AN ADAPTIVE OPTIMAL PHASE FOLLOWING SYSTEM UNDER FREQUENCY STABILIZATION

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Abstract

A method of adaptive control for the optimal phase following under frequency stabilization is discussed in this paper. It is will known that a power feedback LINAC with the optimal coupling has a high utilizing coefficient of power. In order to realize this advantage, we can adjust the phase shifter and the variable coupler in the power feedback loop to minimize the output signal which arises on the detector of the load and maximize the envelop on the entrance of the acceleration tube for different beam load, the optimal efficiency of the LINAC is then preserved. In this system a single chip 8039 is introduced. For every working frequency of the pulse magnetron, the 8039 controls the adaptive process which provides both optimal phase of the loop phase shifter and optimal coupling factor of the variable coupler. The frequency stability of an excellent frequency stabilization system must be constant approximately for different working frequencies and output power of the pulse magnetron. For this purpose, an adaptive gain controller to preserve the maximal output of the frequency discriminator near constant is introduced.

I. Introduction

The energy of the electron beam of a LINAC with a 5Mw pulse power source may be increased over 20MeV by power feedback. The reflection increased by power feedback changes the power spectrum of the magnetron for every working frequency, then the working frequency fixed by the duplexcavity discriminator will deviate from the mean resonant frequency of the duplexcavity preset by a mechanical method, so the stability and intensity of an electron beam with fixed energy are affected by the deviation. In order to eliminate the influence on working frequency caused by the change of the power spectrum of the magnetron a single cavity with Q=15000 is selected as the discriminator. A stable electron beam with the maximal intensity is provided by an adequate method as follows(Fig.1). The power feeds in the acceleration tube through a 3-db bridge. Minimizing absorption power on the load and maximizing superposition envelope on the entrance of the acceleration tube are realized by the adjustment of phase shifters A and B. we can change the output power and oscillation frequency of the magnetron to obtain the electron beams with a variety of energy. In order to preserve the stability and intensity of the electron beam, it is necessay to perform the frequency-phase following.

II. Frequency Stabilization

The width of main lobe of the power spectrum for a magnetron which has been modulated by a power pulse with width =1.7 s and repetition frequency f=1/T=300Hz is 600KHz approximately. The power spectrum of the cavity with Q=15000 is fallen into the main lobe. In order to avoid the unnecessary working frequency due to the side lobe of the power spectrum for the magnetron, I preset a threshold to suppress this possibility. The principle of the frequency stabilization is shown in Fig.2. The output signal of the detector D is input into the adaptive gain controller(its initial gain is identity) through the amplifier and the zero-order holder. The controlled signal is converted by the ADC into a 8-bit data. If the data is less than a preset threshold, then the chip 8039 sent a data FF to the data bus of a DAC, the output of the DAC which controls the stepping rate of the stepping motor to tune the magnetron rapidly. If the data is greater than the preset threshold, an extremum control is performed by the 8039, the stepping rate then is proportional to the difference between the oscillation frequency of the magnetron and the resonant frequency of the cavity. The extremum found by the 8039 is dependent on the output power of the magnetron, so the accuracy of the frequency stabilization is not a constant. Since an adaptive gain controller controlled by the 8039 is introduced, the extremum then equals a preset value approximately. The controller gain changes from the initial value step by step until the extremum arrives at the preset value. As a result the oscillation frequency of the magnetron is stabilized nearby the resonant frequency of the cavity.

1. The adaptive gain controller[1]

A digital linear gain controller is shown in Fig.3. It consists of the resistance networks, switching networks, followers and inverter. The followers referred to as impedance transformers separates the resistance networks apart from the switching networks which are controlled by the output data of the 8039. The signals controlled by the switches are added on the input of the inverter. The gain of the controller is

$$K=(1+R_1/R_2)r_0\left(\sum_{i=2}^{5}1/2^{i-1}r_{1j}+1/2r\right) \qquad (1)$$

where i is the order of the switches and r_{1j} is infinity or r as the correspondent switch is turned on or off accordingly.

