TEMPERATURE CONTROL FOR MAINTAINING RESONANCE OF LINAC TANKS*

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Introduction

For either a drift tube or a side-coupled linac, the resonant frequency of the accelerator structure depends on its dimensions, which in turn depend on the amount of cooling or heating applied. Temperature control is thus necessary to maintain resonance. Since an increasing amount of power is reflected in the input waveguide as the structure drifts away from exact resonance, it can be seen that resonance control interacts with amplitude control. This paper describes the current state of evolution of resonance control systems developed or being developed for the Los Alamos Meson Physics Facility (LAMPF).

The present systems use electrical controllers and actuators. The natural compatibility of an all fluidic system with temperature control has been set aside because of the difficulty in interfacing with other equipment. Most of the controller circuitry is of the analog type. Some of the slower control functions are or will eventually be handled by digital computer control, such as the adjustment of analog set points and the operation of solenoid valves. The computer could, in fact, take over all the controller functions in a slow system of this type. However, a hybrid analog-digital system allows limited operation during maintenance periods when the digital equipment may also be shut down for maintenance.

Electron Prototype Accelerator

The electron prototype accelerator consists of an injector and two side-coupled structures, a 6 cell unit designated Model M and a 100 cell unit designated EPA. The design rf heat load applied to these structures is 3 kW (average) for Model M, and 30 kW for EPA. This heat load is maintained constant during operation in spite of minor deviations from resonance by amplitude control systems on the rf amplifiers. The following remarks will pertain to Model M. The resonance control system for EPA is similar.

Heat is removed from the exterior of Model M by cooling tubes attached with epoxy after final tuning. Water is recirculated through these tubes at high velocity in order to obtain a rapid transfer of heat from the metal to the water. The excess heat is removed by draining off some of the hot water as it emerges from the cooling tubes. A small amount of cold makeup water is admitted to the recirculating loop by a valve which is actuated by a stepping motor. A solenoid operated valve can admit hot water. The recirculating water and copper wall temperatures are sensed by thermistors. The piping and mixing section in the loop was made short in order to have the water cycle time short compared with the time constant of the structure.

A signal flow diagram for the system is shown in Fig. 1; the parameters involved are listed in Table I. Because the epoxy attaching the cooling tubes lowers the heat transfer coefficient[1] by a factor of about 15 below that of a copper-to-water interface, the rf load of 3 kW average is the major factor influencing resonance. In the steady state, a linear relation exists between the rf power input to the tank (Q_{RF}) and both the required cooling water temperature for resonance (T_{Wd}) and the resultant copper temperature (T_{Cu}). This copper temperature is also related to resonance in the transient state; its response has a shape similar to that of the VSWR transient or that of the phase angle between the rf input and the tank. In this instance, the copper temperature is being used to control resonance indirectly because it is single-valued and easier to instrument than phase. The ideal control would then be to manipulate the cooling water temperature, T_{Wi}, according to the equation

$$T_{Wi} = K_6\left(T_{CuRef} - T_{Cu}\right)\left(1 + \tau_4 S\right) + T_{WRef} - K_5 Q_{RF} = T_{Wd}.$$

Unfortunately, cooling water temperature cannot be changed as fast as the rf load can change--here T_{Wi} is adjusted to equal T_{Wd} by the action of a feedback loop. This loop is nonlinear, as indicated by K_4, and the lead-lag circuit in the controller is adjusted so the response is critically damped at the design rf load, with slight under or over damping at lower or higher power levels respectively. The response is different for heating and cooling due to the amount and temperature of cold water or heat from heaters, pump and hot water available from the water loop. The loop keeps T_{Wi} to within ± 0.15°C of T_{Wd} under constant rf load, and its transient response is given by $\Delta T_{Wi}/\Delta T_{Wd}$. An ideal controller would then compensate the water temperature demand T_{Wd} by $\Delta T_{Wd}/\Delta T_{Wi}$. However, this requires anticipation of a change in rf load, not possible in general, and so some transient deviation from resonance is inevitable. The fact that a correction is applied by the feedforward application of the rf heat load to the cooling water controller before an error in resonance occurs reduces this transient significantly over that incurred by a traditional feedback system. In addition, the feedback loop on cooling water temperature and the slower outer feedback loop on copper temperature insure that resonance is maintained within close tolerances at steady state.

