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MILITARY TECHNICAL COLLEGE

CAIRO - EGYPT

STABILITY ANALYSIS OF PASSIVE CONTINUOUS-WAVE DOPPLER SEEKERS

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ABSTRACT

Passive monopulse CW-doppler seeker plays the main role in the guidance and control of semiactive radar homing guided missiles. The most common seeker configuration involves frequency-locked loop (FLL) connected with a phase-locked loop (PLL) through a common phase detector and a local voltage controlled oscillator (LVCO). In this paper, analysis of the operation of such seeker system is presented. The control equations are derived wherefrom the system transfer function is obtained. Stability analysis is also carried out. It is shown that the presence of low-pass filter at the input of the LVCO is essential for system stability. Moreover, the filter time constants should be carefully adjusted to ensure stable operation.

INTRODUCTION

In semiactive guided missiles, the guidance commands are generated on the missile board. A monopulse passive tracking radar placed at the missile nose is designed to accurately track the illuminated target. This radar is known as seeker. The seeker circuits generate the control signals that steer the missile in space. The seeker employs two antennas to perform its function; the front target tracking antenna and the rear reference antenna.

The target front antenna is designed to detect the reflected echo from the target being engaged. The rear antenna; however, is used to detect the reference signal from the parent illuminator. Fig. 1 illustrates the role of each antenna in the guidance process. Recent seeker systems involve a PLL to keep the LVCO locked on the parent illuminator signal. In the mean time, a FLL is often used to track the doppler frequency changes in the target echo return. Both loops are involved instanteneously in the adjustment of the LVCO frequency. Fig. 2 shows the block diagram of the system being considered.

The performance of the FLL and the PLL had been extensively analyzed long time ago [1]-[4]. The control equations and the stability analysis of both types of loops had been established as well. In addition, the behavior of the FLL and the PLL in the presence of two input signals have been a matter of discussion in the last two decades [5]-[7]. The jump phenomenon that occurs in the presence of two input signals had been investigated by many researchers. The importance of the subject is attributed to the role played by the FLL and the PLL in adjusting the operation of the missile seeker and hence; in controlling the guided missile during flight.

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Despite the large effort dedicated in analyzing the performance of the FLL and the PLL individually, very little effort has been done in the investigation of the combined loops as shown in Fig. 2. The purpose of this paper is to investigate the operation and performance of the combined loops shown in Fig. 2. The system elements are assumed to be linear, i.e; the frequency of the different signals across the loops are near their correct values. The system response to the frequency variations of the front and rear received signals is investigated. Routh-Hurwitez stability analysis is applied to the system transfer function. It is shown that a low-pass filter at the input of the LVCO is essential for the system stability; a requirement which is not necessary for the stability of the conventional FLL or PLL. A commonly used first order low-pass filter is employed. The stability conditions derived impose strict requirements on the filter time constants in terms of the FLL time constant and the PLL gain.

SYSTEM OPERATION

The system of concern is shown in Fig. 1. The frequency of the signal received by the front antenna is

$$f_f = f_o + 2f_t + f_m, \tag{1}$$

where f_o is the illuminator frequency, f_t and f_m are the target and missile doppler frequencies; respectively, and are given by

$$f_t = \frac{v_t}{\lambda_o}$$

and

$$f_m = \frac{v_m}{\lambda_o}, \tag{2}$$

where λ_o is the wavelength of the illuminator signal, v_t and v_m are the target and missile radial speeds; respectively. The rear antenna; however, receives the illuminator signal directly. Thus, the frequency of the signal received by the rear antenna will be

