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Analysis and Design of PLL Motor Speed Control System

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Abstract

Phase-locked technology in motor speed control system has a wide range of applications. Especially for high accuracy in the motor steady speed operation situation, more and more use of phase-locked servo control system. This paper describes the block diagram and mathematical model of phase-locked control system, Shows the circuit parameter calculation method. This and combined with design example analysis of phase-locked control system, Indicated through the theory and practice, using PLL can obtain good speed control precision.

Keywords: *Phase-locked technology, motor speed, PFD*

1. Introduction

With the development of digital integrated circuit to reduce cost and phase-locked technology, Phase-locked technology is gradually widely used in motor speed control. Especially in the multi-motor keeps dragging system synchronous operation of, Using the phase-locked loop control, not only make the system has the advantages of simple structure, but also can obtain the control precision is very high. [1, 3]

2. The System Diagram and Mathematical Control Model

Motor speed control system of phase-locked control principle block diagram is shown in Figure 1. The input signal to a system for a certain frequency of the square wave signal. The corresponding frequency and motor given speed, system output is the actual motor speed. Feedback component is the role of the speed signal into frequency and speed is proportional to the square wave signal. There can be multiple ways, generally uses the photoelectric device. If the motor speed is n, the motor speed to a week, pulse photoelectric device outputs the *N* offset, the feedback component output square wave angular frequency: $\omega = 2\pi nN/60$

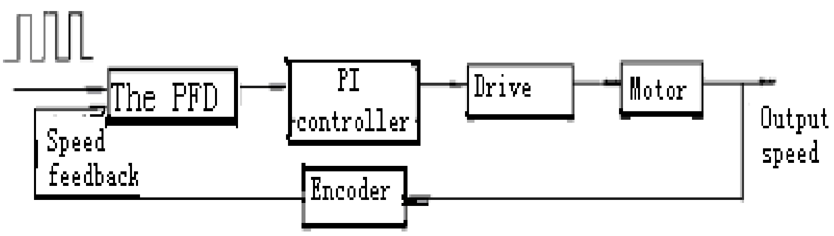

Figure 1. Phase-locked control motor speed control system block diagram

So the system the signal given by the angular frequency ω and the desired speed is:

$$\omega = 2\pi nN/60 \tag{1}$$

Comparison of ωr, ωf to PFD in frequency, phase, frequency difference and phase difference has the following relationship:

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$$\Delta\varphi(t) = \int_{t_0}^{t} \Delta\omega(t)\,\mathrm{d}t = \int_{t_0}^{t} \omega(t) - \omega(t)\,]\,\mathrm{d}t \quad (2)$$

Type (2) for the Laplace transform, too

$$\Delta\omega(S) = \frac{1}{S}[\,\omega(S) - \omega(S)\,] \quad (3)$$

Set the integration time is from ωr, ωf first began with equal, and the initial phase difference $\varphi < 2\pi$. In the time after t0 , when ωr equal to ωf , $|\varphi(t)| < 2\pi$.

PFD generally use the CD4046. Analysis of the internal circuit, the equivalent circuit can be dotted line in Figure 2 on the left side of the said its function. [2]

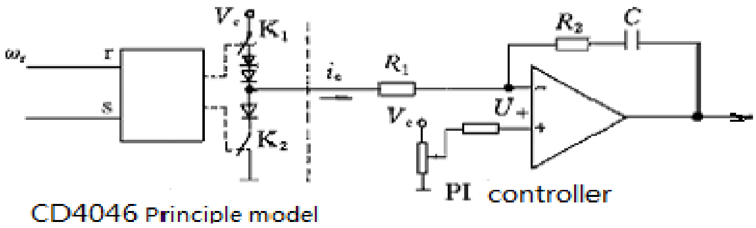

Figure 2. The principle of CD4060 model and the PI control circuit

(1) when ωf < ωr, K_1 conduction, K_2 showed high impedance.

(2) when the ωf > ωr , K_2 conduction, K_1 showed high impedance.

(3) when the $\omega_f = \omega_r$, if $\varphi_f = \varphi_r$ is K_1, K_2 showed high impedance. If $\varphi_f < \varphi_r$ K_2 showed high impedance, In a cycle of $T\ T\ /\ \Delta\varphi\ //2\pi$ time, K_1 conduction, the rest of the time showed a high impedance. If $\varphi_f > \varphi_r$ K_1 showed high impedance, in a cycle of $T\ T\ /\ \Delta\varphi\ //2\pi$ time, K_2 conduction, the rest of the time showed high resistance. In order to said change detection, Using the circuit of the broken line to the right of Figure 2.

