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Estimation of Break-Lock Conditions for Effective Jamming in Missile Borne Monopulse Receivers

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Abstract*—Missile borne Monopulse receivers invariably track the target in three domains, namely frequency, range and angle. For effective jamming of these receivers, it is essential that breaking of the track should be achieved in at least two domains. In frequency domain, so long as the monopulse receiver locks onto the radar echo frequency, the radar tracks the target. When there is a disturbance introduced either in form of deliberate noise or repeat jamming, the receiver loses the lock to the target and is misguided. In this paper, the monopulse receiver with third order PLL (Phase Locked Loop) is designed and the performance of the receiver is analyzed when sinusoidal CW (Continuous Wave) radar echo signal along with sinusoidal jammer signal is applied to the receiver. In addition, when FM (Frequency Modulation) CW jammer signal along with the radar echo signal is injected into the receiver, the value of modulation index for which break-lock occurs for different values of modulating signal voltage is estimated and an empirical relation is also obtained. The mathematical model for FM CW radar receiver is developed and implemented using Visual System Simulator. The model includes the generation of radar echo and jammer signal at the receiver input to achieve effective jamming. The effectiveness of noise jamming is also studied by injecting phase noise and White Gaussian noise signal into the receiver and break-lock condition of the receiver is also reported. It is shown that break-lock in the receiver occurs when the FM modulation index (K_f) exceeds $4x10^6$ without exception with the carrier signal operating at40 MHz and when the modulating signal amplitude is 5 mV.

***Keywords*—Monopulse, Radar echo, Repeat jamming.**

I. INTRODUCTION

Most of the modern missiles are radar guided missiles which are directed against high value targets such as ships, aircrafts, land based vehicles and high value assets. These modern missiles invariably employ monopulse receivers with PLL (Phase Locked Loop) frequency tracking subsystems [1]. The ability of the missile to keep the target on track depends upon its ability to track its echo in the frequency and angle domains. Jamming of such receivers is extremely difficult as the frequency lock and the angle servo lock requires least deviations in the repeater waveform of the jammer and its frequency. In our earlier paper, an analysis on repeat jamming and noise jamming of the monopulse receiver with second order PLL has been reported [2]. Spot frequency repeat jamming and Noise jamming are analyzed in this paper for effective deception of the monopulse receiver with third order PLL when sinusoidal CW (Continuous Wave) jammer signal and FM (Frequency Modulated) CW jammer signal is applied to the receiver in two different cases[3].

II. RADAR RECEIVER WITH ORDER PLL

The horn outputs are summed in a hybrid and the output is amplified, down converted to IF and passed through an AGC amplifier and then given to the PLL as shown in Fig.1. Similarly, the difference of the voltage outputs of the two horn is amplified, down converted to IF and passes through the IF amplifier. This is mixed with PLL corrected VCO output and passes through LPF and given to the azimuth tracking servo system.

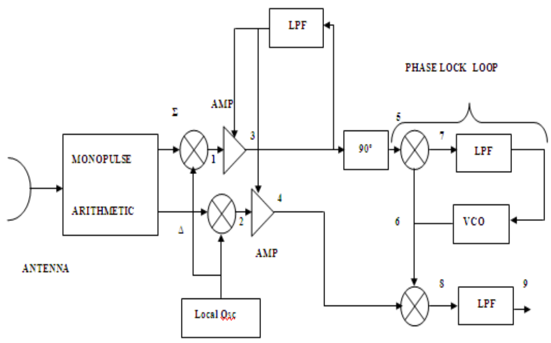

Fig.1 Block diagram of tracking radar

A third order PLL used for our simulation is shown in Fig.2. As shown in Fig.2, the sinusoidal CW radar echo signal along with CW jammer signal after down conversion to IF (Intermediate Frequency) are applied to the PLL.

