Analysis of frequency modulation non-linearity and its impact on range resolution and accuracy of FMCW LiDAR

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Abstract

FMCW LiDAR has attracted huge attention in recent years due to its ability to detect distance and velocity simultaneously, as well as its the ability for improving detection sensitivity. LiDAR accuracy and resolution highly depend on the frequency modulation linearity of the laser source. This paper provides a detailed theoretical analysis of the frequency modulation residual nonlinearity and its impact on both the range resolution and accuracy. The impact of root mean square (RMS) residual nonlinearity and the shape of residual nonlinearity are studied. This analysis aims at providing depth in the understanding of LiDAR systems.

Introduction

With the rapid emerging of autonomous driving and robotic vehicles, the LiDAR market will have a multi-fold increase in the coming years [1]. Currently, the commercially mature LiDAR solutions are based on the time-of-flight (ToF) detection method, where cost effective pulsed lasers are used. However, the maximum range is limited by the output power and the peak power also has eye safety concerns. More recently, a coherent frequency modulated continuous wave (FMCW) LiDAR has been proposed for better sensitivity and higher resolution.

In FMCW LiDAR, a laser transmitter emits a linear frequency-modulated signal to the target object. Then, the reflected signal mixes with the emitted signal in a balanced photodetector to generate a beating signal. Both the distance and velocity information can be extracted through the beat note. Based on the principle of the FMCW, the linearity of the laser frequency sweeping is of crucial importance for the detection performance. Due to the typical nonlinearity of lasing frequency change with injection current, it is not straightforward to realize linear frequency modulation through direct current-based modulation. Some effort has been dedicated to calibrate the lasing frequency by utilizing a frequency tracker [2] or a pre-distortion algorithm [3]. However such approaches need many optical and electrical components to build the feedback loop or generate a dedicated modulation signal, which will dramatically increase the complexity and also the cost of the whole system. FMCW signal could also be generated through external modulator based on linear electro-optical effects [4], but a complicated IQ modulator and bias-driven circuits are needed to realized single-side-band modulation.

Simulation principle and the resolution of linear signal

Based on the principle of FMCW LiDAR, the initial laser electric field can be expressed as equation (1),

$$E_i = \left|\widetilde{E_{i0}}\right| \exp\left(i2\pi(f_0 + kt + f(t))t + \varphi_0\right) \qquad (1)$$

Where $\left|\widetilde{E_{l0}}\right|$ is the amplitude of the electric field, f_0 is the initial frequency, k is the modulation frequency slope, t is the time, $f(t)$ is the nonlinear part of frequency modulation and φ_0 is the initial phase. The echo signal of a target object with a time delay of τ can be expressed in equation (2) as,

$$E_b = \left|\widetilde{E_{b0}}\right| \exp\left(i2\pi(f_0 + k(t-\tau) + f((t-\tau)))(t-\tau) + \varphi_0\right) \qquad (2)$$

Where $\left|\widetilde{E_{b0}}\right|$ is the amplitude of the returned electric field. The emission and return signal will combine in a photodetector to generate a beating note through square-law detection. The detection resolution and accuracy can be extracted from a Fourier transform of the beating waveform. The whole processes are carried out in MATLAB to analyse the impact of the nonlinearity.

Firstly, we study the condition of perfect linear signal by set $f(t) = 0$. The delay time is set as 10 ns in the whole simulation for easy calibration with the experiments. The launch and return frequency-modulated signals are shown in Fig 1(a) under a triangular modulation. The residual nonlinearity is also shown in the right axis and it keeps zero in the whole time span for an perfect linear signal. The residual error is calculated through the difference of the launch signal and its linear fitting. Fig 1(b) shows the generated beating signal waveform in time domain.