Current flowing through the R on the I average value is proportional to the$\Delta\varphi$, As shown in Figure 3a, This is obviously the saturated nonlinear relationship. That is, i_e is a pulse width and $\Delta\varphi$ is proportional to the square wave signal, As shown in Figure 3b, Its AC component of the impact on the performance of the system will be, and should try to filter out . In fact, due to the inertia of the electromechanical system itself and of the PI controller used in the low-pass characteristic. As long as the suitably selected N can wherein the AC component is substantially attenuated.

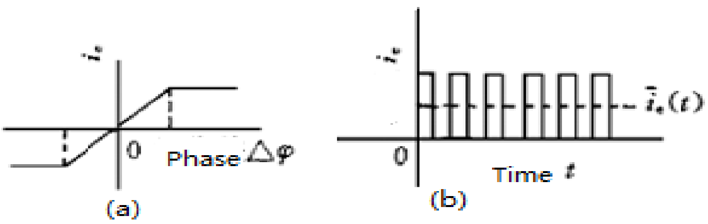

Figure 3. Waveforms

In order to make the i_e pulse height in positive and negative, are equal.Therefore appropriate to adjust the U_+ value , So that $V_e - 1.4 - U_+ = U_+ - 0.7$, That $U_+ = (V_e - 0.7)/2$, Usually $V_e = 5$V , The $U_+ \approx 2.15$V, so the slope of the linear region,

$$K_e = M/2\pi = 1.45/(2\pi R_1) \quad (4)$$

In fact, the frequency characteristic of the CD4046 is shown in Figure 3a,because the frequency difference type (3) of the internal connection. According to the circuit of PI controller

$$\frac{U_c(S)}{I_e(S)} = -(R_2 + \frac{1}{CS}) = -R_2(1 + \frac{1}{R_2CS}) \quad (5)$$

order $R_2C = T_i$ then:

$$\frac{U_c(S)}{I_e(S)} = -R_2(1 + \frac{1}{T_iS}) \quad (6)$$

It should be noted that the PI controller is not connected to the inverter, the speed should a given square wave signal is connected to the MC4046's s end. The feedback signal is connected to the r end, otherwise it will form a positive feedback. Amplification driver for the K_d, the transfer function for DC motor: $D(S) = \frac{K_m}{(1 + T_mS)(1 + T_eS)}$ Wherein T_m and T_e, respectively, the mechanical time constant of the motor and the electrical time constant, Ignore T_e, [5]

$$D(S) = \frac{K_m}{1 + T_mS} \quad (7)$$

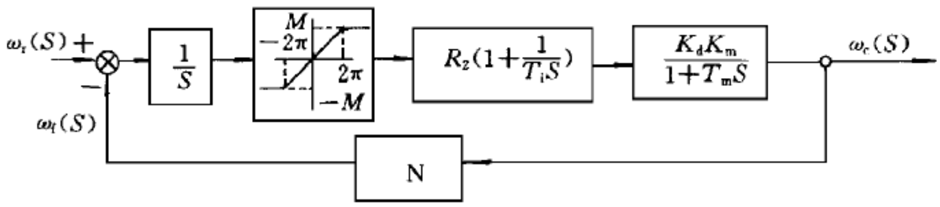

Figure 4. A system configuration diagram

Described by the transfer function of the system structure shown in Figure 4. Linear range, the open-loop transfer function:

$$GH(S) = \frac{K(1 + T_iS)}{S^2(1 + T_mS)} \quad (8)$$

$$K = \frac{NK_eR_2K_dK_m}{T_i} \quad (9)$$

This shows that this is a typical third-order system.

3. Determine the Best Open-Loop Model Parameters of a Typical Third-Order System

Typical third order based on the frequency characteristics of, and the best open-loop model parameters are determined as follows:See Figure 5. system configuration diagram with logarithmic frequency characteristic, a typical third-order system structure shown in Figure 5a. is shown, corresponding to the ring-opening logarithmic frequency characteristic shown in Figure 5b. as shown. [4]

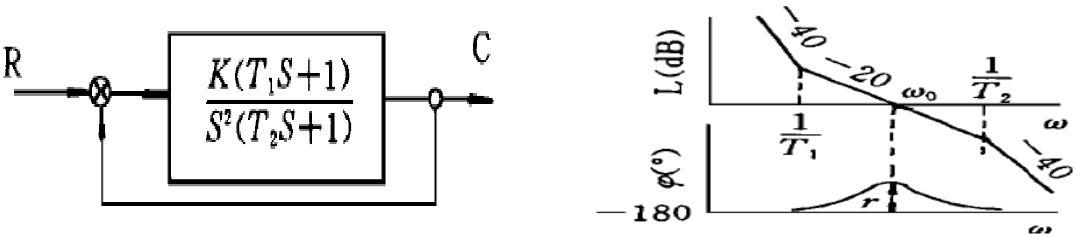

Figure 5. System structure diagram with logarithmic frequency characteristics

The characteristic is determined by three parameters, That ω_1=1 / T_1 , ω_0 and ω_2=1 / T_2 Usually make: $h=\omega_2/\omega_1=T_1/T_2$ (10) h is called the IF width, the band plays a decisive role in the dynamic performance, h is an important parameter of the typical third-order system. It can be proved to make the system stable, must be satisfied: $h>1$ (11) ω_0 is the system of open-loop frequency cut-off angle is easy to prove that when ω_0 is ω_1, ω_2 geometric midpoint when to get the maximum amount of phase margin,