The system is currently operating using electronic hardware except for the outer loop on copper temperature. The hardware loop solves the steady-state part of the above control equation and can

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be used alone during normal steady operation or during maintenance periods. The control computer senses the cavity field level, and if a change is detected, the copper temperature feedback controller and the hot water solenoid valve demand programs are initiated. After the transient period is over, the programs are stopped until needed again. Thus in this case, the computer system plays an augmenting role in the resonance control system. Figure 2 shows the response of the system with and without the computer augmentation for steps of about 1 kW in average power. The system was experimentally optimized; here $\tau_4 = 30$ sec, $K_6 = 3.6$, and hot water is applied during the periods when the motor driven valve is at its lower limit. The system is essentially bang-bang for power steps of this size, since the motor driven valve is often fully open or fully closed and all available resources are being used. This is the reason why the peak transient is not further reduced--it would be if more heating or cooling capacity were available. The augmented system has significantly better settling times. It should be noted that the computer programs are not limited to one τ_4, as used here, but can change τ_4 and K_6 to fit the operating conditions at the start of a transient, change it during the transient, and so on.

The final resonance control for the 805-MHz LAMPF structures will differ primarily because the cooling tubes will be soldered on, with a resultant higher heat transfer coefficient and faster response. Additional work is needed in the cooling water loop to equalize and optimize the cooling and heating modes.

Drift Tube Linac Tanks

Resonance control for drift tube linacs is considerably more difficult than for side-coupled linacs. Resonance is affected by the dimensions of both the tank wall and the drift tube assemblies, and the degree of concavity of the end plates has a small effect as well. The natural response time of the wall and end plates is slow compared to that for the drift tubes. Separate cooling water systems are used for the wall and for the drift tubes and other accessories. One reason for this is that it is desirable to keep the deionized water in the stainless steel, brass, and copper bodies of the drift tubes and other accessories separate from the water in contact with iron at the water jacket and the tank wall. There is a small amount of thermal coupling between the two water systems, principally through the accessories. In a high power linac, the tank wall is completely enclosed by the water jacket, and this means that variations in water pressure cause varying compression of the tank, and hence affect resonance. In order to keep the wall cooling system simple, the wall temperature may be allowed to drift somewhat during power level changes, with resonance being maintained by running the drift tubes with a compensating temperature shift. The wall and drift tube temperatures may not be operated far from their design values, however, without affecting the alignment of the drift tube openings with the beam line.

Four-Foot Drift Tube Linac Model

The 4-foot model is a full size 2-cell structure corresponding to the high energy end of the LAMPF drift tube linac. It does not actually accelerate particles. It was constructed in order to test fabrication techniques, try out various components at high electric field gradients, and to investigate resonance control. The cooling system consists of two recirculating water loops of the type described for Model M. One water loop cools the tank wall; the other cools the drift tubes and other accessories.

A signal flow diagram for an experimental control system for the 4-foot model is shown in Fig. 3. The parameters involved are listed in Table II. The stepping motors for the valves are allowed to run all the time; only their direction is controlled. The result is a form of bang-bang control. Water and tank wall temperatures are sensed by thermistors. The rf phase difference between the input line and the tank is detected by a phase bridge. The signal is made available for controller use by a sample and hold circuit. The sample and hold circuit was designed with the restriction that samples could be taken only during the short interval after the rise time of the rf pulse and before the time the beam would come on.

The wall control loop is closed on tank wall temperature (T_F); the drift tube loop on drift tube inlet water temperature (T_{Wd}) or phase (ϕ). A combination of proportional and rate signals is used. In addition, temperature rates (derivatives of T_{Wc} and T_{WF}) from the points where the makeup water is mixed with the recirculating water are used. The use of these additional state variables decreases the amplitude of oscillation in the steady state (inherent in bang-bang control), and it also limits the rate of change of water temperature with time for large errors (e.g., when starting up) which may cause the proportional amplifiers to saturate. This control system has maintained resonance within ± 10° in phase while changing input power levels. This test was made without the benefit of feedback control on the rf amplitude. When the rf amplitude is held constant, the maximum deviations from resonance will be about ± 5° in phase.

The effect of water pressure in the tank wall jacket on resonant frequency was measured to be 76 Hz/psi. This may be compared to a theoretical estimate of 200 Hz/psi obtained for an infinitely long cylinder. As the end plates on the 4-foot model tend to stiffen it, the difference in the two figures appears reasonable.

Drift Tube Linac Portion of LAMPF

The 201.25-MHz portion of LAMPF will consist of four drift tube tanks with resonant post couplers. Each tank will have cooling systems for the wall, the drift tubes, and the quadrupole magnet windings. The drift tube system will also cool the post couplers and other accessories. Only the wall and the drift tube cooling systems will be used for resonance control. Some of the expected values of the parameters involved are listed in Table III. The expected characteristic response times for the tank walls (τ_{13}) are of the same general magnitude as for the 4-foot model.

