Dynamic Range of PGC Demodulation Technology in Fiber-Optic Hydrophone System

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Abstract. Starting with the principle of PGC demodulation and the spectrum analysis of input and output signals of LPF, the frequency characteristics of LPF are deeply studied in this paper. The necessity of sharp cut-off characteristics and linear phase of LPF is proved by simulation experiments. A method of optimizing cut-off frequency is proposed. By using this method, the cut-off frequency can be selected and the PGC solution can be significantly improved. Adjust the dynamic range of the system.

Keywords: Optical fiber hydrophone · PGC modulation · LPF · Cut-off frequency

Among the demodulation methods of many optical fiber sensors, the phase-generated carrier demodulation (PGC) technology is passive demodulation with high sensitivity, good linearity and large dynamic range, so it has attracted the attention of the industry [1]. PGC modulation and demodulation technology is one of the schemes for signal detection of optical fiber hydrophone [2]. In this scheme, the frequency characteristics of LPF have a great impact on the dynamic range of the system. Improving the dynamic range of the system has become one of the focuses of hydrophone research. Therefore, the frequency characteristics of LPF studied in this paper can improve the performance of LPF.

1 PGC Principle

PGC introduces large-scale phase modulation outside a certain frequency band of the measured signal bandwidth, and the signal is located in the side band of the modulated signal, which transforms the influence of boundary interference into that of the modulated signal, and separates the frequency band of the measured signal from that of the low-frequency interference, so as to facilitate the subsequent noise separation.

In the PGC demodulated fiber optic hydrophone system, Mach-Zehnder dual-beam interferometer is used as the probe of the fiber optic sensor, and Faraday rotating mirror is used to solve the problem of polarization fading [3]. The output signal of the interferometer can be expressed as:

J. H. Abawajy et al. (Eds.): ATCI 2020, AISC 1244, pp. 211–217, 2021.
https://doi.org/10.1007/978-3-030-53980-1_32

$$I = A + Bcos[Ccos\omega_0 t + \varphi(t)] \tag{1}$$

In formula (1), A is the average optical power output by the interferometer, $B = kA$, $k \leq 1$ is the visibility of interference fringes. $Ccos\omega_0 t$ is a phase carrier, $\varphi(t) = Dcos\omega_s t + \Psi(t)$, $Dcos\omega_s t$ is a phase change caused by the signal to be measured, and $\Psi(t)$ is a slow phase change caused by environmental noise. Fig. 1 is the schematic block diagram of PGC demodulation [4].

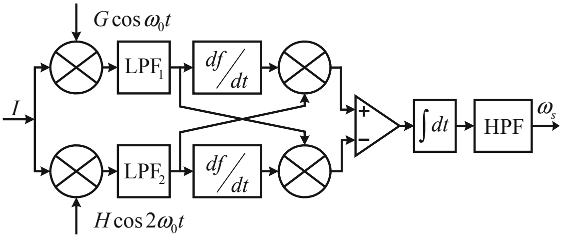


Fig. 1. Principle block diagram of PGC demodulation

As shown in Fig. 1, the cosine signal and the output signal of the interferometer are mixed separately, and the sum is obtained.

$$-BGJ_1(C)sin\varphi(t), \quad -BHJ_2(C)cos\varphi(t) \tag{2}$$

Then, after differential cross multiplication and integral operation, the following results can be obtained:

$$B^2GHJ_1(C)J_2(C)[Dcos\omega_s t + \Psi(t)] \tag{3}$$

It can be seen that the integrated signal contains the signal to be measured and the environmental information of the outside world. The latter is usually a slowly varying signal, which can be filtered by a high-pass filter. The final output of the system is

$$B^2GHJ_1(C)J_2(C)Dcos\omega_s t \tag{4}$$

2 Study on Amplitude-Frequency Characteristics of LPF

By Bessel transformation of $sin\varphi(t)$ and $cos\varphi(t)$ in formula (2), we can get that:

$$\begin{aligned} cos\varphi(t) = {} & \left[J_0(D) + 2\sum(-1)^k J_{2k}(D)cos2k\omega_s t\right] cos\Psi(t) \\ & - 2\left[\sum(-1)^k J_{2k+1}(D)cos(2k+1)\omega_s t\right] sin\Psi(t) \end{aligned}$$

$$\begin{aligned} sin\varphi(t) = {} & \left[J_0(D) + 2\sum(-1)^k J_{2k}(D)cos2k\omega_s t\right] sin\Psi(t) \\ & - 2\left[\sum(-1)^k J_{2k+1}(D)cos(2k+1)\omega_s t\right] cos\Psi(t) \end{aligned} \tag{5}$$