that is,

$$\omega_0 = \sqrt{\omega_1\omega_2} = \sqrt{1/T_1T_2} = \frac{1}{\sqrt{h}\,T_1} \tag{12}$$

when

$$\gamma_{max} = \operatorname{arctg}\frac{h-1}{2\sqrt{2}} \tag{13}$$

When ω_0, ω_1, ω_2 are determined, the open-loop amplification K is also determined, and can be obtained from Figure 6.:

$$K = \omega_0\,\omega_1 \tag{14}$$

Substituting (11), substituting (12) into (14), we have: $K = \frac{1}{h\sqrt{h}\,T_2^2}$ In this case, a typical third-order system of the open-loop transfer function can be represented by the T_2 and h:

$$GH(S) = \frac{1 + hT_2S}{h\sqrt{h}\,T_2^2S^2(1 + T_2S)} \tag{15}$$

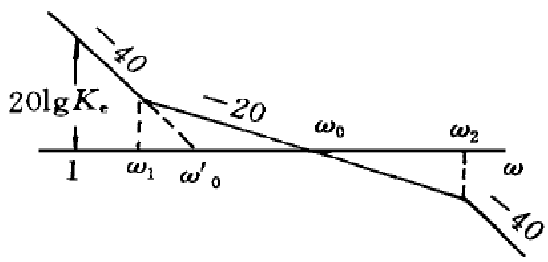

Figure 6. The frequency and the parameters of a typical third-order system

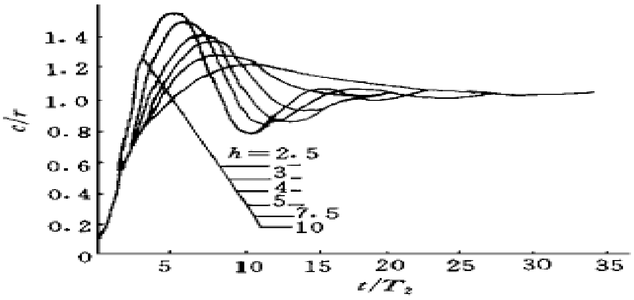

Figure 7. Step response of a typical third-order system

Figure 7 [2, 7] is the use of computer to get different h when the closed-loop step response curve, IF width h respectively taken as 2.5, 3, 4, 5, 7.5 and the 10.The schedule given different performance indexes of the H value, from which we can see that, when h = 4~7. 5 indicators is better, generally take h = 5.

Schedule The relationship of the performance index of a typical third-order system with h

Project	$h = T_1/T_2$	2. 5	3	4	5	7. 5	10
Step response	$M_r(\%)$	58	53	43	37	28	23
	t_s/T_2	20	17	15	14	16	20
Phase margin	$\gamma(°)$	25. 3	30	36. 9	41. 8	49. 9	54

4. Calculation of Parameters in the Control System of Motor Phase-Locked

4.1. Determine the Integral Time and Open Loop Gain:

Take $h=5$

Then $h=T_1/T_m$, $T_1=5T_m$ (16)

$$K = \frac{1}{h\sqrt{h}\,T_m^2} \quad (17)$$

4.2. To Determine the Parameter of Each Component

1. The choice of N: The i_e contains the AC component of the fundamental frequency ω_r, seen by the open loop frequency characteristics of the system, the number $\omega_r > \omega_2$ in these AC component can greatly attenuated, Since $\omega_r = N\omega_c$, ω_c is the angular frequency of the desired output of the system. If the design of speed control system, the minimum steady speed run speed ω_{min} ,

Then the $N\omega_{min} > \omega_2$ $N > \omega_2/\omega_{min}$ (18)

general $N = 1.5\ \omega_2/\omega_{min}$

2. The determination of the R_1, R_2, C: Integrated type (4), (5), (9) have:

$$\begin{cases} R_2C = T_i \\ K = \dfrac{1.45NR_2K_dK_m}{2\pi R_1T_i} \end{cases} \quad (19)$$

Type N, T_i, have been identified, K_d, K_m is known or can be measured through the experiment, The equations (19) have three unknowns R_1, R_2, C, Give one of them to determine the appropriate value according to the specific circumstances and can solve for the remaining two component values.

