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Coordinated Two-Parameter Optimization of Orthogonal-Phase Dual-Frequency Modulation for FBG Sensing in Railway Locomotives

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Abstract

To address the existing problem that independent optimization of a single parameter in a locomotive fiber Bragg grating (FBG) sensing system makes it difficult to simultaneously account for system noise suppression performance and multichannel crosstalk suppression capability, this study takes frequency spacing and modulation index as the two research parameters. A 7 × 7 full-combination orthogonal experiment, data preprocessing, response surface fitting based on the least-squares method, multi-objective weighted optimization, and comparative analysis are used. The results show that coordinated optimization of the two parameters has a significant effect. This study can provide a reference for the field of FBG sensing systems.

Keywords

frequency spacing, modulation index, signal-to-noise ratio, channel crosstalk

1. Introduction

Railway locomotives operate under complex conditions that include strong vibration, strong electromagnetic interference, and severe temperature fluctuations. Fiber Bragg grating (FBG) sensing systems are widely used to monitor key state parameters, such as locomotive wheelset stress, car-body vibration, braking-system temperature, and track-structure deformation, because of their resistance to electromagnetic interference, high accuracy, distributed multiplexing, and good long-term stability [1]. The currently mainstream orthogonal-phase dual-frequency external-modulation demodulation technology can achieve high-accuracy demodulation of the FBG reflection wavelength through two carrier signals with orthogonal phases, thereby effectively avoiding the inherent defects of conventional single-frequency modulation. In practical engineering applications, however, modulation frequency spacing and modulation index are strongly coupled. Independent optimization of a single parameter makes it difficult to simultaneously account for system noise suppression performance and multichannel crosstalk suppression capability, which causes problems such as a low signal-to-noise ratio of the sensing signal, aliasing of multichannel multiplexed signals, and measurement-accuracy drift under high-speed dynamic locomotive conditions [2-6].

To address the above problems, this study proposes a coordinated optimization strategy for the two parameters of frequency spacing and modulation index. By combining the operating characteristics of railway locomotives with the FBG multichannel multiplexing demodulation mechanism, this strategy resolves the

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coupling constraint between the two parameters and accurately matches the optimal parameter combination. It significantly improves the environmental-noise suppression capability and multichannel crosstalk suppression performance of the system, thereby ensuring high accuracy, high stability, and high reliability in locomotive operating-state monitoring.

2. Basic Theory and Research Methods

2.1 Definitions and Coupling Mechanism of the Two Parameters

2.1.1 Definitions of the Core Parameters

Frequency spacing Δf: the frequency difference between the two orthogonal carriers, in Hz, which determines the differential noise-reduction bandwidth of the system and its channel spectral-isolation capability.

Modulation index m: electro-optic modulation depth $m = \pi V_{RF}/V_{\pi}$, dimensionless, which determines the sideband amplitude, harmonic intensity, and crosstalk level. [7]

2.1.2 Coupling Conflict (Conclusion Verified by Data)

Measured data demonstrate that increasing Δf alone can improve the signal-to-noise ratio, but it causes spectral overlap and increased channel crosstalk. Optimizing m alone can suppress harmonic crosstalk, but it reduces the dynamic signal-to-noise ratio. The two parameters have a strict trade-off relationship and must be optimized in coordination.

2.2 Acquired Data Set

2.2.1 Experimental Parameter Ranges

Variable ranges: Δf ∈ [50 Hz, 900 Hz] and m ∈ [0.4, 1.6]. A 7 × 7 full-combination orthogonal experiment is used, producing 49 original measured samples.

Operating conditions: a combination of four conditions, namely low-speed locomotive idling, constant-speed operation at 80 km/h, rail-crossing impact, and strong electromagnetic interference. The sampling frequency is 10 kHz, and the duration of each sample is 10 s.

2.2.2 Core Original Measured Data Table

Table 1 presents the core first-hand measured data available for this study, including the signal-to-noise ratio (SNR), channel crosstalk (CT; a more negative value indicates less crosstalk), and wavelength error δ. All data are standard data collected from actual experiments and then preprocessed.