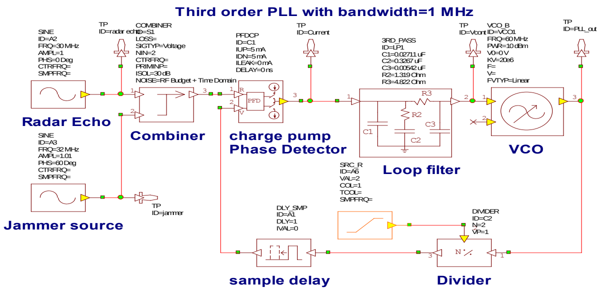

Fig.2 Third order PLL with radar echo and jammer signal

The mathematical modeling of the PLL with radar echo and jammer signal inputs has been carried out using Visual system Simulatior, AWR software. The effectiveness of jamming on the PLL is estimated using computer simulation. The PLL includes charge pump type (as opposed to continuous type) phase detector which compares the input signal phase with VCO (Voltage Controlled Oscillator) output phase and gives output current which has an average DC value proportional to the difference in phase between the two. The loop filter converts the input current into corresponding output voltage which is the control voltage input for the VCO for tuning the PLL. The key parameters in design of the PLL are loop Bandwidth (f_c), phase detector gain (K_{Φ}) and VCO gain (K_{vco}) [4]. The bandwidth of the PLL depends upon loop filter components. Since the loop filter is crucial to robust against jamming, hence careful design of the loop filter has been carried out and inserted into the overall simulation of the PLL. The design of the loop filter involves choosing proper filter order, phase margin, loop bandwidth and pole ratio [5]. From these the time constants of the filter are determined and then the loop filter component are calculated. The loop filter is designed with a typical loop bandwidth of 1 MHz using the standard method. The loop filter components are calculated as:

$$Ctotal = \frac{K\emptyset \cdot Kvco}{wc^2 \cdot N}\sqrt{\frac{1+wc^2 \cdot T2^2}{(1+wc^2 \cdot T1^2)(1+wc^2 T3^2)}} \quad (1)$$

$$N = \frac{Fout}{Fin} \quad (2)$$

$$wc = 2\pi f_c \quad (3)$$

$$C1 = \frac{T1}{T2} \cdot Ctotal \quad (4)$$

$$C2 = Ctotal - C1 - C3 \quad (5)$$

$$C3 = \frac{C1}{5} \quad (6)$$

$$R2 = \frac{T2}{C2} \quad (7)$$

$$R3 = \frac{T3}{C3} \quad (8)$$

where
C_{total} - total loop filter capacitance
K_{Φ}- phase detector gain
K_{vco}- VCO gain
fc-loop bandwidth
N- divide ratio
Fout- RF output frequency
Fin- Comparison frequency
T1, T2 and T3 - loop filter time constants
C1, C2 and C3 - loop filter capacitances
R2 and R3 - loop filter resistances

For our simulations of PLL against jamming, the loop filter of third order is designed with following parameters: fc=1MHz,F_{comp}=30MHz,F_{out}=60MHz,K_{Φ}=5mA,K_{vco}=20 MHz/Volt and N=2. The break lock conditions in the monopulse receiver is carried out in two different cases namely, CW radar echo with CW jammer signal and CW radar echo with FM CW jammer signal which are described below.

A. Spot frequency repeat jamming with CW radar echo and CW jammer signal

With reference to the Fig.2, the radar echo which is assumed to be CW signal after down conversion to IF frequency is applied at the input of the receiver operating at typical frequency of 30 MHz. The jammer signal also applied to the PLL. It is assumed that the jammer signal is away from the radar echo signal by twice the loop bandwidth (32 MHz) which is essential for the stability of the PLL operation [6]. It is assumed that the PLL is operating at the loop bandwidth of 1 MHZ. Initially, the PLL locks onto the radar echo signal as its amplitude is higher compared to the jammer amplitude. As the amplitude of the jammer signal is increased and when jammer amplitude exceeds certain critical value (greater than unity), the PLL loses the frequency lock to the echo signal and jumps onto the jammer signal. This jump phenomenon is observed online using Visual System Simulatorin the frequency spectrum of the signal as observed at the VCO output. The simulation study shows that the jump phenomenon takes place for the J/S (jammer to radar echo signal amplitude ratio) of 1.01 for all cases when the jammer frequency separation from the radar echo frequency is more than twice the loop bandwidth (2 MHz, 3MHz, 5MHz etc.) and is the critical value for the PLL to lose the lock for stable jump operation. Even if the jammer signal is within the loop bandwidth, the jump to the jammer signal frequency occurs at J/S ratio less than unity but with instability. The simulation results are shown below.