As can be seen from the formula, the fundamental wave and its harmonic amplitude are proportional to $J_k(D)$. In engineering applications, when $|J_k(D)| < 0.1$, the k-th harmonic component and higher harmonic component of fundamental wave can be neglected [5]. When $k > D + 1$, $|J_k(D)|$ is always less than 0.1. Therefore, the cut-off frequency ω_c must be placed at least after the (D + 1)th harmonic frequency of the input signal fundamental wave before the PGC demodulation system can recover the signal to be measured. That is:

$$\omega_c > (D + 1)\,\omega_s \tag{6}$$

Formula (7) shows that in the PGC demodulation scheme, the upper limit (D_{max}) of the system dynamic range is limited by the cut-off frequency (ω_s) of the LPF. On the surface, increasing ω_s can improve the dynamic range of the system, but ω_s can not be arbitrarily increased. If ω_s is too large, PGC demodulation will be interfered by high frequency signal. Therefore, choosing the appropriate cut-off frequency is very important to improve the dynamic range of PGC demodulation system.

In order to protect the PGC demodulation from the interference of the lower carrier sideband signal, the cut-off transition band must have enough attenuation at $\omega_0 - \omega_c$ [6]. This attenuation is expressed by δ_0 (dB). So, ω_c satisfy: $\omega_c + \Delta\omega = \omega_0 - \omega_c$. That is: $\omega_c = (\omega_0 - \Delta\omega)/2$. $\Delta\omega$ is the bandwidth of the transition band.

Under the condition that the cut-off characteristic is determined, the size of the $\Delta\omega$ is determined by the reference value δ_0 of the transition band attenuation. Therefore, from the amplitude frequency characteristic curve, it can be obtained that:

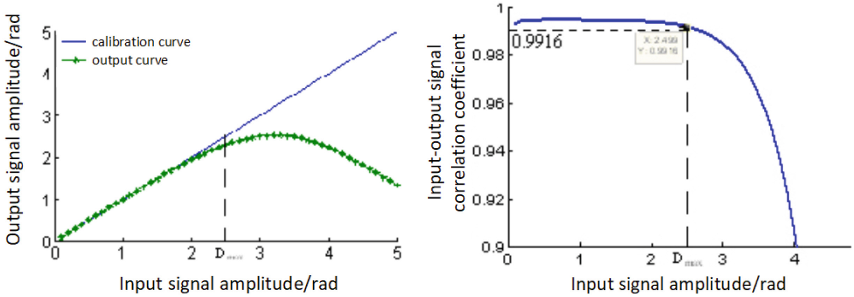
$$\delta_0/\Delta\omega = \delta/\omega_c \tag{7}$$

From Formula (7) and above, we can get:

$$\omega_c = \omega_0/(\delta_0/\delta + 2) \tag{8}$$

Formula (8) shows that as long as δ_0 is optimized, the best value of ω_c can be determined. Next, through the simulation of PGC demodulation system, the cut-off frequency is optimized to obtain a larger dynamic range of the system.

In order to study the influence of different cut-off frequencies on the dynamic range upper limit of PGC demodulation system, the method of obtaining the dynamic range upper limit is introduced first, as shown in Fig. 2(a) and Fig. 2(b).



(a) Amplitude Relation Diagram of Output-Input Signal in PGC Demodulation System
(b) The relationship between input signal amplitude and correlation coefficient

Fig. 2. Simulation results of PGC demodulation system

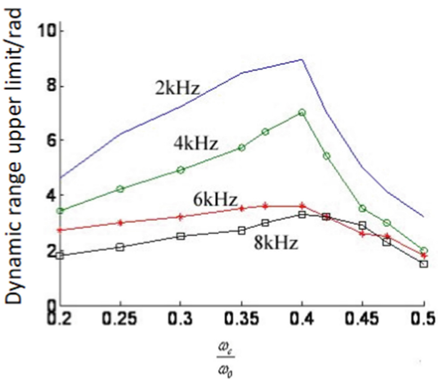


Fig. 3. The influence of different cut-off frequencies of filters on the upper limit of dynamic range of the system

The upper limit of dynamic range proposed is: the output-input correlation coefficient is above 0.99, and the amplitude distortion is less than ±0.1 dB. Comparing Fig. 3 with the above criteria, the upper limit can be read out in Fig. 3.

Figure 3 is a simulation diagram of the influence of different cut-off frequencies on the upper limit of dynamic range of the system.