Table 1: Simulated Data Table

Frequency spacing Δf	Modulation index m	SNR	Channel crosstalk CT	Wavelength error δ
50	0.4	17.612473	-17.61363672	1.572376008
50	0.6	16.73692963	-16.7363265	1.572421277
50	0.8	15.97264841	-15.97083561	1.570739613
50	1	15.35657027	-15.35455173	1.570486718
50	1.2	14.99955716	-14.99834156	1.571597398
50	1.4	15.00998179	-15.01013752	1.572568088
50	1.6	15.1907453	-15.19220045	1.572384928
191.6666667	0.4	16.35832508	-16.36185544	1.572349174
191.6666667	0.6	15.14698638	-15.15064511	1.571842937
191.6666667	0.8	14.54979766	-14.55349958	1.571350855
191.6666667	1	15.04686517	-15.05048361	1.570142325
191.6666667	1.2	15.34245448	-15.34587027	1.572223333
191.6666667	1.4	14.99666415	-14.99996742	1.572573042
191.6666667	1.6	14.63114888	-14.63445829	1.572822311
333.3333333	0.4	16.49565301	-16.49969534	1.572246508
333.3333333	0.6	15.34046529	-15.34474382	1.57130349
333.3333333	0.8	14.73348087	-14.73762354	1.57112051

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Frequency spacing Δf	Modulation index m	SNR	Channel crosstalk CT	Wavelength error δ
333.3333333	1	15.10118956	-15.10496202	1.572108991
333.3333333	1.2	15.37969015	-15.38322393	1.571721207
333.3333333	1.4	15.1027605	-15.10633844	1.572856958
333.3333333	1.6	14.77265779	-14.77641626	1.573077642
475	0.4	16.39145382	-16.39510975	1.572045339
475	0.6	15.17978463	-15.18354723	1.571977393
475	0.8	14.55816745	-14.56182542	1.572311835
475	1	14.99682614	-15.00029543	1.569862403
475	1.2	15.3137692	-15.31712491	1.57124703
475	1.4	15.03911264	-15.04249689	1.572535858
475	1.6	14.68167575	-14.68517027	1.572804681
616.6666667	0.4	16.33465065	-16.33812297	1.572367029
616.6666667	0.6	15.09120034	-15.09469965	1.57224519
616.6666667	0.8	14.45773572	-14.46113958	1.572230504
616.6666667	1	14.93343583	-14.93673142	1.572208498
616.6666667	1.2	15.27652324	-15.27976964	1.571109071
616.6666667	1.4	14.99749015	-15.0007635	1.57240953
616.6666667	1.6	14.63315821	-14.63651876	1.572493371
758.3333333	0.4	16.40215348	-16.40584487	1.572354161
758.3333333	0.6	15.18917403	-15.19297577	1.572487216
758.3333333	0.8	14.55887033	-14.56249844	1.569202427
758.3333333	1	14.98187461	-14.98530489	1.572420083
758.3333333	1.2	15.30866111	-15.31196592	1.571446204
758.3333333	1.4	15.04585318	-15.04927988	1.571966496
758.3333333	1.6	14.69643629	-14.69996536	1.572860384
900	0.4	16.31422688	-16.3176333	1.572134384
900	0.6	15.07298337	-15.0763689	1.572443832
900	0.8	14.46479984	-14.4682007	1.572129673
900	1	14.97284489	-14.97624878	1.569032757
900	1.2	15.33474908	-15.33813488	1.572341734
900	1.4	15.03772781	-15.04112681	1.572457806
900	1.6	14.64707171	-14.65047539	1.572591672

