit and flashlamp transconductance power driver, G_m. The additional summing block would affect a *linear* system by resulting in two closed-loop contributions to the output:

$$P_O = \frac{G}{1+GH} \cdot v_i + \frac{G_2}{1+GH} \cdot V_{os}$$

where, $G_2 = P_O/v_3$. The closer to the output the G-path summing block is inserted, the less closed-loop gain V_{os} has. Consequently, the less sensitive the output is to V_{os}. In the original design, this offset was inserted at the input summer, and consequently affected the output as much as the commanding input, v_i. In the refinement, it was moved into the forward path so that drift or error in V_{os} would not be as detrimental.

This offset is used to compensate for the offset of I_{os} in the flashlamp-laser block. To compensate the nonlinearity, an inverse nonlinearity, the square-root circuit, was inserted earlier in the path. However, both the addition of V_{os} and the G_m block are in-between the two nonlinear blocks. Instead of cascading transfer functions which multiply as they do in linear systems, the successive blocks combine as composite functions, as $P_O(i(v_2(v_e)))$ for large-signal (total-variable) analysis. Like transistor circuit analysis, the large-signal analysis must be done first to establish operating points for nonlinear elements so that linearization can occur around them, resulting in incremental variables. These small changes in quantities around the operating-point are then treated as linear. With a linearized system, the usual feedback control analysis can then be applied.

So, we start by thinking total-variable, and begin with the offending nonlinearity, at the output of G:

$$P_O = k_p \cdot (i - I_{os})^2 = k_p \cdot [G_m \cdot (V_{os} + T_{SQRT}(A_e \cdot v_e)) - I_{os}]^2$$

$$= k_p \cdot \left(G_m \cdot V_{os} + G_m \cdot \sqrt{\left(\frac{R_f}{R_i}\right) \cdot (R_f \cdot I_R) \cdot A_e \cdot v_e} - I_{os} \right)^2$$

Then we set:

$$V_{os} = \frac{I_{os}}{G_m}$$

and:

$$P_O = k_p \cdot G_m^2 \cdot \left[\left(\frac{R_f}{R_i}\right) \cdot (R_f \cdot I_R)\right] \cdot A_e \cdot v_e = k_p \cdot G_m^2 \cdot K_{SQRT} \cdot A_e \cdot v_e$$

The parameters of K_{SQRT} come from the square-root circuit components, as covered in Part 1. When calculated, K_{SQRT} = 5.832 V. A_e = 10 (from the Part 1 circuit diagram of G_1), and substituting all values, the quasistatic (low-frequency) gain of G is:

$$G_0 = \frac{P_O}{v_e} = k_p \cdot G_m^2 \cdot K_{SQRT} \cdot A_e = (0.23\ \text{W/A}^2) \cdot (8\ \text{A/V})^2 \cdot (5.832\ \text{V}) \cdot (10) = 858\ \text{W/V}$$

The feedback path, H, is scaled at the error-summing block as 0.5 V/W. Then:

$$H_0 = 0.5\ \text{V/W}$$

and the quasistatic loop gain is:

$$G_0 \cdot H_0 = 429$$

This gain is high enough to maintain sub-percent accuracy of P_O. Now, can we maintain this value while achieving a dynamically acceptable response?

Incremental G_1 And G_2

The incremental gains, or transfer functions, can be derived for G_1 and G_2 as follows. First, G_2:

$$G_2 = \frac{dP_o}{dv_2} = 2 \cdot k_p \cdot G_m^2 \cdot v_2 \cong (29.44 W/V^2) \cdot v_2$$

Because of flashlamp-laser nonlinearity, the incremental gain that is G_2 depends upon the total-variable value of v_2, which is:

$$v_2^2 = K_{SQRT} \cdot A_e \cdot v_e$$

and:

$$v_2 = \sqrt{K_{SQRT} \cdot A_e \cdot v_e}$$

Then expressed as a function of v_e:

$$G_2 = \frac{dP_O}{dv_2} = 2 \cdot k_p \cdot G_m^2 \cdot \sqrt{K_{SQRT} \cdot A_e} \cdot v_e^{\frac{1}{2}}$$

For G_1:

$$G_1 = \frac{dv_2}{dv_e} = \tfrac{1}{2} \cdot \sqrt{K_{SQRT} \cdot A_e} \cdot v_e^{-\frac{1}{2}} \cong 3.818\ \mathrm{V}^{\frac{1}{2}} \cdot v_e^{-\frac{1}{2}}$$

Then the incremental, linearized:

$$G = \frac{dP_O}{dv_e} = \frac{dP_O}{dv_2} \cdot \frac{dv_2}{dv_e} = \left(2 \cdot k_p \cdot G_m^2 \cdot K_{SQRT}^{\frac{1}{2}} \cdot A_e^{\frac{1}{2}} \cdot v_e^{\frac{1}{2}} \right) \cdot \left(\tfrac{1}{2} \cdot K_{SQRT}^{\frac{1}{2}} \cdot A_e^{\frac{1}{2}} \cdot v_e^{-\frac{1}{2}} \right) = k_p \cdot G_m^2 \cdot K_{SQRT} \cdot A_e$$

Note that the nonlinearities of G_1 and G_2 have cancelled incrementally through multiplication, leaving a linear G. Substituting values:

$$G \cong (0.23\ \mathrm{W/A^2}) \cdot (8\ \mathrm{A/V})^2 \cdot (5.832\ \mathrm{V}) \cdot (10) = 858\ \mathrm{W/V}$$

Throughout the power range, the incremental gains of G_1 and G_2 change, but their product remains constant, at G. This is illustrated in tabular form.

	Total-Variable			**Incremental**	
Op-pt	**P_O, W**	**v_2, mV**	**v_e, mV**	**G_1**	**G_2**
zs	0.1	82.6	0.117	353	2.432
fs	5.0	583	5.83	50.0	17.16

The $G_1 \cdot G_2$ product for both zs and fs is equal to G; the quasistatic gain remains constant over the forward path, and the nonlinearity compensation succeeds in producing a linearized forward path.

The dynamic analysis will continue -- and conclude -- in the next part of this design clinic.