A DIGITAL RESONANCE CONTROL SYSTEM FOR THE DRIFT-TUBE LINAC

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Introduction

An experimental resonance control system for a 4-ft drift-tube linac model has incorporated digital control through an SEL-810A digital computer. Resonance of the model is controlled by regulating the temperature of the cooling water circulating through the system. The flow of cold water to the recirculating water loop is under direct computer control and changes in flow rate are based upon a weighted summation of the state variables of the system. Since the sampling period T is much smaller than the system time constants, a very good approximation to continuous control is achieved.

The system illustrates the power of digital control for system and control analysis as well as the advantages of digital control itself. The flexibility of the computer allows alteration of control algorithms and parameters without changing the hardware configuration. In addition, the computer may be used to simulate a plant different from the actual hardware. For example, the experimental control system for the 4-ft drift-tube model has been used to simulate resonance control of full-size drift-tube linac tanks through the addition of appropriate time delays.

The Resonance Control System

Resonance of the drift-tube linac model is maintained by controlling the temperatures of the tank walls and the drift tubes. Separate cooling water systems exist for each. In order to obtain a rapid heat transfer between metal and water, a high velocity recirculating flow is maintained in the cooling passages. At the cooling passage outlets, the exiting hot water is cooled by direct mixing with cold water before being recirculated. The flow of cold water is regulated by a stepping motor actuated valve.

The direct digital control loops are shown in Fig. 1. The state variables measured include recirculating water and copper wall temperatures. These temperatures are measured with thermistor circuits. RF power and RF phase difference between the forward power in the input line and the tank fields are measured in addition to temperatures. These analog signals are fed into the data acquisition system where voltage levels are adjusted and information is converted into binary form. Using this data, the computer calculates the necessary output M from the control algorithm. This output is in the form of a series of pulses to drive the stepping motor to a new position, thereby changing the cold water flow rate through the valve.

A signal flow diagram for the plant of the 4-ft model is shown in Fig. 2. The variables involved are identified in Table I. All variables in Table I, with the exception of drift-tube copper temperature and the cold water flow rates, are fed back to the computer.

Table I

System Variables of Fig. 2

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
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<tbody>
<tr>
<td>( w_1 )</td>
<td>Cold water flow rate.</td>
</tr>
<tr>
<td>( T_{W1} )</td>
<td>Tank wall inlet water temperature.</td>
</tr>
<tr>
<td>( T_{WC} )</td>
<td>Tank wall copper temperature.</td>
</tr>
<tr>
<td>( T_{WC} )</td>
<td>Drift-tube inlet water temperature.</td>
</tr>
<tr>
<td>( T_{W3} )</td>
<td>Drift-tube mix tank water temperature.</td>
</tr>
<tr>
<td>( T_{DC} )</td>
<td>RF phase difference between input line and tank fields.</td>
</tr>
<tr>
<td>( Q_{RF} )</td>
<td>Average rf power to the tank.</td>
</tr>
<tr>
<td>( M_1 )</td>
<td>Input to tank wall system.</td>
</tr>
<tr>
<td>( M_2 )</td>
<td>Input to drift-tube system.</td>
</tr>
</tbody>
</table>

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Investigation of Alternative Control Schemes

Two different schemes to maintain resonance in the 4-ft drift-tube model are being investigated. One scheme entails controlling the temperature of the tank walls and the drift tubes to the values necessary for resonance without using phase information in the control loop. The drift-tube copper temperatures are inaccessible to measurement, however, so the temperature of the water circulating through them is controlled. This would be a desirable control mode because no phase bridge and related circuitry would be necessary.

Another scheme entails roughly controlling the tank wall copper temperature and using phase information in the drift-tube system to "fine-tune" the phase error to zero. Although this system requires more hardware to implement, it maintains a closer resonance condition and is not as susceptible to unknown system parameter changes as the strictly temperature controller. No matter which scheme is used, the digital controllers are similar.

Whether the tank wall temperature or the phase is being controlled, the plant of the system is of the form of Fig. 3. This system is of order 3 and, therefore, three state variables contain all information necessary. The choice of state variables is not unique. As a first choice of state variables, $R_l$, $dR_l$, and $dR_c$ were chosen. The continuous control algorithm was of the form:

$$ M = K_A E_1(t) + K_B \frac{dR_l}{dt} + K_C \frac{dR_c}{dt} $$

where $E_1(t) = (\text{set point}) - (\text{controlled variable } R_l)$. The resulting signal flow diagram is shown in Fig. 4.

The digital equivalent of this controller is therefore one where $M$ at the $i$th sampling instant is given by:

$$ M_i = K_A E_{1,i} + \frac{K_B (R_{l,i} - R_{l,i-1})}{T} + \frac{K_C (R_{c,i} - R_{c,i-1})}{T} $$

where $T$ = Sampling interval.