In order to facilitate starting up and brief changes in rf power level, the set points (corresponding to T_{cd} and T_{Fd} of Fig. 3) will be adjustable by central computer control. In addition, the wall system may have two parallel motor controlled valves, with solenoid valves to select which of the two water paths is in use. Then if the rf is switched off temporarily, control is switched to the alternate valve, which can be positioned appropriately beforehand. These features can be used to reduce the duration of transients.

Comparison of the initial transient when the accelerator is turned on from week to week by the control computer can give some indication of the amplifier drift. Some amount of drift can be compensated for by readjustment of the set points. The hardware to be used in the controllers will utilize integrated circuit modules; large dc drifts are not expected.

References

1. M. Jacob, G. A. Hawkins, Elements of Heat Transfer (John Wiley & Sons, Inc., New York, 1957), 3rd ed., p. 139.

*Work performed under the auspices of the U. S. Atomic Energy Commission.

TABLE I.

Parameters for Model M Resonance Control

Parameter	Value	Approx. formula, remarks
K_1	3.2°C/kW meas.	Adjusted to be the same as K_5.
K_3	$\frac{1.25\ \text{deg}}{\text{sec -V}}$ meas.	Valve angular vel./control voltage. 90 deg full travel.
K_4		$\frac{Q_{RF}}{\dot{w}_{20}^2\, C_{pW}} \cdot \frac{\Delta \dot{w}_2}{\Delta m}$
K_5	0.95°C/kW calc. 3.2°C/kW meas.	$\frac{1}{hA} + \frac{1}{2\dot{w}C_{pW}}$
K_6	3.6	Empirical setting.
τ_1, τ_2		Lead-lag circuit.
τ_3	100 sec calc. 60 sec meas.	$\left(\frac{1}{hA} + \frac{1}{2\dot{w}C_{pW}}\right) w_C\, C_{pC} + \frac{w_W}{2\dot{w}}$ provided water cycle time small.
τ_4	30 sec	Empirical setting

Q_{RF} = rf power input

$\dot{w}_2$ = make up water mass flow rate

$\dot{w}_{20}$ = quiescent value of above

m = valve position

h = heat transfer coef., metal to water; also through epoxy layer

A = surface area for heat transfer, metal to water

$\dot{w}$ = recirculating water mass flow rate

C_{pW} = specific heat of water

w_W = mass of water in cooling channels

w_C = mass of copper in Model M

C_{pC} = specific heat of copper

(The thermal resistance 1/(hA) is assumed to include the resistance of the epoxy layer and the water surface layer both.)

TABLE II.

Parameters for 4-Foot Linac Model Resonance Control

Parameter	Value	Approx. formula, remarks
K_1	~2 V/°C	Thermistor-preamplifier gain factor.
K_2	2.3	Empirical setting (E.S.).
K_3	18 pulses/sec	Valve motor speed, E.S. Full travel ~4000 pulses.
K_5	0.23°C/kW calc. 0.33°C/kW meas.	$\left(\frac{1}{hA} + \frac{x}{2kA_m} + \frac{1}{2\dot{w}C_{pW}}\right)\frac{Q_{DT}}{Q_{RF}}$ Q_{DT} = power to drift tube.
K_6	15 deg/°C	Not including gain of phase bridge and sample and hold circuit.
K_7	2.2	E.S.
K_8	7 pulses/sec	Valve motor speed, E.S. Full travel ~4000 pulses.
K_{10}	0.24°C/kW 0.30°C/kW	Calc. See K_5 (replace Q_{DT} by Q_F). Meas. Q_F = power to tank wall.
K_{11}	21 deg/°C	See K_5.
τ_1	14 sec	E. S.
$\tau_2, \tau_4, \tau_9, \tau_{11}$	1.5 sec	E.S. to reduce high freq. noise.
τ_3	68 sec	E.S.
τ_5	$\gg 1$	Water loop acts like an integrator.
τ_6	8 sec calc. 10 sec meas.	Water transport delay.
τ_7	4.4 sec calc. <5 sec meas.	$\left(\frac{1}{hA} + \frac{x}{2kA_m} + \frac{1}{2\dot{w}C_{pW}}\right) w_m C_{pm} + \frac{w_W}{2\dot{w}}$, provided last term small.
τ_8	55 sec	E.S.
τ_{10}	90 sec	E.S.
τ_{12}	$\gg 1$	Water loop acts like an integrator.
τ_{13}	120 sec calc. 110 sec meas.	See τ_7

x = thickness of metal to be cooled
k = thermal conductivity of metal
A_m = area of metal conducting heat
w_m = mass of metal to be cooled
C_{pm} = specific heat of metal to be cooled
(Other symbols as defined in Table I.)

