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Posted Date: 5 November 2025

doi: 10.20944/preprints202511.0285.v1

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Article

Enhancing Robustness in Photoacoustic Detection of Dissolved Acetylene in Transformer Oil: Temperature Effects on Resonance Frequency and Suppression Using Perturbation-Observation Method

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Abstract

Photoacoustic spectroscopy is a promising method for detecting dissolved acetylene (C₂H₂) in transformer oil, facilitating early fault diagnosis in power transformers. However, temperature variations significantly influence the resonance frequency of the photoacoustic cell, potentially reducing detection accuracy. This study investigates the temperature effects on the first-order longitudinal acoustic mode of a resonant photoacoustic cell using finite element simulations with thermo-viscous acoustics. Results show that as the temperature increases, the resonant frequency increases linearly and the sound pressure amplitude decreases, consistent with analytical models. To enhance system robustness, a perturbation-observation method is proposed, treating operating frequency as the independent variable and acoustic pressure as the dependent variable. Time-domain simulations validate its effectiveness in tracking resonance frequency shifts under varying temperatures, ensuring reliable detection. Future work should focus on improving frequency resolution, noise filtering, and adaptive step-size optimization for practical applications.

Keywords: photoacoustic spectroscopy; dissolved acetylene; resonance frequency; temperature effects; perturbation-observation method

1. Introduction

Power transformers are critical components in electrical grids, and their reliable operation is essential for maintaining energy supply stability. Internal faults, such as partial discharges or overheating, can lead to the decomposition of insulating oil, generating dissolved gases like acetylene (C₂H₂), which serves as a key indicator of incipient failures [1–3]. Early detection of these gases enables preventive maintenance, reducing downtime and preventing catastrophic breakdowns [4]. Among various detection techniques, photoacoustic spectroscopy (PAS) has emerged as a promising method due to its high sensitivity, non-invasiveness, and ability to perform in-situ measurements [5–8]. In PAS, infrared laser light modulated at a specific frequency excites gas molecules, inducing periodic heating and subsequent acoustic waves that are detected in a resonant photoacoustic cell.

However, the performance of resonant PAS systems is highly susceptible to environmental variations, particularly temperature fluctuations. Temperature changes alter the speed of sound and dynamic viscosity of the gas medium within the photoacoustic cell, causing shifts in the resonance frequency and reductions in signal amplitude [9–12]. Such drifts can degrade detection accuracy, leading to false negatives or positives in acetylene monitoring, especially in field applications where

transformers operate under varying ambient conditions [13–16]. Previous studies have quantified these effects through simulations and experiments, revealing linear frequency shifts of approximately 3 Hz per °C near room temperature [17]. Despite these insights, effective suppression strategies remain underexplored, limiting the robustness of PAS for real-time transformer health monitoring [18–20].

This paper addresses the temperature-induced challenges in PAS detection of dissolved acetylene in transformer oil by investigating the impact on photoacoustic cell resonance frequency and proposing a perturbation-observation method for suppression. Through finite element simulations using COMSOL, we model the frequency response under temperatures ranging from 0°C to 40°C, deriving analytical relationships for frequency shifts and amplitude variations. We then introduce a perturbation-observation algorithm that dynamically tracks the resonance frequency by applying small frequency perturbations and observing signal changes, ensuring optimal operation amid temperature variations. Simulation results in Simulink validate the method's efficacy in achieving rapid convergence to the resonance peak.

The remainder of this paper is organized as follows: Section 2 details the theoretical analysis and simulation of temperature effects on resonance frequency. Section 3 presents the perturbation-observation suppression method and its implementation. Section 4 experimental results. Finally, Section 5 conclusions.

2. Theoretical Analysis and Simulation of Temperature Effects on Resonance Frequency

2.1. Temperature Effects on Resonance Frequency

In resonant photoacoustic cells, operation requires modulating the incident infrared laser's photon frequency at a specific modulation frequency (corresponding to angular frequency ω). When using sinusoidal modulation (as shown in Figure 1a), the photon frequency varies over time as a central frequency $\bar{\nu}$ superimposed with a sinusoidal component:

$$\nu(t) = \bar{\nu} + m\gamma_L \sin(\omega_m t) \quad (1)$$

where γ_L is the half-width at half-maximum of the gas molecule absorption line, and m is the modulation depth.