As shown in Fig. 4, when the cut-off characteristic is −50 dB/octave, ω_c can be selected at $0.4\omega_0$, and the maximum dynamic range can be obtained. Therefore, if $\omega_c = 0.4\omega_0$, $\delta = -50$ is taken into Eq. (11), $\delta_0 = -25$ can be obtained. According to the same simulation model and the method, the cut-off characteristics are changed to simulate the PGC demodulation system, and Table 1 can be obtained.

Table 1. Simulation data and calculation results under different cutoff characteristics

Simulation data		Calculation results
Cut-off characteristics δ (dB/octave)	Optimum value ω_c ($\times\omega_0$)	Transition attenuation δ_0 (dB)
−40	0.37	−28.1
−45	0.38	−28.4
−50	0.4	−25
−55	0.41	−24.1
−60	0.41	−26.3
−65	0.42	−24.8
−70	0.42	−26.6

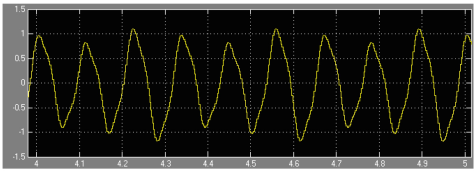
As shown in Table 1, δ_0 fluctuates near a certain attenuation value, which can be used as a reference value for selecting the best cut-off frequency. Considering the reliability, according to the data in Table 1, the final transition band attenuation reference value δ_0 is determined as −30 dB. From the above analysis, under the condition that the cut-off characteristics are determined, selecting the cut-off frequency according to formula (10) can make the fiber-optic hydrophone system obtain a larger dynamic range and improve the overall work efficiency of the PGC demodulation.

3 Phase Frequency Characteristics of LPF

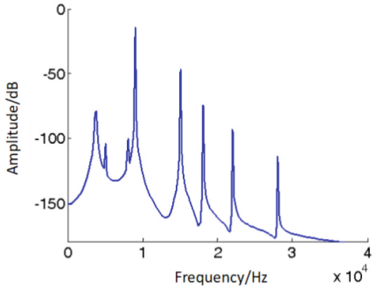
It can be seen from formula (6) that $sin\varphi(t)$ and $cos\varphi(t)$ contain the harmonic components of ω_s. When the mixing signal passes through the filter, if the phase frequency characteristic is linear, the phase shift of the harmonic components of ω_s changes linearly, and the harmonic components in the time domain have the same time delay [7]. The output signal of the filter can still be expressed by formula (2), so it will not affect the PGC demodulation.

If the phase frequency characteristic is nonlinear, the phase shift of each harmonic component of ω_s is nonlinear. The time delay in the time domain is not exactly the same [7]. At this time, each harmonic component passing through the filter no longer satisfies the relationship of Eq. (6), so the output signal of the filter cannot be represented by Eq. (2). This will lead to the distortion of the output signal of PGC system.

The above conclusions are illustrated by simulation. Figure 5 shows the influence of the non-linear phase of the LPF on the PGC demodulation system. Simulation model: input signal: 9 kHz single frequency signal; signal amplitude: 1 rad; sampling frequency: 480 kHz; carrier frequency: 60 kHz; filter cut-off frequency: 20 kHz; filter cut-off characteristic: −50 dB/octave; filter phase frequency characteristic: non-linear phase.



(a) After the whole process of PGC demodulation, the system output signal waveform



(b) Spectrum of system output signal

Fig. 4. Effect of nonlinear phase filter on PGC demodulation

As shown in Fig. 4, besides the frequency of the signal to be measured (9 kHz), many new frequency components appear in the spectrum, which brings serious interference to the spectrum analysis of the output signal of PGC demodulation system. If the PGC demodulation system uses a linear phase LPF under the same detection conditions, the demodulation result is very ideal. There is only one frequency component in the output signal of the system. In the practical application of fiber optic hydrophone, in order to identify or locate the test target, the spectrum of the detected signal needs to be analyzed and processed. Therefore, the linear phase of LPF is particularly important for the PGC demodulated fiber optic hydrophone system.

4 Concluding Remarks

The above analysis shows that the LPF plays an important role in the PGC demodulation system. The change of its frequency characteristics directly affects the final demodulation results. In PGC demodulation fiber-optic hydrophone system, a LPF with steep cut-off characteristics and linear phase should be used. According to the cut-off characteristics of the filter and the simulation experiment of the PGC demodulation system, this paper proposes a method to optimize the cut-off frequency setting, which has a certain reference value for improving the performance of the PGC demodulation system and obtaining a larger dynamic range of the system.

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