$$f_r = f_o - f_m. \tag{3}$$

As shown in Fig. 2, the signal received by the rear antenna is mixed with the LVCO output. The phase of the resultant signal (rear IF) is compared with the phase of another signal generated by the front FLL. The phase detector output is filtered and then used to control the frequency of the LVCO. In the mean time, the LVCO output is mixed with the front received signal in the mixer M1. The output of M1 (first IF) is then amplified and filtered. Practically, the frequency band of the first IF is not suitable for further processing. Thus, the first IF is mixed in M2 with a locally generated sinusoidal signal. The frequency of M2 output (second IF) is in the low frequency band where frequency discrimination can be performed efficiently. After discrimination, integration, and amplification, the output signal is used to control the frequency of a voltage controlled oscillator (VCO). The output of the VCO is then mixed with another locally generated sinusoidal signal in M3. The phase of M3 output is compared with the rear IF phase as mentioned before.

FREQUECY-LOCK-LOOP OPERATION

The frequency of the signal at the output of the mixer M1 is

$$f_1 = f_{lo} - f_f, \tag{4}$$

where f_{lo} is the frequency of the LVCO output. Usually the frequency f_1 is in the megahertz band which is not suitable for further processing. Thus, further reduction is made in the mixer M2 by mixing the output of the band-pass filter (BPF) with a sinusoidal signal of frequency f_{o1}. The frequency of the mixer M2 output is

$$f_2 = f_1 - f_{o1}. \tag{5}$$

The output of the mixer M2 is fed to a frequency discriminator with frequency center at f_{dis} and gain k_d. Thus, its output voltage is

$$V_d = K_d(f_{lo} - f_f - f_{o1} - f_{dis}). \tag{6}$$

The central frequency of the first IF bandpass filter is denoted by f_{xtl} and is related to f_{o1} and f_{dis} by

$$f_{xtl} = f_{o1} + f_{dis}. \tag{7}$$

The frequency discriminator output is integrated, amplified, and then used to drive a VCO with gain K_v. The VCO output frequency will thus be

$$f_3 = \frac{V_d K_a K_v}{T' s} + f_{o3}, \tag{8}$$

where T' and K_a are the integrator time constant and the amplifier gain; respectively. f_{o3} is the base frequency of the VCO (the VCO output frequency for zero input voltage). The VCO output frequency is stepped up in the mixer M3 as

$$f_4 = \frac{V_d K_a K_v}{T' s} + f_{o3} + f_{o2}, \tag{9}$$

where f_{o2} is the frequency of a locally generated sinusoidal signal. It is noted that the following relation holds

$$f_{xtl} = f_{o2} + f_{o3}. \tag{10}$$

Thus, f_4 can be rewritten as

$$f_4 = f_{xtl} + \frac{1}{Ts}(f_{lo} - f_f - f_{xtl}), \tag{11}$$

where T defines the time constant of the FLL and is given by

$$T = \frac{T'}{K_a K_v K_d}.$$

PHASE-LOCK-LOOP OPERATION

After mixing the received signal from the rear antenna in M4 with the LVCO output and filtering out the higher frequency components, the frequency f_5 of the phase detector input will be

$$f_5 = f_{lo} - f_r = f_{lo} - f_o + f_m. \tag{12}$$

The phase difference between the phase detector inputs is detected in the phase detector and can be written as

$$V_{pd} = K_{pd}(\phi_5 - \phi_4) = \frac{2\pi K_{pd}}{s}(f_5 - f_4). \tag{13}$$

In view of equations 11, 12, and 13, the LVCO frequency can be written as

$$f_{lo} = f_o + f_{xtl} + K_{lo} F(s) V_{pd}, \tag{14}$$

where $f_o + f_{xtl}$ is the base frequency of the LVCO and $F(s)$ is the low-pass filter (LPF) transfer function.