2. Accuracy of frequency stabilization

The cavity can be equivalent to a parallel resonant circuit, the impedance of the circuit is:

$$Z(s)=(s+G)/c(s^2+Gs+w_c^2) \qquad (2)$$

where G=R/L is the full width at half maximum of the resonant curve of the cavity, L and C are the equivalent inductance and capacitance respectively, R is the series resistance of L, and $w_c=1/LC$ is the resonant frequency of the cavity. The input current of the cavity is

$$I(s)=\int_0^{\tau}e^{-st}\sin w_0 t\,dt=(w_0-(s\sin w_0\tau+w_0\cos w_0\tau)\cdot e^{-s\tau})/(s^2+w_0^2) \qquad (3)$$

where $w_0=2\pi f_0$ is the oscillation frequency of the magnetron For the sake of convenience on computation, it is reasonable that we set a limit to time t for the equivalent voltage on the cavity. Since the output pulse signal on the detector D is held, time t can be limited to less than or equal to . From (2) and (3), the voltage on the Z(s) is obtained as follows:

$$v_0(t)=\mathcal{L}^{-1}\left(\int_{\sigma-jw}^{\sigma+jw}((w_0-(s\sin w_0\tau+w_0\cos w_0\tau)(s+G)\cdot e^{-s\tau})e^{st}/2\pi jc(s^2+w_0^2)(s^2+Gs+w_c^2))\,ds\right)$$

$$\underset{t\leq\tau}{=}(Gw_c^2\sin w_0 t/w_0-(w_0^2-w_c^2-G^2)\cos w_0 t+((w_0^2-w_c^2+G^2)\cos w_c t-G(3w_c^2-w_0^2-G^2)\sin w_c t/2w_c)\cdot e^{-Gt/2})/c((w_0^2-w_c^2)^2+w_0^2G^2) \qquad (4)$$

If $w_0=w_c$, we have

$$v_{oc}(t)=((1-e^{-Gt/2})\sin w_c t+G(1+e^{-Gt/2})\cos w_c t/w_c)/cGw_c$$

the amplitude of $v_{oc}(t)$ is

$$v_{oca}(t)=(1-e^{-Gt/2})/cGw_c \tag{5}$$

If $w_0=w_c\pm G/10$, then

$$v_o(t)=25(1-e^{-Gt/2})(\sin w_c t\pm\cos w_c t/5)/26cGw_c$$

the amplitude of $v_o(t)$ is

$$v_{oa}(t)\approx 5(1-e^{-Gt/2})/\sqrt{26}cGw_c \tag{6}$$

It is obvious that the relative change is

$$(v_{oca}(t)-v_{oa}(t))/v_{oca}(t)=1/51 \tag{7}$$

If the maximal stepping rate of the stepping motor is 1300step/sec, for the frequency deviation $\pm G/10$($f_0=\pm 20$kHz), the stepping rate is 25step/sec(it is in correspondence with 170 kHz/sec). Then we can say the deviation of the oscillation frequency with respect to the resonant frequency is less than or equal to ± 20kHz as the oscillation frequency shifting due to the temperature change is not greater than 170kHz/sec. The frequency stability is $7\cdot 10^{-6}$ approximately for $f_0=2856$MHz. In order to guarantee the stability as mentioned above, a limiting device is introduced to limit the output of the digital-analog converter in 6.2V which is in correspondence with the maximal stepping rate 1300step/sec. The stepping rate 25step/sec iscorresponded to 200mV at the output of DAC.

3. The digital control process[2]

In the process of frequency stabilization and change, the 8039 is seen as a digital controller. An equivalent signal flow graph of the process is shown in Fig.4, where $D(z)$ is the pulse transfer function of the digital controller, $G(s)$ is the overall transfer function including those of the amplifier, zero-order holder, stepping motor servo and controlled plant, $V(s)$ is a ramp, i.e. the reference input which has changed the oscillation frequency of the magnetron, $N(s)$ is a ramp too which is the oscillation frequency shifting of the magnetron due to the ambient temperature.