Under this modulation, if the modulation center $\bar{\nu}$ coincides with the center ν_0 of a gas molecule absorption line, the gas molecules in the photoacoustic cell will periodically absorb energy from the modulated laser, generating heat and exciting acoustic waves through thermo-acoustic coupling. The effective component of these acoustic waves has a frequency $f = 2f_m$ that is twice the modulation frequency f_m , as illustrated in Figure 1b and Figure 1c. These acoustic waves interfere within the photoacoustic cell, eventually forming a stable standing wave distribution.

The photoacoustic cell itself has several acoustic vibration modes, each corresponding to a standing wave pattern and eigenfrequency f_c . When the acoustic excitation source frequency f_a approaches an eigenfrequency f_c , the standing wave in the cell tends to distribute according to the corresponding pattern, resulting in a higher acoustic pressure amplitude P_m . Conversely, when the source frequency f_a deviates from f_c , the acoustic pressure amplitude P_m for that mode decreases.

When the background temperature T_0 in the photoacoustic cell changes, the gas sound speed c_0 and dynamic viscosity ν change accordingly. The change in sound speed c_0 causes a shift in the eigenfrequency f_c , while the change in dynamic viscosity ν affects the peak height of the response, causing the overall frequency response curve of the photoacoustic cell to shift, as shown in Figure 1d.

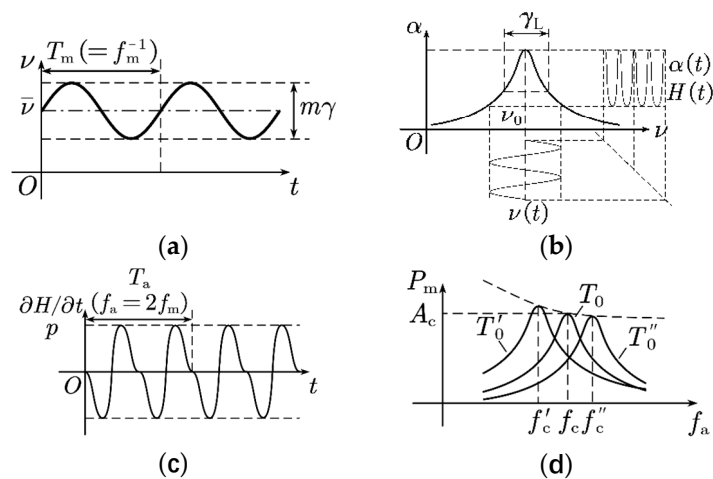


Figure 1. Various physical processes in the photoacoustic cell. (a) Schematic of laser wavelength modulation; (b) Excited heating of gas molecules; (c) Acoustic pressure waveform from thermo-acoustic effect; (d) Frequency shift caused by temperature change.

This subsection aims to use acoustic simulation, under a given geometric shape of the photoacoustic cell, to obtain the eigenfrequency f_c of the first-order longitudinal acoustic vibration mode and the response peak of its frequency response curve A_c as a function of background temperature T_0 . Additionally, it seeks to obtain the frequency response curves of the photoacoustic cell at different background temperatures T_0 .

The geometric model of the photoacoustic cell in this section adopts a single-tube non-differential structure with a microphone cavity. Its geometric schematic and related parameters are shown in Figure 2 and Table 1.

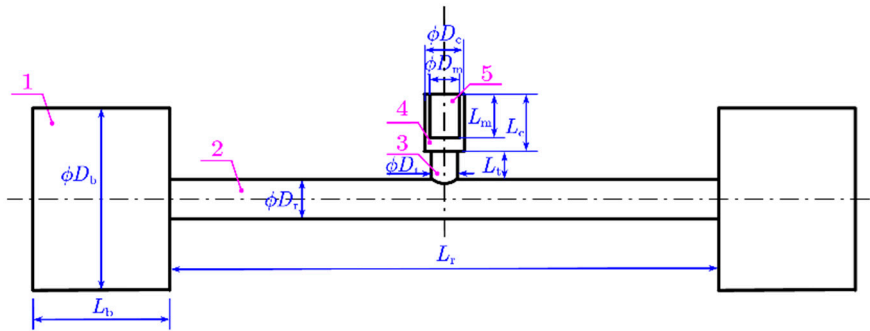


Figure 2. Schematic of microphone cavity geometry. (1—Buffer cavity; 2—Resonance tube; 3—Connection hole; 4—Microphone cavity; 5—Microphone).