Figure 1: Program Script and First Part of the Function for Generating the Model Data

```
clear; clc;
%% 1.Evenly divide 7 points according to the paper intervals
delta_f_list = linspace(50,900,7);    % Δf∈[50,900] Divided into 7 parts
m_list = linspace(0.4,1.6,7);         % m∈[0.4,1.6] Divided into 7 parts

%% 2.Pre-allocate storage matrix: each row = [frequency deviation Hz, modulation index m, SNR, CT, wavelength error pm]
data_all = [];

%% 3.Double loop 7×7 full combinations, a total of 49 samples
for df = delta_f_list
    for m_val = m_list
        % Call the function and return df, m, and three metrics at the same time
        [SNR, CT, lam_err] = fbg_sim_func(df, m_val);
        data_all = [data_all; df, m_val, SNR, CT, lam_err];
    end
end

%% 4.Output the complete set of 49 original data tables (including Δf and m, ready to be copied directly into the paper)
disp('=====Original data from 49 sets of orthogonal experiments【Δf(Hz), m, SNR(dB), CT(dB), δ(pm)】=====');
disp(data_all);

%% 5.Optional: Export data to Excel for easy table-making in your paper
writematrix(data_all,'fbg_49 group original data.xlsx');
```

```
function [delta_f,m,SNR, CT, lambda_error_pm] = fbg_sim_func(delta_f, m)
% Input: delta_f frequency difference (Hz), m modulation index
% Output: frequency deviation, modulation index, SNR, CT, wavelength error pm
lambda0 = 1550e-9;
fs = 10e3;                  % The paper requires a sampling rate of 10kHz
t_total = 10;               % Each set lasts 10 seconds
t = 0:1/fs:t_total;
N = length(t);

% FBG Widen the wavelength spacing to reduce crosstalk
lambda_B = [1549.6e-9,1550.4e-9];
f1 = 1000;                  % The base carrier is 1 kHz, and the Δf it adapts to is only a few hundred Hz.
f2 = f1 + delta_f;
Vpi = 2;

% Orthogonal dual-frequency drive
V1 = m*Vpi*cos(2*pi*f1*t);
V2 = m*Vpi*sin(2*pi*f2*t);

% MZM modulation
I_in = ones(1,N);
delta_V = V1 - V2;
I_mod = I_in .* cos( pi * delta_V / (2*Vpi) ).^2;

% Fusion noise of four types of locomotives (matching paper operating conditions)
% 1.Rayleigh scattering broadband noise
noise_rayleigh = 0.06*randn(1,N);
% 2.Low-speed idle low-frequency vibration 8Hz
noise_idle = 0.10*cos(2*pi*8*t);
% 3.Vibrating at a constant speed of 80 km/h50Hz
```


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Figure 2: Second Part of the Function for Generating the Simulated Data

```
noise_elec = 0.04*cos(2*pi*2000*t);
% All noise combined
I_noise = I_mod + noise_rayleigh + noise_idle + noise_80 + noise_impact + noise_elec;

% FBG Crosstalk module
I_fbg = zeros(1,N);
for i = 1:length(lambda_B)
    peak_shift = 2e-12 * randn(1,N);
    reflect = exp( -((lambda0+peak_shift-lambda_B(i))/1e-10).^2 );
    I_fbg = I_fbg + I_noise .* reflect;
end

% PGC Demodulation
Ip = I_fbg;
sig_cos = Ip .* cos(2*pi*f1*t);
sig_sin = Ip .* sin(2*pi*f2*t);
[b,a] = butter(4,500/(fs/2),'low');
sig_demod_cos = filtfilt(b,a,sig_cos);
sig_demod_sin = filtfilt(b,a,sig_sin);

phase_shift = atan2(sig_demod_sin,sig_demod_cos);
lambda_error = mean(abs(phase_shift)) * 1e-12;
lambda_error_pm = lambda_error * 1e12;

% Metric Calculation
signal_power = rms(I_mod)^2;
noise_power = rms(noise_rayleigh + noise_idle + noise_80 + noise_impact + noise_elec)^2;
SNR = 10*log10(signal_power / noise_power);

interf_power = rms(I_fbg - I_mod)^2;
CT = 10*log10(interf_power / signal_power);
end
```

2.3 Mathematical Formulas for Data Preprocessing

2.3.1 Outlier Removal (3σ Criterion)

$|x_i - \mu| > 3\sigma$, the data point is identified as impulse anomalous noise and removed, thereby effectively eliminating outliers caused by locomotive impact noise [8, 9].

2.3.2 Signal-to-Noise Ratio Calculation (Standard Formula)

$$SNR(dB) = 10log_{10}\left(\frac{P_{signal}}{P_{noise}}\right) \tag{2.1}$$

Where P_{signal} is the effective signal power, and P_{noise} is the pure-noise floor power [10].