In order to ensure the output $Y(s)$ to follow the input $V(s)$ rapidly and accurately, two relations should be satisfied as follows:

$$e(\infty)=\lim_{z\to 1}(1-z^{-1})(1-T(z))V(z)$$
$$=\lim_{z\to 1} k_v Tz^{-1}(1-T(z))/(1-z^{-1})=0 \tag{8}$$

and
$$1-T(z)=(1-z^{-1})^2H(z) \tag{9}$$

where $T(z)$ is the system pulse transfer function, and $H(z)$ is a polynomial for z^{-1} without $1-z^{-1}$. For the sake of simplicity, we set $H(z)=1$, so $T(z)=2z^{-1}-z^{-2}$ (10)

then the respondse process is steepest. If we desire $Y(z)$ has no swing around its mean value, $U(z)=E_1(z)/k_vV(z)=T_M(z)/G(z)$ should be a polynomial with finite terms, where the pulse transfer function $T_M(z)$ has to include the numerator of $G(z)$.

$$G(z)=(\oint G(s)ds/(1-z^{-1}e^{-sT}))/2\pi j$$
$$=(\oint K_1K_0(1-z^{-1})ds/(1-z^{-1}e^{-sT})s(s+R_L/L_M)\cdot(s^2+2qw_ns+w_n^2))/2\pi j=(Az^{-1}+Bz^{-2}+Cz^{-3})/J(z) \tag{11}$$

where R_L, L_M, q and w_n are the series resistance, winding inductance, damping factor and natural frequency of the stepping motor, and $A=K_1K_0(w_n^2\cdot L_m(1-e^{-R_LT/L_M})-R_L(2qw_n-R_L/L_M)+R_L((q^2-1)^{\frac{1}{2}}(2qw_n-R_L/L_M)ch(q^2-1)^{\frac{1}{2}}w_nT-(R_Lq/L_M-2q^2w_n+w_n)sh(q^2-1)^{\frac{1}{2}}\cdot w_nT)e^{-qw_nT})$, $B=K_1K_0((R_L^2/L_M-2w_nqT)(q^2-1)^{\frac{1}{2}}(e^{-2qw_nT}-e^{-R_LT/L_M})+2L_M(q^2-1)^{\frac{1}{2}}((R_L^2/L_M^2-2qw_nR_L/L_M+w_n^2)\cdot e^{-R_LT/L_M}-w_n^2)e^{-qw_nT}+R_L(1+e^{-R_LT/L_M})(((q^2-1)^{\frac{1}{2}}(2qw_n-R_L/L_M)ch(q^2-1)^{\frac{1}{2}}w_nT+(qR_L/L_M-2q^2w_n+w_n^2)\cdot sh(q^2-1)^{\frac{1}{2}}w_nT)e^{-qw_nT})$, $C=-K_1K_0(L_M(q^2-1)^{\frac{1}{2}}((R_L^2/L_M^2-2qw_nR_L/L_M+w_n^2)e^{-R_LT/L_M}-w_n^2)e^{-2qw_nT}+R_L((q^2-1)^{\frac{1}{2}}(2w_nq-R_L/L_M)ch(q^2-1)^{\frac{1}{2}}w_nT+(R_Lq/L_M-2q^2w_n+w_n^2)\cdot sh(q^2-1)w_nT)e^{-(R_LT/L_M+qw_n)})$, $J(z)=R_Lw_n^2(q^2-1)^{\frac{1}{2}}(R_L^2/L_M^2-2qw_nR_L/L_M+w_n^2)(1-z^{-1}e^{-R_LT/L_M})(1-z^{-1}e^{-(q+(q^2-1)^{\frac{1}{2}})w_nT})(1-z^{-1}e^{-(q-(q^2-1)^{\frac{1}{2}})w_nT})=M(1-z^{-1}\cdot e^{-R_LT/L_M})(1-z^{-1}e^{-(q+(q^2-1)^{\frac{1}{2}})w_nT})(1-z^{-1}e^{-(q-(q^2-1)^{\frac{1}{2}}w_nT})$.