SYSTEM TRANSFER FUNCTION

Eq. 14 can be rearranged as

$$f'_{lo} = \frac{1}{sT_{pll}} F(s)[(f'_{lo} + f_o - f_r) - \frac{1}{Ts}(f'_{lo} + f_o - f_f)], \tag{15}$$

where T_{pll} and f'_{lo} are given by

$$T_{pll} = \frac{1}{K} = \frac{1}{2\pi K_{pd} K_{lo}}$$

and

$$f'_{lo} = f_{lo} - (f_o + f_{xtl}).$$

It is noted that T_{pll} is the inverse of the open PLL gain K. Rearrangement of Eq. 15 leads to

$$f'_{lo} = G(s)[sT(f_o - f_r) + (f_f - f_o)], \tag{16}$$

where $G(s)$ is given by

$$G(s) = \frac{F(s)}{s^2TT_{pll} - sTF(s) + F(s)}. \tag{17}$$

Equation 16 represents the control equation of the FLL and the PLL connected as shown in Fig. 2. It is obvious that the filter is necessary for the system stability. In the absence of this filter ($F(s) = 1$), the two loops will not be able to adjust the LVCO frequency to follow the frequency variations in $(f_o - f_r)$ and $(f_f - f_o)$.

SYSTEM STABILITY

The system under consideration is a two-input, single-output system. The most frequently used LPF is given by [1]

$$F(s) = \frac{1 + \tau_2 s}{1 + \tau_1 s}, \tag{18}$$

with τ_2 being smaller than τ_1. By employing this filter, the transfer function $G(s)$ can be rewritten as

$$G(s) = \frac{1 + \tau_2 s}{TT_{pll}\tau_1 s^3 + T(T_{pll} - \tau_2)s^2 + (\tau_2 - T)s + 1}. \tag{19}$$

Application of Routh-Hurwitz stability test leads to the following stability conditions

$$\frac{1}{K} > \tau_2 > T$$

and

$$\tau_1 < (1 - K\tau_2)(\tau_2 - T). \tag{20}$$

It is known that the PLL working alone is unconditionally stable. However, for the present system, the two conditions given by Eq. 20 are necessary for stable operation. Inspection of Eq. 20 shows that the PLL gain should not exceed a limit value given by $\frac{1}{\tau_2}$. Moreover, the time constant of the FLL should not exceed the filter time constant τ_2. The fact that the natural frequency of the PLL is inversely proportional to τ_1 [1], which should not exceed a limit value given by Eq. 20, indicates that the tracking speed of the PLL should not exceed a limit value as well.

In the steady state; however, the LVCO frequency is merely determined by the second term of Eq. 16 as:

$$f_{lo_{ss}} = f_{xtl} + 2f_t - f_m. \tag{21}$$

It is seen from Eq. 21 that the mixer M1 steady state output frequency is equal f_{xtl} but due to the dynamic nature of the frequencies of the input signals, the frequency of M1 output can not be held at f_{xtl}. However, any deviation form f_{xtl} is detected by the frequency discriminator which adjusts the VCO frequency so that f_4 matches f_5. Any mismatch between f_4 and f_5 is detected by the phase detector which tune the LVCO so that balance is achieved.

CONCLUSIONS AND FUTURE RESEARCH

The operation of the FLL-PLL combination is investigated. The system transfer function is derived. Routh-Hurwitez stability analysis is carried out. It is found that a low-pass-filter has to be inserted at the input of the LVCO for system stability. In addition, the filter time constants have to be carefully adjusted to obtain stable operation. The relative stability margins and the system response to more than one input signal from the front antenna are points of increasing interest and need more investigations.