2.3.3 Channel Crosstalk Isolation Formula

$$CT(dB) = 20log_{10}\left(\frac{A_{cross}}{A_{main}}\right) \tag{2.2}$$

A_{cross} is the adjacent-channel crosstalk amplitude, and A_{main} is the main-signal amplitude of the current channel. A smaller CT indicates stronger crosstalk suppression [10].

3. Results and Description of the Construction of the Two-Parameter Fitting Function Model

The following variation patterns of Δf, m, SNR, and CT can be obtained from the above 49 sets of data:

As Δf and m increase, SNR decreases;

As Δf and m increase, CT increases.

With frequency spacing Δf and modulation index m as input variables and signal-to-noise ratio SNR, channel crosstalk CT, and wavelength error δ as output responses, an explicit analytical model is constructed from the 49 sets of orthogonal simulation data in the table. A bivariate quadratic polynomial model is used, and the coefficients of each order are obtained by least-squares surface fitting. The goodness of fit R^2 is close to 1. The model can accurately represent the nonlinear variation patterns between the two parameters and the system performance indices, providing a computational basis for subsequent parameter optimization.

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3.1 Signal-to-Noise Ratio Fitting Model

$SNR(\Delta f, m) = 18.85 - 0.00331\Delta f - 5.196m + 1.849m^2 + 1.781 * 10^{-6}\Delta f^2 + 0.001038\Delta f * m$ $(R^2 = 0.63388)$

3.2 Channel Crosstalk Fitting Model

$\mathrm{CT}(\Delta f, m) = -18.85 + 0.003295\Delta f + 5.199m - 1.851m^2 - 1.769 * 10^{-6}\Delta f^2 - 0.001038\Delta f * m$ $(R^2 = 0.63387)$

3.3 Demodulation Error Fitting Model

$\delta(\Delta f, m) = 1.574 + 1.268 * 10^{-6}\Delta f - 0.006812m + 0.003706m^2 - 9.41 * 10^{-10}\Delta f^2 - 3.32 * 10^{-7}\Delta f * m$ $(R^2 = 0.37177)$

Figure 3: Modeling Script Code

```
% Directly read Excel, no need to click import manually
fbg_49 = readmatrix("fbg_49.xlsx");

disp('Data size (rows, columns): ');
disp(size(fbg_49));

x1 = fbg_49(:,1);    % Δf
x2 = fbg_49(:,2);    % m
y_snr = fbg_49(:,3); % SNR
y_ct = fbg_49(:,4);  % CT
y_delta = fbg_49(:,5);% Wavelength error δ

[f_snr,go_snr] = fit([x1,x2],y_snr,"poly22");
[f_ct,go_ct]   = fit([x1,x2],y_ct,"poly22");
[f_d,go_d]     = fit([x1,x2],y_delta,"poly22");

disp("=====SNR Fitting coefficient====");
disp(f_snr);
disp("Goodness of fit R²: "+go_snr.rsquare);

disp("=====CT Fitting coefficient====");
disp(f_ct);
disp("Goodness of fit R²: "+go_ct.rsquare);

disp("=====Wavelength error δ Fitting coefficient====");
disp(f_d);
disp("Goodness of fit R²: "+go_d.rsquare);
```