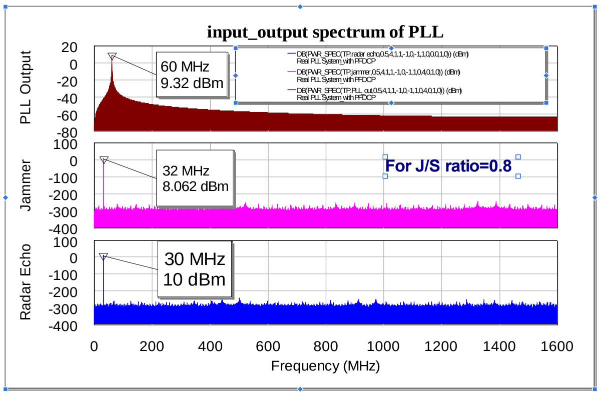

Fig.3 Response at j/s ratio = 0.8

It is seen fromFig.3 that the radar echo is operating at 30 MHz and the jammer is at 32 MHz. For the J/S ratio of 0.8, the PLL output frequency is 60 MHz which is double the radar echo frequency indicating that the receiver tracks the radar echo signal at 30 MHz as the divide ratio of the PLL is 2.

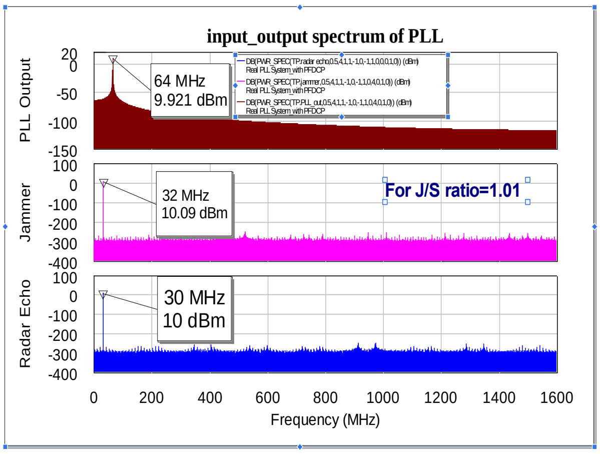

Fig.4 Response at j/s ratio = 1.01

It is seen fromFig.4 that the radar echo is operating at 30 MHz and the jammer is at 32 MHz For the J/S ratio of 1.01, the PLL output frequency is 64 MHz which is double the jammer signal frequency indicating that the receiver tracks the jammer signal at 32 MHz as the divide ratio of the PLL is 2. These two simulation cases demonstrate that the PLL tracks the jammer only if the J/S ratio is 1.01.

B. Spot frequency repeat jamming with CW radar echo and FM CW jammer signal

With reference to Fig.2, an FM CW modulating signal frequency (f_m) of 200 KHz and amplitude of 5 mV is applied as a typical case to the PLL along with the down converted radar echo signal operating at typical frequency of 30 MHz. Initially, the PLL locks onto the radar echo signal frequency when the modulation index (K_f) is very low (of order of 100 or so). When the modulation index of the FM modulator is increased and attains the value of $4x10^6$, the PLL loses the lock to the radar echo and tracks the FM carrier. The simulations were carried out by keeping modulating voltage at different values such as 5mV, 10 mV and so on. The simulations show that the modulation index required for break-lock varies with modulating frequency exponentially and an extrapolated imperial relation is obtained as:

$K_f = 1.1962 \times 10^6 \times exp^{2.03 f_m}$ (9)

It is seen in Fig.5that the radar echo frequency is operating at 30 MHz and the FM carrier frequency is at 40 MHz frequency. At the K_f value of $1x10^6$, the PLL output frequency is 60 MHz which is double the radar echo frequency indicating that the receiver tracks the radar echo signal at 30 MHz as the divide ratio of the PLL is 2.

