Signal Distortion Due to Low-pass Filtering in Phase Generated Carrier Demodulation Schemes for Interferometric Sensors

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Abstract— This paper analyses the signal distortions in phase generated carrier demodulation schemes used in fibre optic sensing applications due to errors in the estimation of the quadrature components of the signal at the output of low pass filtering stage.

Index Terms— **Fibre optic hydrophone, PGC-Demodulation, Distortion**

1. Introduction

Phase generate carrier (PGC)-Arctangent and PGC-DCM (differentiation and cross-multiplication) schemes and their variants estimate a pair of quadrature components of the signal ($\sin\phi(t)$ and $\cos\phi(t)$ where $\phi(t)$ is the phase shift signal) from the interferometer output [1,2]. In all these schemes, the quadrature components of the signal are recovered from the interferometric signal by mixing it with even and odd harmonics of the carrier signal and low-pass filtering. These quadrature components are further processed to reconstruct the signal. An error in the estimate of the quadrature components can lead to distortions in the demodulated output even in the absence of laser intensity noise or variations in the modulation depth. The errors in the estimation of quadrature components of phase shift signal increases with phase amplitudes and these effects can introduce significant distortions in the demodulated output especially when the signal frequencies are substantial in comparison to the modulation frequency.

2. Theory

Figure 1(a) shows the block diagram of the algorithm used for retrieval of the quadrature components of the signal from the interferometer output in PGC demodulation schemes considered in the current study. The output of the photo detector is mixed with an even and an odd harmonic of the carrier signal and then low pass filtered to remove terms above half the modulation frequency to obtain the quadrature components. Equation 1 shows the ideal values of the quadrature components estimated in the PGC scheme when mixing signals of unit amplitude is employed. In equation 1, B is proportional to the input optical power, C is the modulation depth, J_n are the Bessel functions of first kind of order n. For the analysis of distortion characteristics, the signal of interest is considered to be a sinusoidal. Thus, the quadrature components of the signal of interest can also be represented using Bessel series expansion as given in [3]. A pictorial representation of the application of the low pass filter to obtain $\sin\phi(t)$ from signal marked I_1 in Figure 1(a) is given in Figure 1(b). As shown in Figure 1(b), the low pass filtering results in removal of some of the higher order Bessel harmonics of the quadrature components of the phase signal. In addition, the spectral overlapping of the higher order Bessel harmonics of the quadrature components of the phase signal carried on the adjacent Bessel harmonics of the carrier signal will also manifest as spurious signals in the estimates of $\cos\phi(t)$ and as marked in Figure 1(b).

$$\begin{aligned} S_1 &= -BJ_1(C)\sin\phi(t) \\ S_2 &= -BJ_2(c)cos\phi(t) \end{aligned} \quad (1)$$

$$\begin{aligned} S_{dcm} &= \int (S_2\dot{S_1} - S_1\dot{S_2})dt \\ &= B^2 J_1(C) J_2(C) \int \dot{\phi(t)}\, dt \end{aligned} \quad (2)$$

$$\begin{aligned} S_{\mathrm{arctan}} &= \arctan\left(\frac{S_1}{S_2}\right) \\ &= \arctan\left(\frac{J_1(C)}{J_2(C)}\tan\phi(t)\right) \end{aligned} \quad (3)$$

In PGC-DCM scheme, the signals S_1 and S_2 in equation 1 is differentiated, cross-multiplied, subtracted and then integrated to retrieve the signal back as show in equation 2. In PGC Arctangent scheme, arctangent of the ratio of S_1 to S_2 reproduces the signal as represented in equation 3 when $J_1(C) = J_2(C)$. Thus the PGC-arctangent scheme requires the modulation depth to be maintained at the optimum value of 2.63 radians to ensure that the amplitudes of the first and second Bessel harmonics are equal.

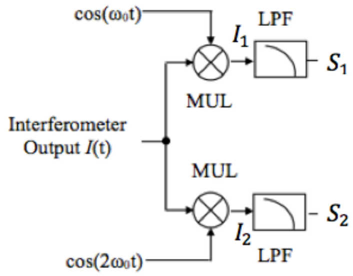

Fig.1(a) Block diagram of the technique used for estimation of the cosφ(t) and sinφ(t) from interferometer output

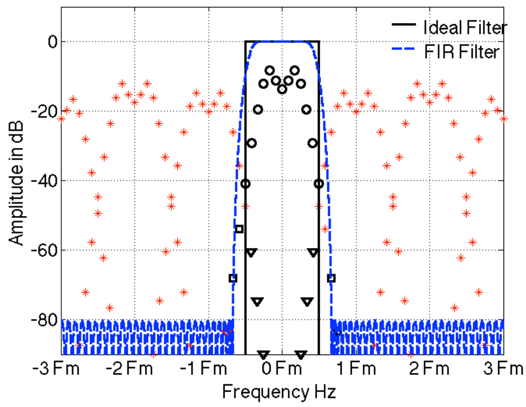

Fig.1(b) Application of the filter on the signal I_1 to estimate $sin\phi(t)$. * - sideband signal components on the sidebands of higher order harmonics, ° - in-band components of quadrature signal,∇ - spectral overlapping from quadrature components on adjacent carrier harmonics and □ - out of band components of quadrature signal

3. Distortion Analysis

In this section distortion characteristics of PGC-DCM and PGC-Arctangent schemes are compared for two different filter characteristics; 1) Ideal filter which eliminates all the frequencies above half the modulation frequency and 2) FIR filter with a frequency response as represented in Figure 1(b). To compare the effect of the low pass filtering on the performance of the PGC-DCM and PGC-Arctangent schemes, the spectral components in the pass-band of the ideal filters for the signals S_1 and S_2 were estimated using the Bessel harmonics of the carrier and signal. This spectral information is converted in to time domain signal for further processing using equations 2 and 3. A carrier signal of 2.63 radians amplitude is used in the simulation to ensure ideal operating parameters for PGC-arctangent scheme. Distortion ratio parameter, defined as the ratio of the sum total of the energy at the signal harmonics and the spurious signals to the energy at signal frequency in the demodulated output, is used for performance comparison of the demodulation schemes.