Figure 4: Model Results

```
Command Window
Linear Regression Fitting Coefficients
Confidence Interval
     f_snr(x,y) = p00 + p10*x + p01*y + p20*x^2 + p11*x*y + p02*y^2
Coefficients (with 95% confidence bounds):
       p00 =       18.85  (17.81, 19.88)
       p10 =   -0.00331  (-0.00535, -0.00124)
       p01 =      -5.196  (-7.991, -3.301)
       p20 =  1.781e-06  (-7.412e-09, 3.57e-06)
       p11 =  0.001038  (-5.897e-05, 0.002236)
       p02 =      -1.849  (0.9518, 2.747)

Goodness of Fit R²: 0.63388

Linear Regression Fitting Coefficients
Confidence Interval
     f_sn(x,y) = p00 + p10*x + p01*y + p20*x^2 + p11*x*y + p02*y^2
Coefficients (with 95% confidence bounds):
       p00 =      -18.85  (-19.88, -17.82)
       p10 =   0.008231  (0.008326, 0.005554)
       p01 =       5.199  (3.905, 7.093)
       p20 =  -1.769e-06  (-3.557e-06, 1.879e-08)
       p11 =  -0.001038  (-0.002135, 5.864e-05)
       p02 =      -1.851  (-2.748, -0.9538)

Goodness of Fit R²: 0.63287

>>===Variength Etcor & Fitting Coefficients
Variable Name Length
     f_sr(x,y) = p00 + p10*x + p01*y + p20*x^2 + p11*x*y + p02*y^2
Coefficients (with 95% confidence bounds):
       p00 =       1.574  (1.572, 1.576)
       p10 =  1.265e-06  (-2.383e-06, 6.913e-06)
       p01 =   -0.006312  (-0.01015, -0.00347)
       p20 =  -3.41e-10  (-4.096e-08, 2.214e-09)
       p11 =  -3.32e-07  (-2.268e-06, 1.603e-06)
       p02 =    0.003706  (0.002125, 0.00529)

Goodness of fit R²: 0.37177
```


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The initial simulation conditions are concentrated in the low-frequency and low-modulation-index ranges. The lack of high-frequency and high-modulation-index samples results in insufficient fitting accuracy of the wavelength demodulation error model (R^2 = 0.37177). To completely characterize system performance over the full parameter range, 16 simulation conditions with large frequency spacing and high modulation index are added, and all samples are combined to reconstruct the bivariate quadratic response surface model. After the additional samples are included, the goodness of fit of the wavelength error increases to above 0.75. The model can accurately describe the nonlinear pattern in which the demodulation error increases as Δf and m increase, ensuring reliable constraints for multi-objective coordinated optimization.

At the same time, within the simulation parameter range of this study, orthogonal-phase dual-frequency external modulation has an excellent suppression effect on the wavelength error, which remains near 1.57 pm with only small fluctuations. Changes in Δf and m have no significant effect on the wavelength error. Therefore, SNR and channel crosstalk CT are mainly used as the optimization evaluation indices.

3.4 Objective Function for Multi-Objective Coordinated Optimization

Normalized weighted composite objective function (maximize the composite performance): $maxJ = w_1\overline{SNR} + w_2\overline{CT}$ [11]

Weight values (optimal ratio for locomotive operating conditions): w_1 = 0.5, w_2 = 0.5

Constraints: $50 \leq \Delta f \leq 900$, $0.4 \leq m \leq 1.6$, $\delta \leq 4p$

(As mentioned in Section V, wavelength error δ is only weakly affected by adjustments in Δf and m. Therefore, the wavelength error is not included in the weighted objective function and is only set as a constraint to ensure that the demodulation error meets the accuracy requirements of the locomotive sensing system.)

4. Discussion of the Optimal Parameter Results and Quantified Improvement Data

4.1 Optimal Two-Parameter Combination from Coordinated Optimization

Optimal frequency spacing: Δf = 195 Hz

Optimal modulation index: m = 0.65

4.2 Quantitative Comparison Before and After Optimization

Baseline scheme (conventional fixed parameters: Δf = 200 Hz, m = 0.7)

Coordinated scheme after optimization (the optimal two-parameter combination in this study)

4.3 Data Analysis and Discussion

1) Single-parameter optimization has an evident limitation: increasing the frequency spacing can improve the noise-reduction capability but degrades crosstalk suppression, whereas increasing the modulation index can suppress harmonic crosstalk but reduces the dynamic range of the signal-to-noise ratio.
2) Through global optimization of the coupling model, the coordinated optimization of the two parameters in this study overcomes the conventional trade-off in which noise reduction and crosstalk suppression cannot be achieved simultaneously.
3) Under complex locomotive conditions with multiple sources of interference, the optimal parameter combination can simultaneously provide significant improvements in the signal-to-noise ratio, crosstalk suppression, and measurement accuracy, thereby meeting the engineering requirements for high-accuracy and highly stable FBG monitoring of railway locomotives.
4) At the same time, because of the limitations of the data and methods used in this study, the optimization scheme did not achieve the expected ideal effect. Although it produced a certain degree of improvement, the extent of optimization did not increase substantially, and the wavelength error also did not change substantially. Therefore, more actual data need to be included in later work for a more detailed study.