Table 1. Geometric parameters of the photoacoustic cell.

Geometric Parameter	Value	Geometric Parameter	Value
D_b	20 mm	L_b	50 mm
D_r	3 mm	L_r	100 mm
D_t	1 mm	L_t	1 mm
D_c	3 mm	L_c	4.3 mm
D_m	2.8 mm	L_m	3.3 mm

2.2. Simulation of Temperature Effects

Under the above geometric configuration, this report uses COMSOL's thermo-viscous acoustics module for simulation. A volumetric heat source H is used to equivalent the laser's effect, with the expression for H as follows:

$$H(r) = A_2 c \frac{\exp(-\frac{r^2}{2\sigma^2})}{2\pi\sigma^2} \quad (2)$$

where A_2 is the second harmonic factor; c is the molar concentration of the gas to be measured; σ is the standard deviation parameter of the Gaussian beam.

This report sets the background temperature T at intervals of 5°C in the $(0-40)^\circ\text{C}$ range [i.e., $(273.15-313.15)$ K] (including endpoints, totaling 9 groups). At each background temperature, frequency-domain simulations are performed with excitation frequencies in the $(1520-1710)$ Hz range, sequentially obtaining the sound pressure distribution in the photoacoustic cell under sinusoidal steady state. The sound pressure at the axial center of the photoacoustic cell is used to measure the strength of the standing wave sound pressure. The response curve of the central sound pressure versus excitation frequency is plotted for each temperature, with the maximum point of the amplitude-frequency response curve at each temperature taken as the eigenfrequency for that temperature. The sound pressure data is normalized by the central sound pressure amplitude at the eigenfrequency under 20°C .

The simulation yields the curves of the photoacoustic cell eigenfrequency f_c and normalized sound pressure amplitude A_c^* as functions of background temperature T_0 , as shown in Figure 3. From the simulation results, it is evident that in the $(0-40)^\circ\text{C}$ temperature range, the eigenfrequency f_c of the photoacoustic cell increases with rising background temperature T_0 , approximately in a linear relationship, with the eigenfrequency increasing by about 2.78 Hz per 1°C rise in background temperature. The sound pressure amplitude p_n in the photoacoustic cell decreases with rising background temperature T_0 .

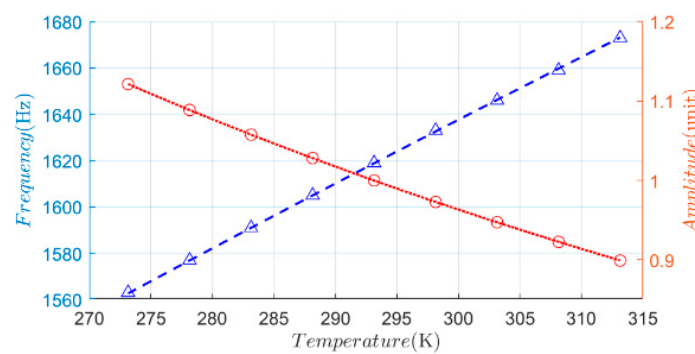


Figure 3. Eigenfrequency/sound pressure amplitude - background temperature curves.

The simulation also yields the amplitude-frequency response curves of the photoacoustic cell at different temperatures, as shown in Figure 4. From the results, it can be seen that as temperature increases, the amplitude-frequency response curve of the photoacoustic cell shifts toward the lower right of the coordinate axis (i.e., higher frequency, lower amplitude); the eigenfrequency points f_c and corresponding sound pressure amplitudes A_c^* are approximately distributed along a straight line.