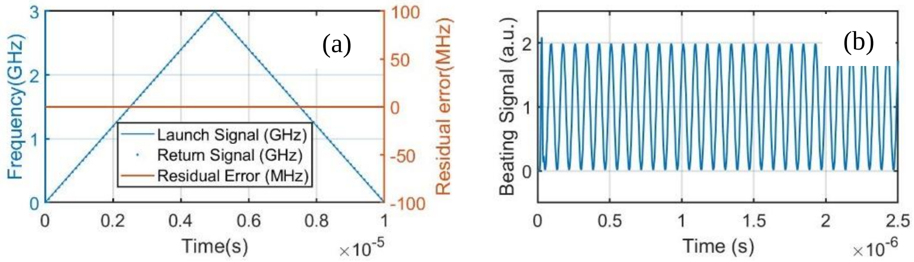

Fig 1(a) Launch and return frequency-modulated signals and residual nonlinearity of the signal. (b) Generated beating signal waveform in time domain.

Through a Fourier transform of the beating waveform, we can get the frequency domain beating signal, where we can easily extract the detection resolution and accuracy. Since there is a one-to-one correspondence between beating frequency and delay time, we simply transform the beating frequency as the delay time in the x-axis. Fig 2(a) shows the Fourier transformed signal of the perfect linear launch signal in Fig 1(a), where a resolution of 0.048m is achieved after applying a Lorentz fitting and extracting its full width half maximum (FWHM). As can be seen, the peak of the signal is perfectly aligned with the delay time of 10 ns, which means a perfect detection accuracy. Regarding the principle of FMCW discussed above, the best achievable distance resolution (Δd) depends on the chirp bandwidth (B) with a relationship given in equation (3),

$$\Delta d = \frac{c}{2nB} \qquad (3)$$

Where c is the speed of light and n is the refractive index of the transmission medium. To calibrate our simulation, we extract the resolution under different chirp bandwidth as shown in Fig 2(b). The theoretical curve is also shown, which matches well with our simulation.

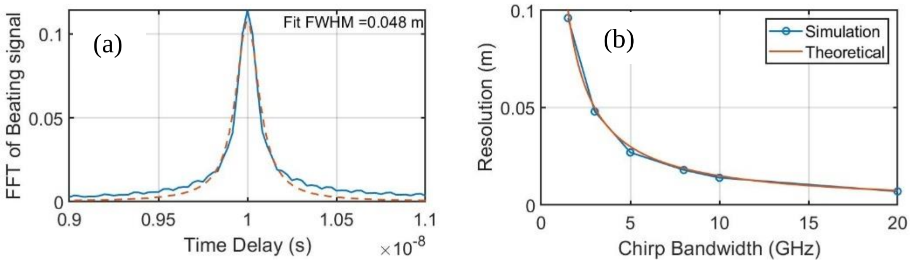

Fig 2(a) Frequency domain beating signal after Fourier transform. (b) Simulated resolution under different chirp bandwidth.

Analysis of nonlinearity and its impact on range sensing

Then, a second-order nonlinearity ($f(t) = At^2$, where A is a parameter to calibrate the amplitude) is added in the launch signal with different RMS residual nonlinearity. Fig. 3 (a) shows the launch/return frequency modulated triangle signal as well as the residual nonlinearity curve. The RMS residual nonlinearity of this signal is 3.02 MHz, which is calculated using equation (4).

$$RMS = \sqrt{\frac{\sum_1^N (f_{laser} - f_{linear-fit})^2}{N}} \qquad (4)$$

, where f_{laser} is the instantaneous lasing frequency, $f_{linear-fit}$ is the linear fit to f_{laser}, and N is the sample number.

The Fourier transform of the beating signal shows a resolution of 0.086 m as shown in Fig. 3(b), where the nonlinear induced deterioration results in almost twice the detection resolution compared with the linear case. In addition, the detection peak is also shifted from 10 ns, which means a deterioration of the detection accuracy. Fig. 4 (a) and (b) show the resolution and peak position shift under different RMS error induced by second-order nonlinearity. As can be seen, both the resolution and accuracy would deteriorate severely with the increase of residual nonlinearity.

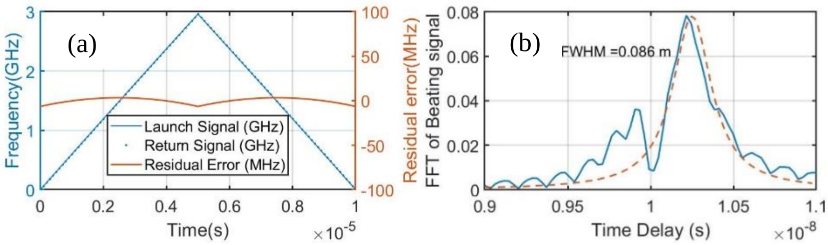

Fig 3 (a) launch and return frequency-modulated signals with 3 MHz RMS nonlinearity, as well as the residual nonlinearity of the signal. (b) Fourier transform of the beating signal.

