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SERVO CONTROLLER FOR SCANNING GALVANOMETER

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Introduction

In the rapidly emerging field of electro-optics the scanning galvanometer is a fundamental building block. Typically, it consists of a moving-iron galvanometer with limited rotation and attached mirror of fairly substantial inertia that is servoed to follow a sawtooth input to give a linear scan with flyback.1 Applications include such new systems as those that transmit photographs by wire using a laser beam to obtain reproductions of photographic quality.

This article describes the design of the servo controller for a scanning galvanometer, Model 300 FD of General Scanning Incorporated. The major design problems stem from the stringent type of input, the sawtooth with its linear ramp and periodic step function type of input, and from the galvanometer characteristics of limited linear region of operation and lightly damped oscillatory response. In order to use the major portion of this linear region the output response is limited to the no overshoot condition, a difficult task considering the lightly damped free response. Design by way of analog simulation techniques resulted in a system with zero steady state error and satisfactory transient response with no overshoot. The use of a real-time model on the analog simulator made it possible to verify the performance by replacing the model with the actual galvanometer.

The Model

The galvanometer is described in terms of seven parameters using the transfer function given as Equation (1).

\[
\frac{s}{E} = \frac{J}{K_g} + \frac{B}{K_g} + \frac{J}{K_g} \frac{s}{K_g} + \frac{(T_m - K_g K_y) B}{K_g K_y K_y + 1} + 1
\]

(1)

The variables are defined as follows:

- \( E \) is the applied coil voltage in volts
- \( s \) is the rotation in radians
- The model constants are defined as follows:
- \( R \) is the total coil circuit resistance in ohms
- \( L \) is the coil inductance in henrys
- \( K_y \) is the back emf constant in volts/rad/sec.
- \( K_g \) is the torque constant in \( \frac{\text{ft} \cdot \text{lb}}{\text{amp}} \).
- \( J \) is the total inertia in \( \frac{\text{slug} \cdot \text{ft}^2}{\text{sec}^2} \).
- \( B \) is the mechanical viscous friction in \( \frac{\text{ft} \cdot \text{sec}}{\text{rad}} \).
- \( K_y \) is the spring constant in \( \frac{\text{ft}}{\text{sec}} \).

In Table 1 the values of these model constants as obtained by measurement along with the nominal values of the manufacturer are listed. The value for \( B \) was determined by simulation.

Using the values from Table 1 the expression for the transfer function in factored form is given as Equation (2).

\[
\frac{s}{E} = \frac{0.105}{2.46 \times 10^{-6} (s+65)(s+100+786)(s+100-786)}
\]

(2)

*Employed by Harris Electronics Systems Division during Summer 1974.

<table>
<thead>
<tr>
<th>Table 1: VALUES OF MODEL CONSTANTS</th>
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<tr>
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<td>K_y</td>
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This gives one real pole and two lightly damped complex poles. Since the input is a repetitive ramp function, a type two system or a high gain type one system is needed to prevent a large steady state error.

Controller Design

With the choice of a type one system the controller is designed to have an integrator pole along with the three poles of \( \frac{s}{E} \) to give the potential of two complex pairs of roots. The first compensation tried was two zeros on the negative real axis. Even with the addition of rate feedback from the output this approach was completely unsatisfactory. Many combinations were tried on the simulated model without success in that one of the two pairs of complex roots or the other was too lightly damped.

The next approach is to use a compensator with three zeros. Two of these zeros are chosen as a complex pair with sufficiently large damping ratio \((>0.70)\) so that two of the complex roots are essentially masked by these two zeros. This basic idea is the key to the success of this controller and is best understood by considering the root locus sketch shown in Figure 1. With the appropriate gain the two poles at the origin give roots that are effectively cancelled by these two zeros. The other pair of complex roots as shown on this sketch are too lightly damped. This part of the response is now the dominant pair of roots. Rate feedback of the output is used to obtain satisfactory transient response with the amount of feedback determined by simulation. The galvanometer is provided with a position transducer by the manufacturer with a gain of 9.17 volts/radian. The output of this transducer is fed to an operational amplifier differentiator to obtain a negative rate feedback as shown in Figure 2.