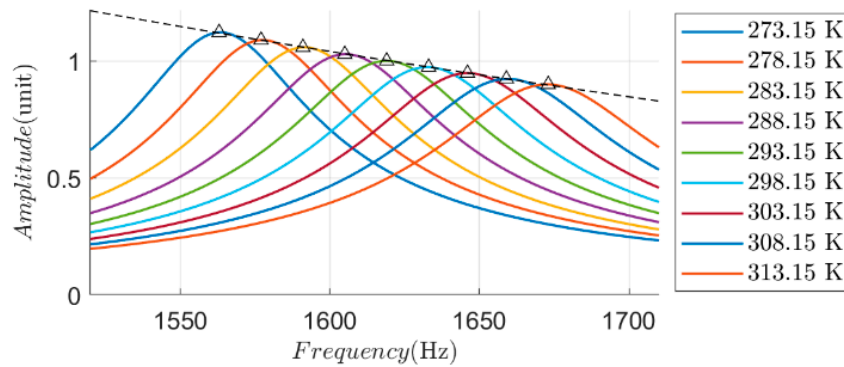


Figure 4. Amplitude-frequency response curves of the photoacoustic cell.

First, discuss the $f_c - T_0$ relationship. When a standing wave forms in the photoacoustic cell according to the first-order longitudinal acoustic vibration mode, the wavelength λ of the acoustic wave is approximately twice the length L_r of the resonance tube:

$$\lambda_c = 2L_r \quad (3)$$

Substituting this into the relationship among wavelength, frequency, and sound speed $\lambda f = c$, the eigenfrequency f_c is obtained:

$$f_c = \frac{c_0}{2L_c} \quad (4)$$

where the sound speed $c_0 = \sqrt{\gamma RT_0 / M}$, substituting into the above equation gives the relationship between f_c and background temperature T_0 :

$$f_c = \frac{1}{2L_r} \sqrt{\frac{\gamma RT_0}{M}} \quad (5)$$

where γ is the specific heat ratio of the gas, generally taken as 1.4 for gases similar to air; R is the universal gas constant, with a value of 8.314 J/(K·mol); M is the average molar mass of the gas, generally taken as 29 g/mol for gases similar to air.

From (5), it is evident that the resonance frequency f_c of the photoacoustic cell is proportional to the $\sqrt{T_0}$:

$$f_c = \alpha K \sqrt{T_0} \approx \alpha f_{c0} \left(1 + \frac{1}{2} \frac{\Delta T}{T_{20^\circ C}}\right) \quad (6)$$

$$K = \frac{1}{2L_r} \sqrt{\frac{\gamma R}{M}}; f_{c0} = K \sqrt{T_{20^\circ C}}$$

where the coefficient α is used to correct for non-ideal boundary conditions introduced by the buffer cavity and the disruption to the cylindrical geometric region caused by introducing the microphone cavity.

The value of coefficient k is calculated as 1715.08 Hz with the given parameters. Using the simulation value at 20°C to calculate the correction coefficient α , it is found to be 0.9440. The correction coefficient is close to 1, indicating that the approximation conditions underlying Equation (6) hold within the selected temperature range; the correction coefficient is slightly less than 1, consistent with the recognition that introducing the microphone cavity increases the resonance volume, slightly reducing the eigenfrequency compared to before introduction.

The eigenfrequencies for the remaining data points are calculated using the computed coefficients and compared with simulation results, with errors shown in Table 2.

Table 2. Errors in eigenfrequency formula.

Temperature/°C	0	5	10	15	20	25	30	35	40
Simulation value/Hz	1562.4	1576.5	1590.6	1604.9	1619.1	1632.7	1646.1	1659.0	1673.2
Formula value/Hz	1563.9	1577.7	1591.5	1605.3	1619.1	1632.9	1646.7	1660.5	1674.3
Error value/Hz	1.5	1.2	0.9	0.4	—	0.2	0.6	1.5	1.1
(Δf / ΔT)sim / (Hz / °C)	2.78				(Δf / ΔT)eq / (Hz / °C)				2.76

From the error calculation results, it is evident that in the (0-40)°C temperature range, the change in the photoacoustic cell eigenfrequency f_c with background temperature T_0 approximately follows a linear relationship, and its slope can be obtained by measuring the eigenfrequency f_{c0} at a certain temperature point T_p and then dividing by $2T_p$. Near room temperature, a 1°C change in background temperature can cause a frequency shift of about 2.8 Hz.