Finally, we can obtain the satisfied equation for the pulse transfer function $T_M(z)$ as follows:

$$T_M(z)=\sum_{m=1}^{2}p_m z^{-m}(Az^{-1}+Bz^{-2}+Cz^{-3}) \tag{12}$$

and $T_M(z)$ should satisfy the relation (13) too

$$:\quad 1-T_M(z)=(1-z^{-1})^2H(z) \tag{13}$$

Parameters p_1 and p_2 are found by solving Eqs. (14) and (15):

$$T_M(1)=(p_1+p_2)(A+B+C)=1 \tag{14}$$

$$dT_M(z)/dz\big|_{z=1}=-p_1(2A+3B+4C)-p_2(3A+4B+5C) \tag{15}$$

then we obtain $p_1=-(3A+4B+5C)/(A+B+C)^2$ and $p_2=-(2A+3B+4C)/(A+B+C)^2$. From Fig.4, we have the pulse transfer function $D(z)$ of the digital controller as follows:

$$D(z)=U\sum_{i=1}^{5}m_iz^{-i}/(1+\sum_{j=1}^{5}n_jz^{-j}) \tag{16}$$

where $U=M/(A+B+C)^2=M/P$, $n_1=0$, $n_2=-A(3A+4B+5C)/P$, $n_3=-((4B+5C)B-(2A+4C)A)/P$, $n_4=-((3A+5C)C-(2A+3B)B)/P$, $n_5=(2A+3B+4C)C/P$, $m_1=3A+4B+5C$, $m_2=-(3A+4B+5C)(e^{-R_LT/L_M}+2e^{-qw_nT}ch(q^2-1)^{\frac{1}{2}}w_nT)-(2A+3B+4C)$, $m_3=(3A+4B+5C)(e^{-2qw_nT}+2e^{-(R_LT/L_M+qw_nT)}ch(q^2-1)^{\frac{1}{2}}w_nT)+(2A+3B+4C)(e^{-R_LT/L_M}+2e^{-qw_nT}ch(q^2-1)w_nT)$ $m_4=-(2A+3B+4C)(e^{-2qw_nT}+2e^{-(R_LT/L_M+qw_NT)}ch(q^2-1)^{\frac{1}{2}}w_nT)-(3A+4B+5C)e^{-(R_LT/L_M+2qw_nT)}$, $m_5=(2A+3B+4C)e^{-(R_LT/L_M+2qw_nT)}$. Corresponding to Eqs.(16), the relation between input and output of the 8039 is obtained as:

$$E_2(k)=-n_2E_2(k-2)-n_3E_2(k-3)-n_4E_2(k-4)-n_5E_2(k-5)+U(m_1E_1(k-1)+m_2E_1(k-2)+m_3E_1(k-3)+m_4E_1(k-4)+m_5E_1(k-5)) \tag{17}$$

If $V(z)=0$ $N(z)\neq 0$, we have the steady-state output as follows:

$$y(\infty)=\lim_{z\to 1}(1-z^{-1})k_n N(z)/(1+D(z)G(z))$$
$$=\lim_{z\to 1} k_n Tz^{-1}(1-T_M(z))/(1-z^{-1}) \qquad (18)$$

from Eq.(13),we know that $1-T_M(z)$ has a factor $(1-z^{-1})^2$,whence $y(\infty)=0$.

III. Adaptive Phase Following

In order to obtain the electron beams with different energy,the output power and oscillation frequency of the magnetron must be changed , and the shifter φ_1 and φ_2 must be adjusted automatically to maximize the superposition envelope on the entrance of the acceleration tube and minimize the output on the detector D_2 of the load.The output on the detector D_1 is converted to DC voltage by the zero-order holder and is then converted to current through the V/I converter to charge a capacitor C.The voltage on C then represents the area of the superposition envelope.On the other hand,the output on D_2 is amplified by a Log amplifier. These signals are converted by the ADC to two 8-bit data which are maximized and minimized by the chip 8039 respectively.The principle mentioned above is shown in Fig.5.

Field intensity b_4 and b_2 at the load and the entrance of the acceleration tube respectively are written as follows[3]:

$$b_4=a_1\cos(\varphi_2/2)/(1-\theta\sin(\varphi_2/2)\cos(\varphi_1+\varphi)) \qquad (19)$$

$$b_2=a_1(\sin(\varphi_2/2)-\cos(\varphi_1+\varphi))/(1-\theta\sin(\varphi_1+\varphi)\cos(\varphi_1+\varphi)) \qquad (20)$$

where θ is the loop transfer coefficient which is independent of φ_1 and φ_2 approximately but dependent on the beam intensity,a_1 is the input field intensity,φ is the phase shifting in the microwave loop for the oscillation frequency f_0 of the magnetron.The relationship between φ and f_0 is:

$$\Delta\varphi/(\varphi_1+\varphi)=(1-c_0/V_g)\Delta f_0/f_0 \qquad (21)$$

where c_0 is the light velocity and V_g is the group velocity.From Eqs.(19) and (20) we have a ratio as follows:

$$b_4/b_2=\cos(\varphi_2/2)/(\sin(\varphi_2/2)-\theta\cos(\varphi_1+\varphi)) \qquad (22)$$

As a result of the adaptive phase following, the maximal b_4/b_2 is performed.