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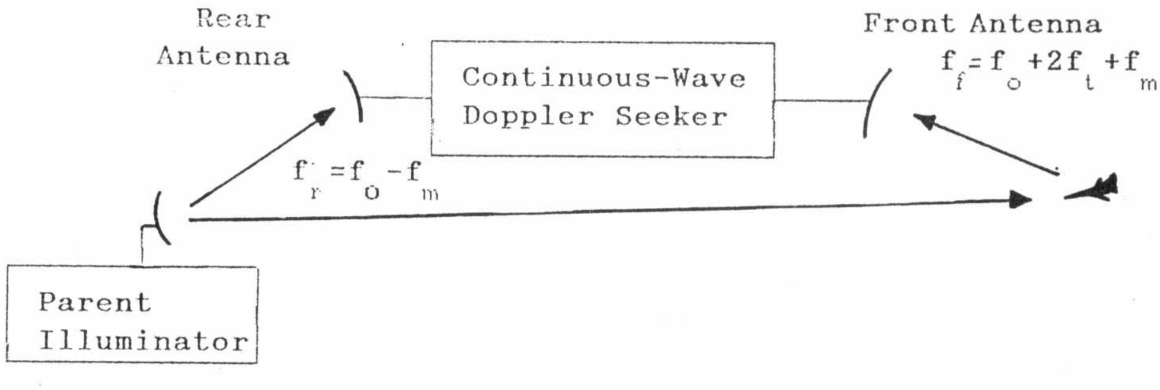

Figure 1: Operation Principle of Continuous-Wave Doppler Seeker

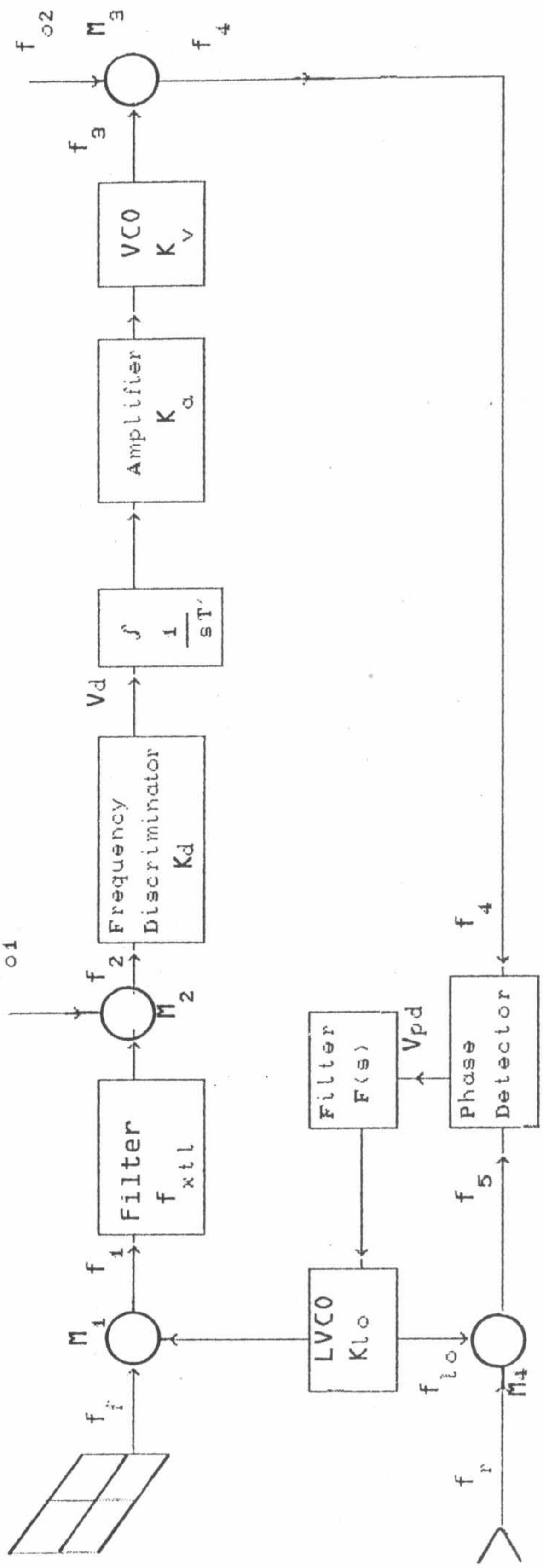

Figure 2: Functional Block Diagram of Continuous Wave Doppler Seeker.