Next, discuss the $A_c^* - T_0$ relationship. When the photoacoustic cell is excited acoustically at the eigenfrequency f_c , if there is no loss in the gas within the cell, the sound pressure amplitude would theoretically be infinite. In other words, the presence of loss terms limits the sound signal amplitude at the resonance point in the photoacoustic cell. It is inferred that the background temperature T_0 affects the sound pressure amplitude A_c^* at the resonance point by influencing the loss terms. From previous studies, the loss in the photoacoustic cell depends on the viscous interaction between gases, and the strength of viscous loss is measured by the dynamic viscosity coefficient μ of the gas. The value of μ for the same gas is affected by its background temperature T_0 , with the relationship given by the Sutherland formula:

$$\mu(T_0) = \mu_p \left(\frac{T_0}{T_p}\right)^{1.5} \left(\frac{T_p + T_B}{T_0 + T_B}\right)$$

(7)

where T_p is a reference temperature, μ_p is the dynamic viscosity coefficient of the gas at that reference temperature; for air, when T_p is 288.15 K, μ_p is 1.7894×10-5 Pa·s; T_B a constant, generally 110.4 K for air.

Intuitively, the larger the loss factor μ , the smaller the sound signal amplitude A_c^* at the resonance point in the photoacoustic cell. Therefore, assume that A_c^* and μ satisfy $A_c^* \propto 1/\mu^r$ relationship:

$$A_c^* = \frac{K_A}{[\mu(T_0)]^r} = K_c^* \left(\frac{T_0 + T_B}{T_0^{1.5}}\right)^r$$

(8)

Using the least squares method to perform regression fitting on the simulation data according to the above equation, the parameters K_c^* and r are obtained. The value of the proportional parameter K_c^* is 192.3, with a 95% confidence interval of [189.7, 195.0]; the power parameter r is 2.086, with a 95% confidence interval of [2.081, 2.092]. The narrow 95% confidence intervals for both parameters, and the power coefficient r close to the integer 2, indicate that the adopted fitting model (8) has a high likelihood of conforming to physical reality.

The normalized amplitude A_c^* of the sound signal in the photoacoustic cell at each temperature is calculated according to model (8) and its fitted coefficients, and compared with simulation values, with errors shown in Table 3.

Table 3. Errors in sound pressure amplitude formula.

Temperature/°C	0	5	10	15	20	25	30	35	40
Simulation value/unit	1.1213	1.0887	1.0577	1.0281	1.0000	0.9729	0.9473	0.9227	0.8991
Formula value/ unit	1.1229	1.0900	1.0587	1.0291	1.0001	0.9739	0.9483	0.9239	0.9005
Error value/unit	0.0016	0.0013	0.0010	0.0010	0.0001	0.0010	0.0010	0.0012	0.0014

From the error results, it is evident that for every 5°C rise in background temperature, the sound pressure at the resonance point attenuates by about 3%. The error between the simulation and formula value is close to 0, verifying that in the (0-40)°C temperature range, the sound pressure amplitude at the resonance point in the photoacoustic cell is approximately inversely proportional to the square of its dynamic viscosity μ .

3. Perturbation-Observation Suppression Method

3.1. Principle of the Perturbation-Observation Method

The perturbation-observation method is an approach for finding an approximate maximum point of a unimodal function. Its implementation is as follows: apply a perturbation amount to the independent variable, observe the change in the dependent variable, and check whether the signs of the perturbation and the change are consistent. If consistent, apply the perturbation amount to the independent variable again; otherwise, apply the perturbation amount in the reverse direction. Repeat the above process until the independent variable converges near the maximum point of the unimodal function. Since the frequency response curve of the photoacoustic cell is unimodal within a certain frequency range, the operating frequency f can be taken as the independent variable, the detected acoustic pressure amplitude P_m as the dependent variable, and a given step size for the operating frequency perturbation. Using the perturbation-observation method, the operating frequency can gradually converge near the resonant frequency of the photoacoustic cell. When the initial setting value of the operating frequency is on the left branch of the frequency response curve, the process of converging to the vicinity of the resonant frequency using the perturbation-observation method is shown in Figure 5.