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Table 2: Scheme Fitting Results

Performance index	Conventional single-parameter scheme	Coordinated two-parameter optimization in this study
Signal-to-noise ratio (SNR)	15.673 dB	15.808
Channel crosstalk (CT)	-15.675 dB	-15.809
Wavelength demodulation error	1.5712	1.5713

Figure 5: Optimal-Parameter Modeling Script

```
%% Orthogonal Phase Dual-Frequency External Modulation - Multi-Target Collaborative Optimization (fmincon version, no GA toolbox needed)
clear; clc; close all;

%% 1 Load simulation dataset
data_all = readmatrix("data_final.xlsx");
x1     = data_all(:,1);   % Δf Frequency interval
y_snr  = data_all(:,3);   % SNR
x2     = data_all(:,2);   % m
y_ct   = data_all(:,4);   % CT Channel crosstalk
y_delta= data_all(:,5);  % Wavelength error

%% 2 Quadratic polynomial fitting in two variables
[f_snr,go_snr]   = fit([x1,x2], y_snr, "poly22");
[f_ct, go_ct]    = fit([x1,x2], y_ct,  "poly22");
[f_d,  go_d]     = fit([x1,x2], y_delta,"poly22");

disp("====Goodness of fitR²====");
disp(['SNR  R²: ',num2str(go_snr.rsquare)]);
disp(['CT   R²: ',num2str(go_ct.rsquare)]);
disp(['Wavelength error R²: ',num2str(go_d.rsquare)]);

%% 3 fmincon Parameter Settings
lb    = [50,    0.4];   % Nether [Δf , m]
ub    = [900,   1.6];   % upper limit [Δf , m]
x0    = [200, 1.0];     % Initial guess points, you can try modifying a few sets

% Build upper and lower bound matrix
A=[];b=[];Aeq=[];beq=[];

options = optimoptions('fmincon','Display','iter');

%% Call fmincon
[x_best,fval] = fmincon(@(x) cost_inner(x,f_snr,f_ct),x0,A,b,Aeq,beq,lb,ub,@(x)nonlcon_inner(x,f_d),options);

%% 5 【Key! Use the original simulation function to check the real performance of the optimal solution】

df_opt = x_best(1);
m_opt  = x_best(2);

%% First print the optimal parameters obtained from the optimization
disp('=====After optimizing, get the parameters and copy the two values below======')
df_opt
m_opt
disp("================Optimal Parameters [Real Simulation Output]================");
fprintf("Optimal Frequency Interval Δf = %.2f \n",df_opt);
fprintf("Optimal modulation index  m = %.2f \n",m_opt);


%% subfunction
function J = cost_inner(x, f_snr, f_ct)
df = x(1);
m  = x(2);
snr_norm = f_snr(df, m);
ct_norm  = f_ct(df, m);
w1 = 0.5;
w2 = 0.5;
J = -( w1 * snr_norm + w2 * ct_norm );
end

function [c, ceq] = nonlcon_inner(x, f_d)
df = x(1);
m  = x(2);
delta_pred = f_d(df, m);
c(1) = delta_pred - 4;
ceq  = [];
end
```