The transfer function of the controller in its final form as obtained by simulation is as follows:

\[
G_c(s) = \frac{0.0195 K(s+500)(s^2+1000s+4.1x10^5)}{s(s+2000)(s+4850)}
\]

(3)

The value of \( K \) was set to 4850.

With the sawtooth type of input used in this application the use of rate feedback produces an error in the
steady state response. This is readily corrected here by summing a constant of the correct value to the the input of the summing amplifier as the slope of the sawtooth is fixed. This same constant can also be used to correct for the very small error in the steady state resulting from the use of a type one system.

In other applications where the rate feedback is not desirable it is possible to get the equivalent effect by adding another zero on the real axis to the above controller. This would require another lead network.

**Transient Response**

The response of the analog model to a step function as obtained by simulation is given in Figure 3. The accuracy of the simulation is easily seen by comparing this response with that of the actual galvanometer controlled by the simulated controller as shown in Figure 4. In Figure 5 the response to the sawtooth input for the analog simulation is given, and in Figure 6 the sawtooth response of the galvanometer with this controller is shown. This performance is very satisfactory in that it is fast with no overshoot and has no steady state error.

With the parameters for the simulated model changed to their nominal values as given in Table 1 and without changing the controller in any way the response to the sawtooth input is given in Figure 7. Again the response is very satisfactory. This suggests that this controller would be satisfactory for all Model 6300 TD scanning galvanometers meeting the manufacturer's specifications and used in this application.

**Circuit for the Controller**

In Figure 8 is given a three operational amplifier circuit design for the controller. The amplifier on the left sums the input, the position feedback, the rate feedback, and the correction voltage. It has a gain of -10. The second amplifier is based on reference 3; it provides the complex pair of zeros in a simple and economical way. This is in contrast with the typical simulator circuit that requires three operational amplifiers. The transfer function for the second amplifier is:

\[ \frac{R_3}{R_2+R_3} \frac{[1+ s(R_1C_1+R_2C_2)]}{(1 + sR_1C_1)(1 + sR_2C_2/R_2+R_3)} \]  \hspace{3cm} (4)

With the appropriate values this becomes:

\[ \frac{0.111}{(1 + 0.00244s + 2.44 \times 10^{-5}s^2)} \]  \hspace{3cm} (5)

The third amplifier is used to obtain the following transfer function:

\[ \frac{-1}{sR_4C_3} \]  \hspace{3cm} (6)

The combination of the three amplifiers gives the same transfer function as given in Equation 3.

**Conclusions**

The design presented herein proved satisfactory as a controller for a scanning galvanometer driven by a sawtooth input. The transient response is fast with no overshoot and zero steady state error. The controller changed the system from type zero to type one and utilized three zeros and rate feedback to obtain satisfactory transient response. An important feature of this design is the use of a pair of complex zeros to cancel effectively a pair of complex roots of the response. A constant correction term is used to insure zero steady state error. A practical economical design utilizing three operational amplifiers is presented.

**References**


2. General Scanning Incorporated, Watertown, Massachusetts, Series G Optical Scanners, G304R 6.7323M.


**Figure 1: Root Locus Sketch**

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Figure 2: Rate Feedback Circuit

\[ E_1 = \frac{0.47}{2.3K} \]
\[ E_2 = \frac{-5R_2C_1}{E_1 (1+5R_1C_1)(1+5R_2C_2)} \]

Figure 3: Step Response of Model

\[ V(t) = \begin{cases} 0 & \text{for } t \leq 0 \\ 1 & \text{for } t > 0 \end{cases} \]

Figure 4: Step Response of Galvo

\[ V(t) = \begin{cases} 0 & \text{for } t \leq 0 \\ 1 & \text{for } t > 0 \end{cases} \]

Figure 5: Sawtooth Response of Model

\[ V(t) = 0.5V/cm \quad 100\text{mm/sec} \]

Figure 6: Sawtooth Response of Galvo

\[ V(t) = 0.5V/cm \quad 100\text{mm/sec} \quad k = 4850 \]

Figure 7: Sawtooth Response of Model with Nominal Parameters

Figure 8: Operational Amplifier Controller Circuit