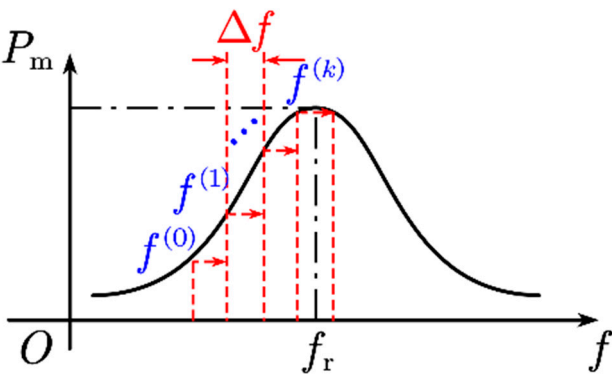


Figure 5. Schematic diagram of resonance point tracking using the perturbation-observation method. (In the figure, Δf represents the frequency perturbation step size, and $f^{(k)}$ represents the operating frequency after the k -th perturbation is applied.).

During the operation of the photoacoustic cell, the acoustic pressure is measured by a microphone connected to the center of the photoacoustic cell and converted into a voltage signal. The latter is an AC voltage signal, which requires matching hardware circuits for detection and conversion into a DC signal that reflects its acoustic pressure amplitude. After each frequency perturbation is applied, the gas molecules in the cell need to undergo a certain relaxation time to reach a new steady-state acoustic pressure distribution; at the same time, the detection circuit also requires a certain response time. Therefore, applying the perturbation-observation method for resonance point tracking also requires a matching control timing sequence, as shown in Figure 6.

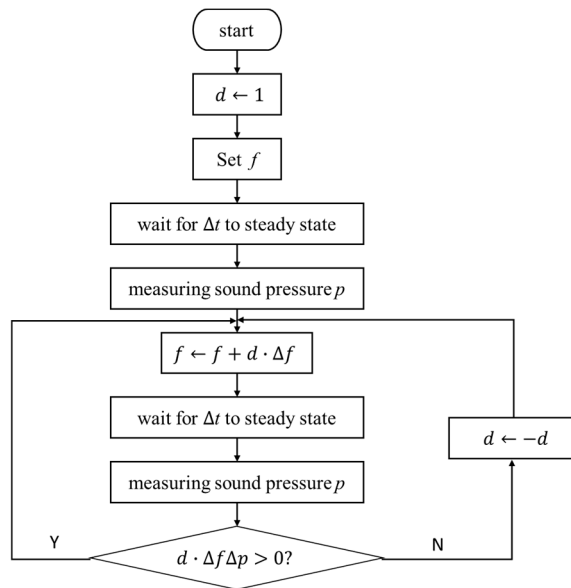


Figure 6. Program block diagram for resonance point tracking using the perturbation-observation method. (In the figure, D is the direction factor, indicating the direction of the applied frequency perturbation.).

3.2. System Modeling and Equivalent Transfer Function

To verify the feasibility of using the perturbation-observation method for resonance point tracking, the physical processes involved in the photoacoustic cell from gas sound generation to microphone measurement of the acoustic signal are equivalent to the block diagram model shown in Figure 7, and time-domain simulation is performed using Simulink.

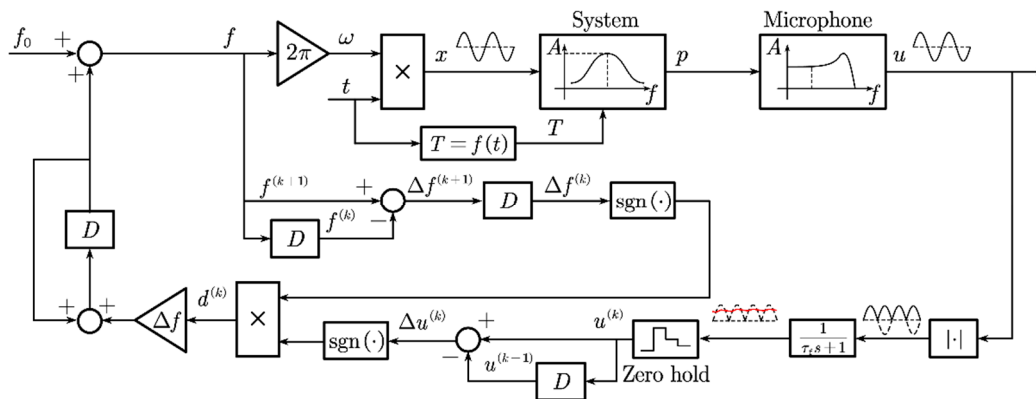


Figure 7. Block diagram model of the photoacoustic cell system. (In the figure, f_0 represents the initial operating frequency; Δf is the frequency perturbation step size; System represents the equivalent frequency-domain model of the photoacoustic cell; Microphone represents the acoustic-to-electric conversion link of the microphone.).