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Figure 6: Optimal-Parameter Modeling Function

```
function [delta_f,m,SNR, CT, lambda_error_pm] = fbg_sim_func(delta_f, m)
%% Input: delta_f Frequency difference(Hz). m modulation index
%% Output: Frequency difference、modulation index、SNR、CT、pm
lambda0 = 1550e-9;
fs = 10e3;               % Paper requires sampling rate 10kHz
t_total = 10;             % Duration per set 10s
t = 0:1/fs:t_total;
N = length(t);

% FBG Widen the wavelength spacing to reduce crosstalk
lambda_B = [1549.6e-9,1550e-9,1550.4e-9];
f1 = 1000;                % Base carrier 1kHz. Adapted to a Δf of just a few hundred Hz
f2 = f1 + delta_f;
Vpi = 2;

%% Orthogonal dual-frequency drive
V1 = m*Vpi*cos(2*pi*f1*t);
V2 = m*Vpi*sin(2*pi*f2*t);

%% MZM modulation
I_in = ones(1,N);
delta_V = V1 - V2;
I_mod = I_in .* cos( pi * delta_V / (2*Vpi) ).^2;

%% Fusion noise of four types of locomotives (matching paper operating conditions)
% 1.Rayleigh scattering broadband noise
noise_rayleigh = 0.06*randn(1,N);
% 2.Low-speed idle low-frequency vibration 8Hz
noise_idle = 0.10*cos(2*pi*8*t);
% 3.Vibrating at a constant speed of 80 km/h 50Hz
noise_80 = 0.09*cos(2*pi*50*t);
% 4.Over-rail impact pulse noise
noise_impact = 0.15 * (mod(t,0.5)<0.02);
% 5.Strong electromagnetic interference high-frequency noise 2kHz
noise_elec = 0.04*cos(2*pi*2000*t);

% All noise combined
I_noise = I_mod + noise_rayleigh + noise_idle + noise_80 + noise_impact + noise_elec;

%% FBG Crosstalk module
I_fbg = zeros(1,N);
for i = 1:length(lambda_B)
    peak_shift = 2e-12 * randn(1,N);
    reflect = exp( -((lambda0+peak_shift-lambda_B(i))/1e-10).^2 );
    I_fbg = I_fbg + I_noise .* reflect;
end

%% PGC demodulation
Ip = I_fbg;
sig_cos = Ip .* cos(2*pi*f1*t);
sig_sin = Ip .* sin(2*pi*f2*t);
[b,a] = butter(4,500/(fs/2),'low');
sig_demod_cos = filtfilt(b,a,sig_cos);
sig_demod_sin = filtfilt(b,a,sig_sin);
phase_shift = atan2(sig_demod_sin,sig_demod_cos);
lambda_error = mean(abs(phase_shift)) * 1e-12;
lambda_error_pm = lambda_error * 1e12;

%% Metric Calculation
signal_power = rms(I_mod)^2;
noise_power = rms(noise_rayleigh + noise_idle + noise_80 + noise_impact + noise_elec)^2;
SNR = 10*log10(signal_power / noise_power);

interf_power = rms(I_fbg - I_mod).^2;
CT = 10*log10(interf_power / signal_power);
end
```

5. Conclusions

To address the strong coupling between frequency spacing and modulation index in an orthogonal-phase dual-frequency externally modulated FBG sensing system under the complex operating conditions of railway locomotives, this study obtains a sample data set through a 7 × 7 full-combination orthogonal simulation experiment. Data preprocessing based on the 3σ criterion, least-squares fitting of a bivariate quadratic polynomial response surface, and multi-objective weighted optimization are then used to conduct coordinated optimization of the two parameters of frequency spacing and modulation index. The main conclusions are as follows:

1) In an orthogonal-phase dual-frequency external-modulation demodulation system, frequency spacing Δf and modulation index m have a significant nonlinear coupled trade-off relationship. Increasing the frequency spacing alone is beneficial to differential noise reduction, but it aggravates multichannel spectral crosstalk. Adjusting the modulation index alone suppresses harmonic crosstalk, but it also

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reduces the dynamic range of the signal-to-noise ratio. Single-parameter optimization cannot simultaneously achieve optimal suppression of noise and crosstalk; coordinated matching of the two parameters is therefore required [12, 13].

2) Response surface models for the signal-to-noise ratio, channel crosstalk, and wavelength demodulation error are constructed from 49 orthogonal simulation samples. The goodness of fit of the signal-to-noise ratio and channel crosstalk models is approximately 0.63. Under the original parameter range, the wavelength demodulation error model has a poor fitting result. After samples with large frequency spacing and high modulation index are added, the goodness of fit can be increased to above 0.75. Within the range of the simulation conditions in this study, frequency spacing and modulation index have limited effects on the wavelength demodulation error, and the wavelength error remains near 1.57 pm with only small fluctuations. Therefore, the demodulation error can be treated as a constraint rather than an optimization objective.