5. Examples of Application

Design a motor phase-locked speed control system, the requirements of the load constant speed rotation, Motor speed error is less than 1/1000, the experimental validation even with high-precision regulated power supply powering the motor to reach the above requirements, using PLL design of motor speed error is only 1/3000.The principle of control circuit as shown in Figure 8. [6, 8]

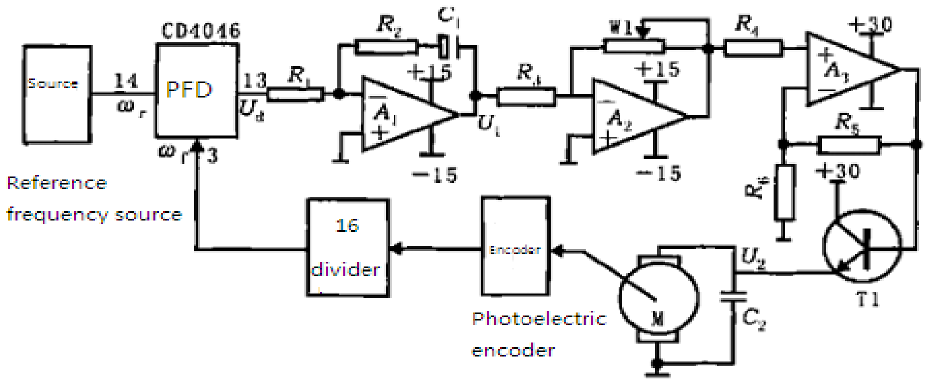

Figure 8. Principles of control circuit diagram

The reference frequency after 10^4 divide by $2MH_Z$ crystal oscillator sent to the CD4046 14 feet. Motors rotate the encoder 64 pulses enlarged plastic divider (divide by 16) sent to the CD4046 pin 3 as the feedback signal. CD4046 CMOS PLL chip structure.There are two internal phase comparator, ω_f ω_r to PFD in frequency, phase comparison by the pin 13 output error voltage U_d,The loop filter is the active proportional integral filter to ensure the stable operation of the phase-locked loop op amp. When the loop is locked r advance f 1/4 cycle K_1 (s) = 20.

When considering the role of the loop filter, the entire control loop is a third-order system. In order to ensure the stable operation of the system, the loop filter must have a leading phase correction function,Here the choice the active proportional integral filter, Bode plots analysis taken: $T_1 = R_1C_1 = 56k\times200 = 11.2$s, $T_2 = R_2C_1 = 5k\times200 = 1$s.While f_r changes in the range of 115~225H_Z, the system stable work. The K_1 value directly affect the size of φ, φ phase lag difference φ and motor stable rotating speed range. K_1 becomes larger, the φ smaller, system transition time is short, and the overshoot. While the K_1 value is too large, so that the lower limit of f_r value change tracking system; The smaller value of K_1, φ becomes large, the system transition time is long, but the K_1 value is too small, the upper bound of the system f_r to track the value of smaller. So that the system timing belt narrowing, Debugging with an oscilloscope to observe the CD4046 first pin voltage waveform, Adjust the value of K_1 f_r lags behind the f_r the phase control in less than 45° is appropriate, system stability, All levels of output voltage waveform is shown in Figure 9. [9]

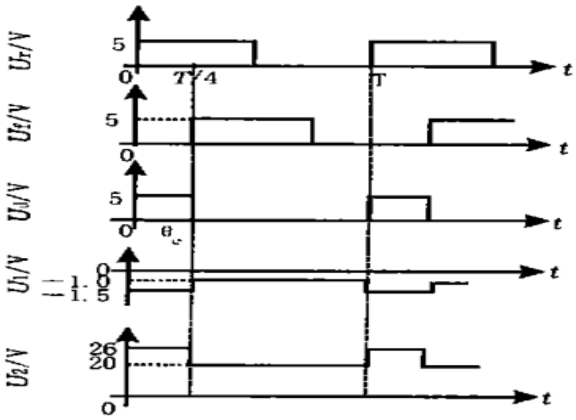

Figure 9. Levels of waveform

Motor with a brush motor,Brush sparks easy to interfere with the signal output of the encoder assembly. Therefore, filtering and other measures should be taken to eliminate, clean *fr* signal. [10]

Otherwise, the loop not work stable.If the motor excitation voltage of U_2 wave has a high frequency interference. The U_2 side parallel to appropriate capacitance eliminate. If the fixed frequency divider into a programmable frequency divider. Adjust the speed of the motor can be achieved, has good prospect of application.

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