TABLE III.

Expected Values of Selected Parameters for LAMPF Drift Tube Linac Tanks

Parameter	Tank No. 1	Tank No. 2	Tank No. 3	Tank No. 4
Beam energy out (MeV)	5.39	41.33	72.72	100.00
Tank length (cm)	326.0	1968.8	1875.0	1792.0
Tank dia. (cm)	94.0	90.0	88.0	88.0
$\frac{K_{10}}{Q_F/Q_{RF}}$ (°C/kW)	0.15	0.02	0.02	0.02
τ_{13} (sec)	120	95	90	90

Parameter notation corresponds to Fig. 3 and Table II.

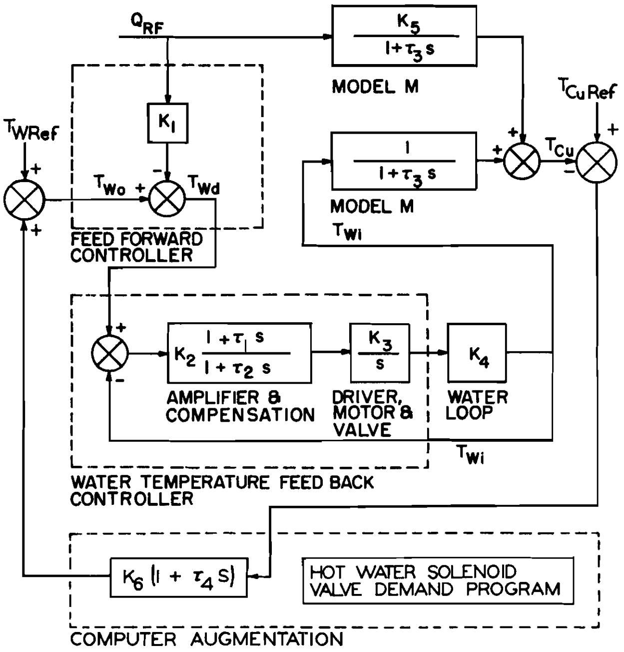

Fig. 1 Signal flow diagram for Model M resonance control system.