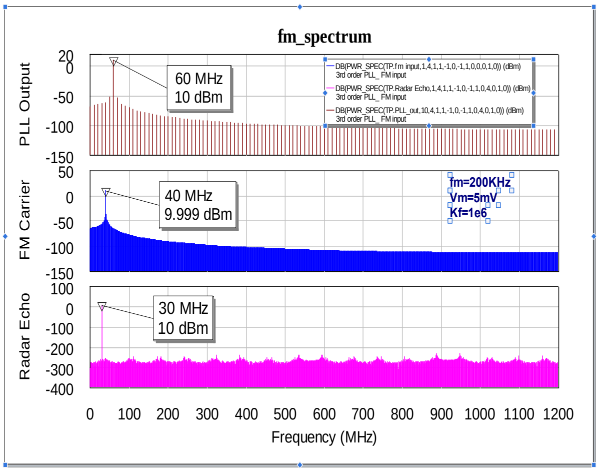

Fig.5 Response at K_f=1 $x10^6$

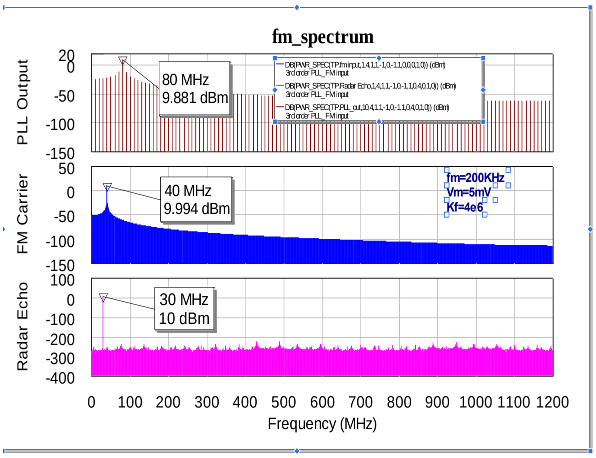

Fig.6 Response at K_f=4 $x10^6$

It is seen in Fig.6 that the radar echo frequency is operating at 30 MHz and the FM carrier frequency is at 40 MHz frequency. At the K_f value of $4x10^6$, the PLL output frequency is 80 MHz which is double the FM carrier frequency indicating that the receiver tracks the FM carrier signal at 40 MHz as the divide ratio of the PLL is 2. In both the above simulations, we have chosen the modulating signal voltage of 5 mV and frequency of 200 KHz.

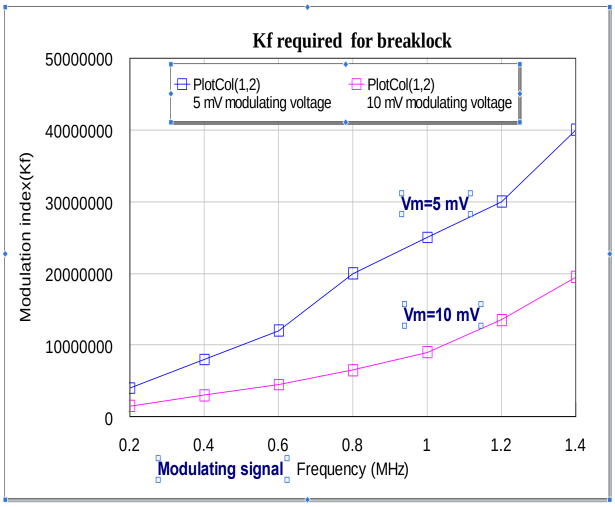

Fig.7 Modulation index Vs Modulating frequency

The variation of FM modulation indexrequired for breaking the frequency lock in receiverwith modulating signal frequency for different values of modulating signal voltage is shown in Fig.7.The variation of modulation index with modulating signal frequency is observed to be nearly exponential. It is plotted for the modulating signal voltage of 5 mV and 10 mV. It can be seen that K_f value required for break lock is more for larger values of modulating signal voltage (V_m).

III. NOISE JAMMING WITH ADDITIVE GAUSSIAN NOISE AND PHASE NOISE

With reference to Fig.2, the White Gaussian noise along with the down converted radar echo signal is injected into the radar receiver and the break lock conditions for the receiver are obtained. This white Gaussian noise model generates independent Gaussian noise samples with zero mean. Through the simulation study, it is seen that the break-lock in the receiver occurs at the Gaussian noise power of -12.02 dBm while the radar echo power is 10 dBm. The similar simulation study has been carried out by injecting the phase noise into the PLL. The Phase Noise Source generates colored noise that may be added to the phase of a signal to simulate phase noise. The simulation results are presented below.