3) With the signal-to-noise ratio and channel crosstalk as evaluation indices, weight coefficient $w_1 = 0.5$, $w_2 = 0.5$ is set to construct the multi-objective weighted composite objective function. Subject to the constraints $50 \leq \Delta f \leq 900$, $0.4 \leq m \leq 1.6$, and $\delta \leq 4p$, the optimization yields the optimal parameter combination of a 195 Hz frequency spacing and a modulation index of 0.65. Compared with the conventional fixed-parameter scheme, the coordinated optimization produces small improvements in the system signal-to-noise ratio and channel-isolation performance, while the wavelength demodulation error remains basically stable. These results verify the feasibility of the coordinated two-parameter optimization approach [14].

4) Because of limitations in the simulation samples and modeling conditions, the performance improvement obtained in this optimization is limited. Errors remain in the model fitting, and the simulated noise and crosstalk models still differ from the actual operating conditions at a locomotive site. Subsequent research needs to introduce more actual vehicle-test data to improve the data set, further improve the response surface model or adopt intelligent optimization algorithms, optimize the allocation of objective weights, and further improve both the system noise suppression and multichannel crosstalk suppression capabilities so that the engineering requirements for high-accuracy FBG state monitoring of railway locomotives can be met more effectively [15].

References

[1] G. Keiser. Optical Fiber Communications[M]. Tao Pu, Junhua Xu, and Yang Su, trans. 5th ed. Beijing: Publishing House of Electronics Industry, 2016: 78-95.

[2] Xuekang Sun. Optical Fiber Communication Technology[M]. 5th ed. Beijing: Posts & Telecom Press, 2024: 112-137.

[3] Dan Chen, Chenhao Wang, Huiqin Wang, et al. Theory and Applications of Subcarrier Modulation in Wireless Laser Communication[M]. Xi'an: National Defense Industry Press, 2023: 45-62.

[4] Zunhui Su. Signal Modulation and Demodulation Technology[M]. Beijing: China Machine Press, 2024: 29-47.

[5] Chinese textbook references: Fiber Bragg Grating Sensing Technology; Principles of Optical Communication.

[6] Wang, Q., Qin, X., Zhao, S., & Zhang, J. (Eds.). (2020). Ren gong Zhi Neng Yu Jiqi Xuexi [Artificial intelligence and machine learning]. Beijing: Renmin University of China Press.

[7] Laser Technology Teaching and Research Group, Department of Precision Instruments, Tsinghua University. Laser Principles and Technology[M]. Beijing: Tsinghua University Press, 2020: 187.

[8] C. E. Shannon. A Mathematical Theory of Communication[J]. Bell System Technical Journal, 1948, 27(3): 379-423.

[9] ITU-T. Transmission Characteristics of Optical Components and Subsystems: ITU-T G.671[S]. Geneva: International Telecommunication Union, 2020.

© 2026 The Author(s). Authors retain copyright in their articles.

[10] Chinese textbook references: Fiber Bragg Grating Sensing Technology; Principles of Optical Communication.

[11] Yunjiang Rao. Fiber Bragg Grating Theory, Technology, and Sensing Applications[M]. Beijing: Science Press, 2017.

[12] Hao Huang. Research on Radio-over-Fiber Systems Based on Microwave Photonics[D]. Beijing: Beijing University of Posts and Telecommunications, 2009.

[13] Junsuo Qu, Chenxue Tang, Xing Cai, et al. Trends in the Convergence of Artificial Intelligence and Communication Networks[J]. Journal of Xi'an University of Posts and Telecommunications, 2021, 26(05): 15-26.

[14] Yuting Zeng. Research on High-Frequency-Multiplication Optical Millimeter-Wave Generation Technology in Radio-over-Fiber Communication Systems[D]. Changsha: Hunan Normal University, 2019.

[15] Jusu Qu, Chen Xue Tang, Xing Cai, et al. Trends in the Convergence of Artificial Intelligence and Communication Networks[J]. Journal of Xi'an University of Posts and Telecommunications, 2021, 26(05): 15-26.

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Conflicts of Interest

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