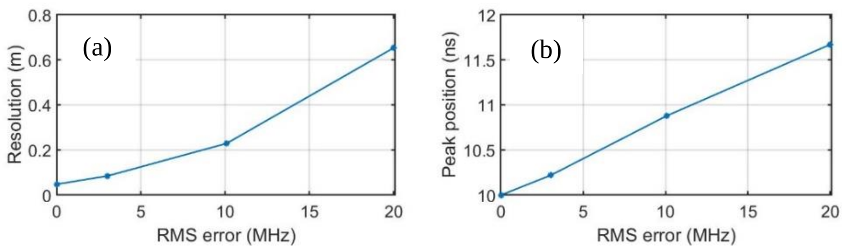

Fig 4 (a) resolution and (b) peak position under different RMS error induced by second-order nonlinearity

Since the second-order nonlinearity would have both positive and negative signs, we also simulate the condition with different sign and keep the same RMS nonlinearity. As shown in Fig. 5 (a) and (b), different sign will not change the detection resolution but the peak position is shifted from positive side to the negative side. The peak shift originates from the adiabatic shift of the beating frequency caused by the nonlinearity.

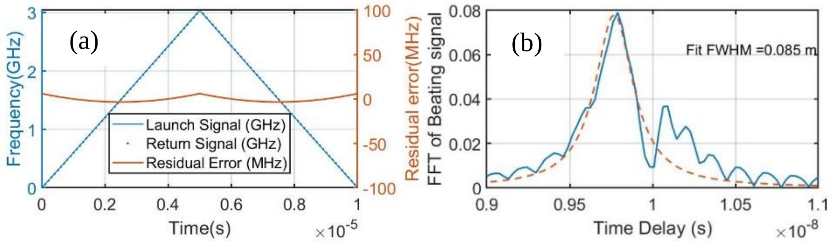

Fig 5 (a)launch and return frequency-modulated signals with 3 MHz RMS nonlinearity and the negative second-order residual nonlinearity. (b) Fourier transform of the beating signal

To further investigate the impact of the shape of the residual nonlinearity, we add a sine-type of nonlinearity ($f(t) = Asin(2\pi t/T)$, where A is a parameter to calibrate the amplitude and T is the ramp time of the triangle waveform) with the same RMS error of 3 MHz. Fig 6 (a) and (b) shows the launch signal and the Fourier transform of the beating signal. As can be seen, several peaks appear at both the positive side and negative side around the delay time. This peak distribution lead to an even worse resolution (~ 0.44 m) compared with the second-order nonlinearity with the same RMS error.

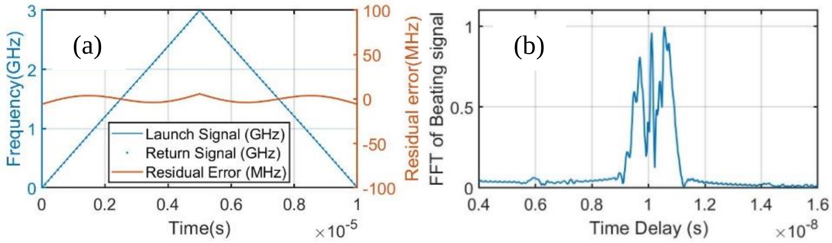

Fig 6 (a)launch and return frequency-modulated signals with 3 MHz RMS nonlinearity and the sine-type residual nonlinearity. (b) Fourier transform of the beating signal.

Conclusion

In this paper, a detailed theoretical analysis of the frequency modulation nonlinearity and its impact to the range resolution and the accuracy is provided. The impact of root mean square (RMS) residual nonlinearity and the shape of residual nonlinearity are studied. This analysis gives in-depth understanding of LiDAR system performance and their dependence on FMCW linearity.

Acknowledgments

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