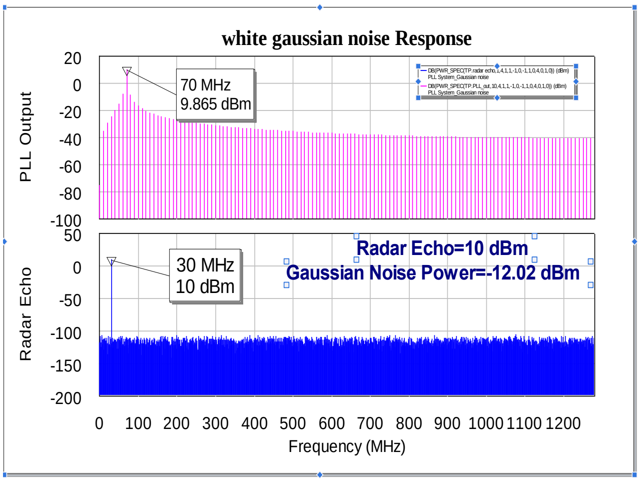

Fig.8 White Gaussian noise response of PLL

The response of the receiver with white Gaussian noise input is shown in Fig.8. It is seen that at Gaussian noise power of -12.02 dBm, the PLL output frequency deviates from radar echo signal operating at 30 MHzand is locked onto some other frequency which is 70 MHz as obtained through simulation. So, the break-lock in the receiver occurs at the Gaussian noise power of -12.02 dBm while radar echo power is 10 dBm.

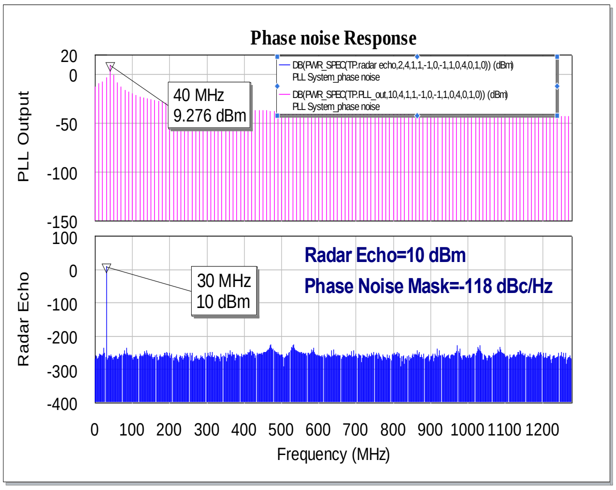

Fig.9 Phasenoise response of PLL

It is seen in Fig.9 that at the phase noise mask of -118 dBc/Hz, the PLL output frequency deviates from radar echo signal operating at 30 MHz and locked onto some other frequency which is 40 MHz as obtained through simulation in this case. So, the break-lock in the receiver occurs at the phase noise mask of -118 dBc/Hz while radar echopower is 10 dBm.

IV. CONCLUSION

In this paper, the spot frequency repeat jamming and additive noise jamming of monopulse radar receiver employing PLL has been discussed. The jump phenomenon is exhibited when the J/S amplitude ratio exceedsthe value of 1.01. The response of the radar receiver with FM CW input signal is also studied. The simulation study shows that the modulation index of the FM modulator required for break lock is $4x10^6$ or more with the modulating signal frequency of 200 KHz and amplitude of 5 mV. The method developed here permits computation of modulation index for other values of modulating frequency and voltage. An empirical relation is obtained which shows that the modulation index increases exponentially with increase in modulating frequency. It is also seen that lower values of modulation index are enough for break lock to occur at higher values of modulating signal voltage. It is also verified that the noise power of -12.02 dBm is required for the PLL for break-lock when radar echo signal power of 10 dBm along with white Gaussian noise signal is injected into the PLL. In the case of phase noise when injected into the PLL, the break-lock occurs at the phase noise mask of -118 dBc/Hz.

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