IV. Discussion

The adaptive phase following is an effective method to maximize the efficiency of the LINAC. The efficiency must be guaranteed by the optimal φ_1 and φ_2.For different oscillation frequency of the magnetron,the $\varphi_1-\varphi_2$ corresponds to an extremum rather than a maximum of b_4/b_2. So it is necessary to fix a pair of initial values $\varphi_{10}-\varphi_{20}$ from which φ_1 and φ_2 are adjusted each time,and maximum of b_4/b_2 may be found.

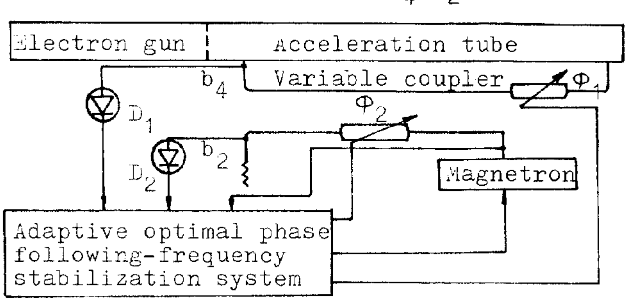

Fig. 1

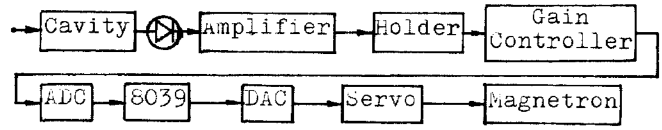

Fig. 2

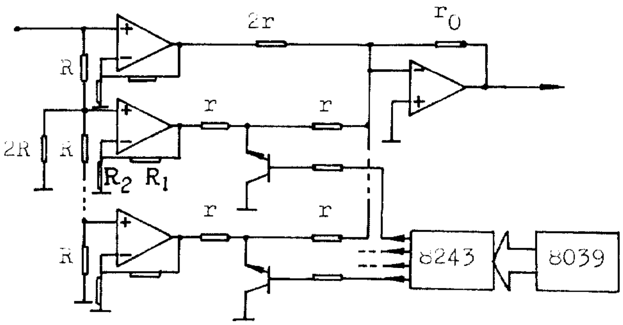

Fig. 3

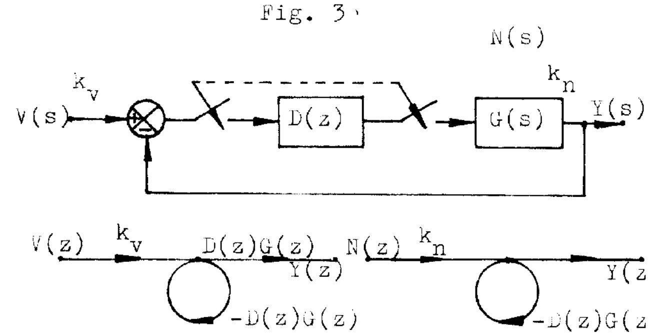

Fig. 4

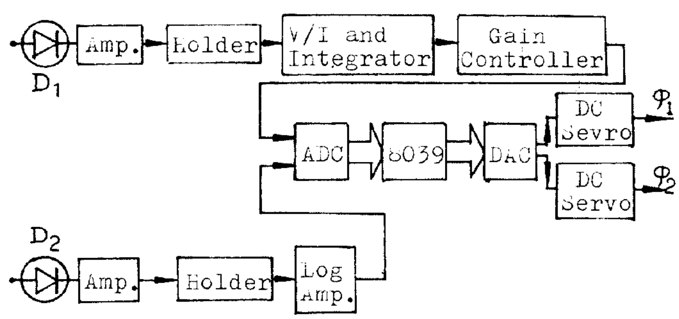

Fig. 5

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