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Lock threshold deterioration induced by antenna vibration and signal coupling effects in hypersonic vehicle carrier tracking system of Ka band

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Abstract The envelope of a hypersonic vehicle is affected by severe fluctuating pressure, which causes the airborne antenna to vibrate slightly. This vibration mixes with the transmitted signals and thus introduces additional multiplicative phase noise. Antenna vibration and signal coupling effects as well as their influence on the lock threshold of the hypersonic vehicle carrier tracking system of the Ka band are investigated in this study. A vibration model is initially established to obtain phase noise in consideration of the inherent relationship between vibration displacement and electromagnetic wavelength. An analytical model of the Phase-Locked Loop (PLL), which is widely used in carrier tracking systems, is established. The coupling effects on carrier tracking performance are investigated and quantitatively analyzed by imposing the multiplicative phase noise on the PLL model. Simulation results show that the phase noise presents a Gaussian distribution and is similar to vibration displacement variation. A large standard deviation in vibration displacement exerts a significant effect on the lock threshold. A critical standard deviation is observed in the PLL of Binary Phase Shift Keying (BPSK) and Quadrature Phase Shift Keying (QPSK) signals. The effect on QPSK signals is more severe than that on BPSK signals. The maximum tolerable standard deviations normalized by the wavelength of the carrier are 0.04 and 0.02 for BPSK and QPSK signals, respectively. With these critical standard deviations, lock thresholds are increased from −12 and −4 dB to 3 and −2 dB, respectively.

1. Introduction

Serious challenges are encountered during the transmission of information between hypersonic vehicles and the ground Tracking Telemetry and Command (TT&C) station. For instance, thin-walled structures are extensively used in the structural design of hypersonic vehicles to reduce weight.[1–3] However, a thin-walled structure can withstand high-level

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acoustic load because the engine jet noise is combined with aerodynamic noise.[4–9] And, severe fluctuating pressure is produced by the acoustic load and causes the thin-walled structure to vibrate. Therefore, the airborne antenna is likely to vibrate slightly because of structure vibration. Antenna vibration can mix with the signals transmitted by the airborne antenna, and a rapid change in the signal phase occurs; these conditions result in parasitic phase modulation effects. Given the short wavelength of Ka band signals (mostly less than 1 cm), the coupling phenomenon is harmful to the transmission of Ka band phase modulated signals, especially coherent demodulation in the TT&C tracking system, and causes degradation of the communication performance.

The structural vibration of hypersonic vehicles has been extensively investigated in previous studies. Suzuki and Abe[10] conducted aerodynamic tests on a reentry blunt cone under the conditions of near-sonic, supersonic, and hypersonic speeds. The aerodynamic characteristics of the aircraft were obtained mainly from the viewpoint of system stability. Bolender et al.[11] studied the effect of unsteady viscoelastic aerodynamics on the aerodynamic characteristics of an aspirated hypersonic vehicle, and the unstable boundary conditions were provided. Rizzi and Robinson[12] investigated the dynamic response of hypersonic vehicles at the NASA Langley Research Center and provided the corresponding fluctuating pressure spectra. However, the corresponding results for the vibration response of the aircraft were not sufficiently considered. Fortunately, the vibration response of an aircraft can be calculated based on fluctuating pressure. An accurate vibration model is crucial in investigating the influence of this coupling phenomenon on carrier tracking performance. In 2007, Kim et al.[13] examined the interaction between hypersonic vehicle structures and shock disturbances in the presence of acoustic load, and the vibration response was determined. It can be seen that the aerodynamic characteristics of hypersonic vehicles have been extensively investigated, and the structural dynamic response has been obtained. Nevertheless, the coupling effects between airborne antenna vibration and communication signals are yet to be evaluated. A coherent demodulation mode is generally adopted in the actual transmission process of TT&C signals. Carriers locked precisely at a low-input SNR are essential for reliable communication, and the influence of this coupling effects on carrier tracking should be considered. This paper investigates the coupling effects and its influence on carrier tracking, especially two classic phase-modulated signals of Ka band. The effect of this phenomenon on PLL lock threshold is quantitatively analyzed in detail. Quantitative analysis results can provide a reference for actual system design and engineering applications.

Theoretical results on the lock threshold of PLL are complex because of the multiplicative nature of phase noise; however, these results have been rarely obtained. The influence of this phenomenon is quantitatively investigated through simulation, compared, and verified with that obtained through a basic theoretical analysis. This paper is divided into the following parts. Section 2 investigates the coupling effects between airborne antenna vibration and tracking signals by establishing a vibration model and determining the phase noise. Section 3 presents the analytical model of PLL with multiplicative phase noise. Phase noise is imposed on the PLL model for further analysis in Section 4. The last section provides the conclusions.

2. Coupling effects between airborne antenna vibration and tracking signals

2.1. Airborne antenna vibration model

Hypersonic vehicles, the speeds of which reach 5 Mach or above, are affected by engine jet noise combined with aerodynamic noise. The thin-walled structure of such vehicles withstands high-level acoustic load. Furthermore, interaction exists between the structure and the shock wave. Kim et al.[13] investigated the interaction between hypersonic vehicle structures and shock disturbances in the presence of acoustic load. The power spectrum of vibration displacement was provided (see Fig. 1). The flight condition is that the flight speed is 5 Mach, the acoustic load is 120.2 dB, the angle between the shock and the wall is 4°, and the flight altitude is 17 km. The frequency-domain data of vibration displacement are obtained through the periodogram method using the power spectrum. The inverse Fourier transform technique is adopted to obtain vibration displacement data in the time domain (see Fig. 2).

With the power spectrum provided by Ref.[13], the first-order statistics of vibration displacement are obtained. The Probability Density Function (PDF) of the vibration displacement is shown in Fig. 3. The statistical law of vibration displacement is similar to that of Gaussian distribution. The mean value is 0, and the standard deviation is 1.2744×10^{-4} m.

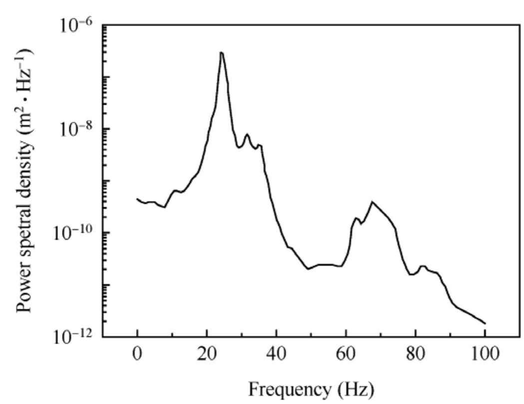

Fig. 1 Power spectrum obtained from Ref.[13].

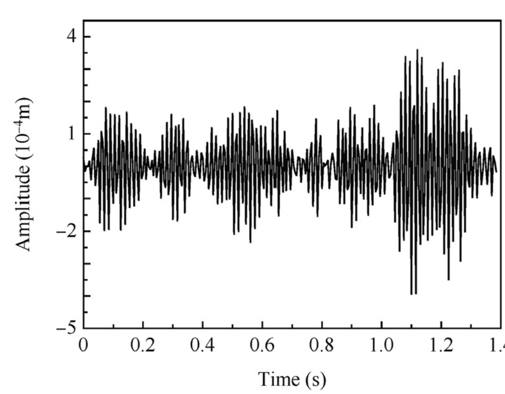

Fig. 2 Time domain data after processing (areodynamic reposnse).