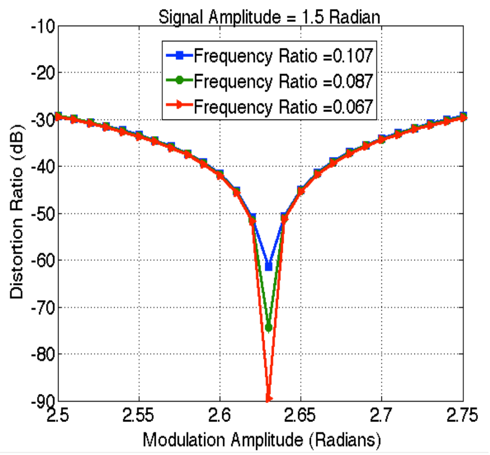

Fig. 2 Variation in distortion characteristics of PGC-Arctangent scheme with frequency ratio while modulation depth is maintained at the ideal value of 2.63 Radians

Figure 2 compares the distortion ratios for PGC-arctangent schemes at different signal frequencies at 1.5 radians amplitude when the modulation amplitude is maintained at 2.63 Radians. While the analytical estimation of total harmonic distortion is independent of frequency of the signal [1], the distortion ratio decreases with increase in signal frequency.

Figure 3(a) shows the variation of the distortion ratio at different signal frequencies scaled by modulation frequency represented as frequency ratio in the plots. In practice, the frequency response characteristics of the low pass filters deviate from that of ideal filter. A typical FIR low-pass filter with frequency response characteristics as represented in Figure 1(b), is employed in the simulation. Typical values of fibre laser frequency noise and intensity noise observed in the output of distributed feedback fibre laser hydrophone is used in the study to simulate the noise in the interferometer output [4]. Modulation amplitude of 2.6 radians, which corresponds to a deviation of approximately 1% from the ideal value, is considered in the simulation. Figure 3(b) shows the distortion ratios for the PGC-DCM and PGC-Arctangent scheme. It can be observed that the performance of PGC-arctangent scheme deviates significantly from the ideal performance due to the non-ideal modulation amplitude. When signal amplitudes are smaller than 1 radian, the PGC-DCM scheme has lower signal distortions and its distortion ratio decreases rapidly as the amplitude and frequency of the signal increases. Similarly, when the signal amplitudes are of the order of a few radians, PGC-arctangent scheme offers better distortion ratio performance.

4. Conclusion

The distortion characteristics of the PGC-DCM and PGC-arctangent schemes arising due to errors in estimation of the quadrature components of the phase shift signals are presented.

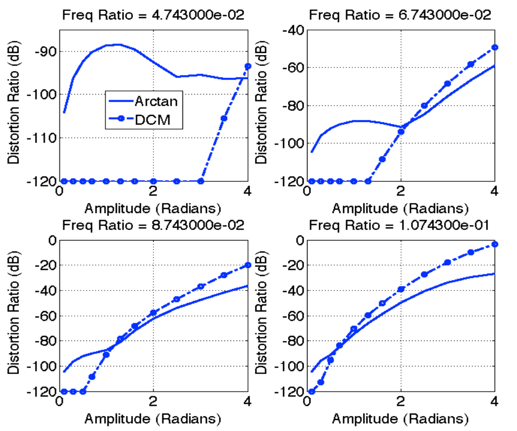

Fig. 3(a) Distortion characteristics when an ideal filter is employed in the estimation of quadrature components

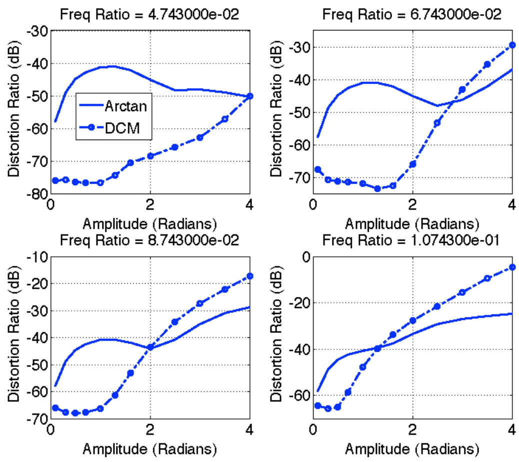

Fig. 3(b) Distortion characteristics when FIR filter is employed in the estimation of quadrature components

It was observed that, even when operating under the ideal conditions, (modulation amplitude =2.63 radians, ideal low pass filter and absence of laser intensity and frequency noise) the distortion ratios of PGC-arctangent schemes varies with frequency of the signal and these values are higher than the analytical estimates of THD that are independent of the frequency of the signal. The PGC-Arctangent offers better distortion free performance when the signal amplitudes are of the order of a few radians while PGC-DCM scheme offers better performance for lower amplitudes for typical application of distributed feedback fibre laser as a hydrophone.

References

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