$R_{l,i}$ = Variable $R_l$ at sampling instant $i$

$R_{c,i}$ = Variable $R_c$ at sampling instant $i$

$E_{1,i}$ = (Set point) - $R_{l,i}$

As a means to reduce the effect of bad data at a particular sampling instant, the derivative used in the algorithm was actually an averaged derivative over the last four sampling intervals instead of the single interval shown above. This introduced an effective time delay into the system but since $T$ was considerably smaller than the system time constants, this delay was small and no measurable effect was observed.

This algorithm produced a control function having reasonably good steady-state response. Temperatures of the tank wall and drift-tube inlet water were maintained within 0.15 °F of their set-point values. However, transient response to a change in rf power level was not acceptable. For the tank wall system, a change in power level was not detected by the controller until the tank wall temperature was affected, a considerable time later and much too late to take corrective action. In order to improve this transient response, it was decided to attempt to feed forward the rf power information to the controller in such a way that it would begin corrective action as soon as a change was detected.

To implement this feed-forward configuration, a new set of states variables needs to be chosen. If the state variables are $R_l$, $R_c$, and $dR_c$ then the set point of $R_c$ can be a function of the power level. Specifically, the steady state inlet water temperature in the tank wall loop ($R_c$) should be a linear function of power level. As the power level increases, the water temperature must decrease in order to remove the excess heat. Thus, we have a continuous control algorithm of the form:

$$ M = K_A E_1(t) + K_B E_2(t) + K_D \frac{dE_2}{dt} $$

where

$E_1(t) = (\text{set point of } R_1) - R_1(t)$

$E_2(t) = (\text{set point of } R_2) - R_2(t)$

$(\text{set point of } R_2) = a - bQ_{rf}$

As an example of how this feed-forward scheme might work, consider the following:

$$ M = K_A E_1(t) + K_B E_2(t) + K_D \frac{dE_2}{dt} $$

where $E_1(t) = (\text{set point of } R_1) - R_1(t)$

$E_2(t) = (\text{set point of } R_2) - R_2(t)$

$(\text{set point of } R_2) = a - bQ_{rf}$
The resulting signal flow graph is shown in Fig. 5.

Figure 5.

The digital equivalent of this is:

\[ M_1 = K_D (R_1 \text{Set pt.} - R_{2,1}) K_E ((a-b q) - R_{2,1}) \frac{K_F (R_{2,1} - R_{2,1} - 1)}{Q} \]

This digital algorithm is now being evaluated.

The values of feedback coefficients for these algorithms \((K_1, \ldots, K_n)\) were derived in two ways. Experimentally, optimization of the system for a particular operating point produced one set of coefficients. Analytically, they were derived by optimizing the system to a quadratic performance index of the form.

\[ \text{P.I.} = \int_0^\infty (S_1^2 + S_2^2 + S_3^2) dt \]

where \(S_1, S_2, \text{and } S_3\) are the state variables of the system. The feedback coefficients which minimize this infinite time integral were obtained by solving the matrix Riccati equation for its time independent solution.\(^2\) This far, limited experimental data indicates a close correlation between experimentally and analytically obtained coefficients.

These optimal feedback coefficients are functions of the system time constants and loop gain. This situation illustrates an interesting advantage of direct digital control over conventional techniques. In the water cooling loops, the mix tank dynamics are of the form

\[ \frac{\text{Output water temp}}{\text{Cold water flow rate}} = \frac{K}{1 + \tau s} \]

where \(s = \text{Laplace operator. The time constant } \tau \text{ is inversely proportional to the cold water flow rate which, in turn, is dependent upon the rf power level. If the accelerator is operating at a particular steady-state condition, both the flow rate and } \tau \text{ will be reasonably constant, implying a fixed set of coefficients for optimal response. If the power level is increased, the flow rate must increase and } \tau \text{ will decrease. The optimal feedback coefficients for the previous operating point will now result in an overdamped system response. Thus, at different accelerator operating points, the feedback coefficients should be different to maintain optimal response. The flexibility of the computer lends itself easily to power dependent feedback coefficients, whereas conventional analog techniques do not.}

In order to make certain that experiments mad on the 4-ft model were relevant to the resonance control of longer tanks, simulation of a full size drift-tube linac tank was made. The major difference between the plant of the large tank and the plant model involves longer transport delays in the water loops.\(^3\) These delays were easily simulated using computer-timing capabilities. If the delay \(T_d \) occurred between \(R_1\) and \(R_2\), then the controller did not use data point \(R_{2,i}\) until the sampling instant \((i + T_d)\). Results of this simulation indicated that the \(T \) time delays would not introduce enough phase shift to significantly affect the control system.

References