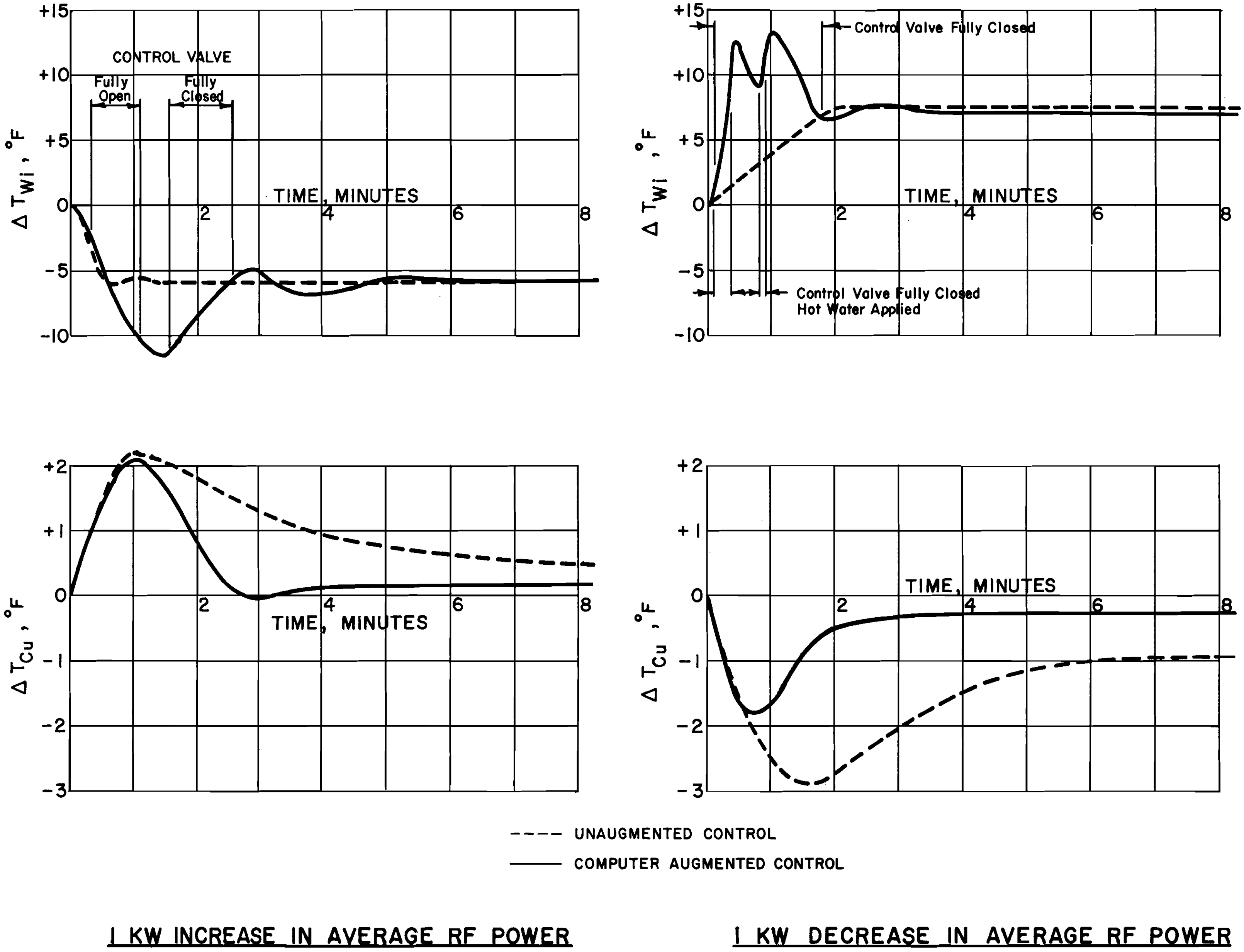

Fig. 2 Response of Model M system to a change in input power.

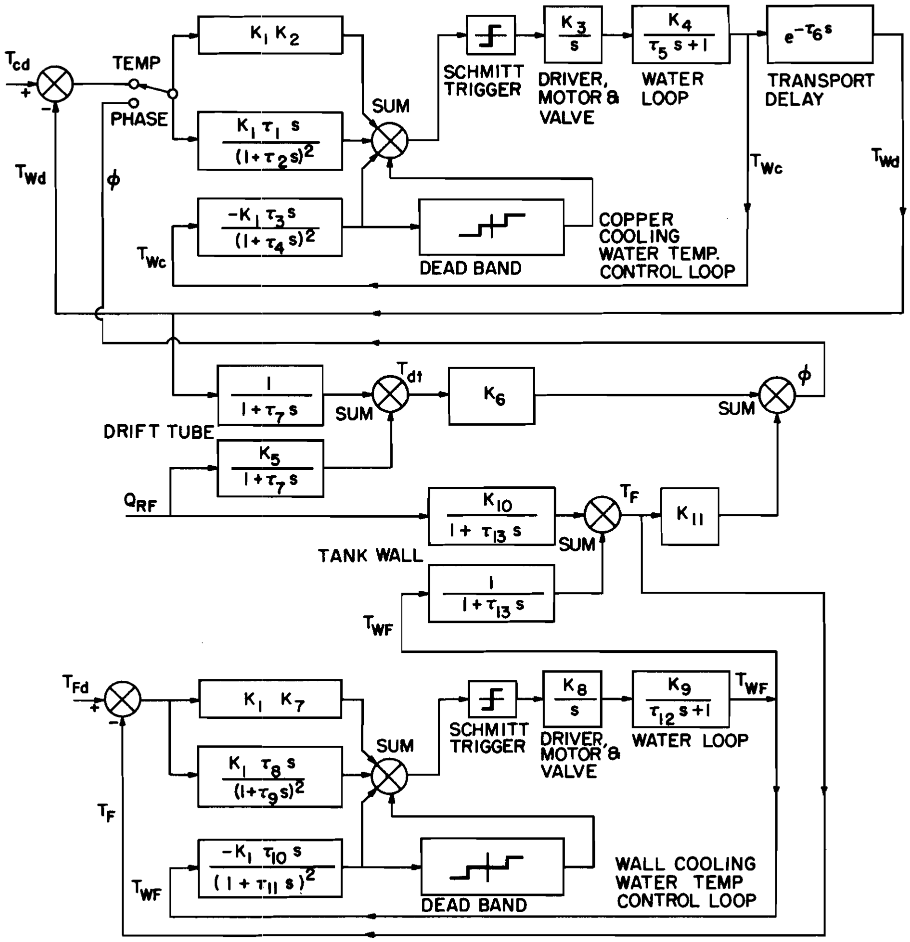

Fig. 3 Signal flow diagram for 4-foot drift tube linac model resonance control system.