In the block diagram model, the photoacoustic cell is approximated as a link described by a frequency-domain transfer function, and this frequency-domain function varies with the temperature variable T . To describe the unimodal characteristics of the photoacoustic cell, a second-order bandpass transfer function is used for approximation:

$$H(s) = A \frac{2\xi\omega_0}{s^2 + 2\xi\omega_0 s + \omega_0^2} = A \frac{\frac{1}{Q}\omega_0}{s^2 + \frac{1}{Q}\omega_0 s + \omega_0^2} \quad (9)$$

where ω_0 is the system's resonance point; A is the gain at the resonance point; ξ and Q are the system's damping ratio and quality factor, respectively, with the quantitative relationship $Q = 1/(2\xi)$.

Previous studies based on acoustic finite element methods simulated the frequency response curves of the photoacoustic cell between 273.15 K and 313.15 K. This report uses the data at the resonance points and the 3 dB bandwidth to inversely calculate the parameters A , ω_0 , and Q in the equivalent second-order bandpass model of the photoacoustic cell. The parameters calculated according to the frequency response curves of the photoacoustic cell at 273.15 K, 293.15 K, and 313.15 K are shown in Table 4, and the system's amplitude-frequency response curves are shown in Figure 8.

Table 4. Calculated parameters for the approximate second-order bandpass model of the photoacoustic cell.

$T(K)$	273.15	293.15	313.15
$f_0(Hz)$	1562	1619	1673
$A(1)$	1.12	1.00	0.89
$Q(1)$	26.74	24.12	22.74

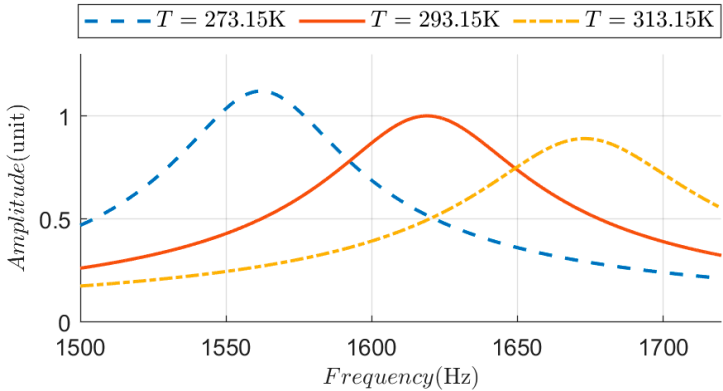


Figure 8. Amplitude-frequency response curves of the approximate second-order bandpass model for the photoacoustic cell.

3.3. Simulation Verification of the Control Method

To verify that the perturbation-observation method can track the resonance point of the photoacoustic cell under changing temperatures, a certain time-varying excitation is set for the temperature. This report adopts a three-stage temperature loading method, with the three stages of temperatures being T_1 , T_2 , and T_3 , each lasting for time t_s . When the temperature set value changes, a negative exponential function with time constant τ_t is used for smooth transition. This loading method is shown in Figure 9.

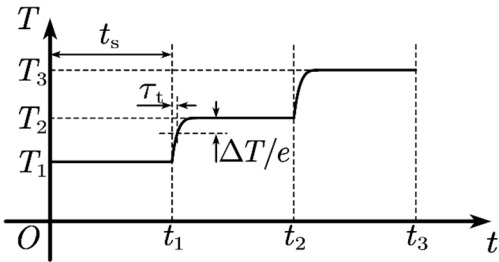


Figure 9. Temperature loading method.

4. Experimental Results

In the Simulink environment, the block diagram model shown in Figure 7 is built in Simulink, with the initial operating frequency f_0 set to 1580 Hz and the frequency perturbation step size Δf set to 1 Hz. The three-stage temperatures are set to 273.15 K, 293.15 K, and 313.15 K, respectively, and the temperature transition time constant τ_t is taken as 2 s. The simulation results show the curves of the photoacoustic cell operating frequency f and acoustic signal P varying with time under the control of the perturbation-observation method, as shown in Figure 10.

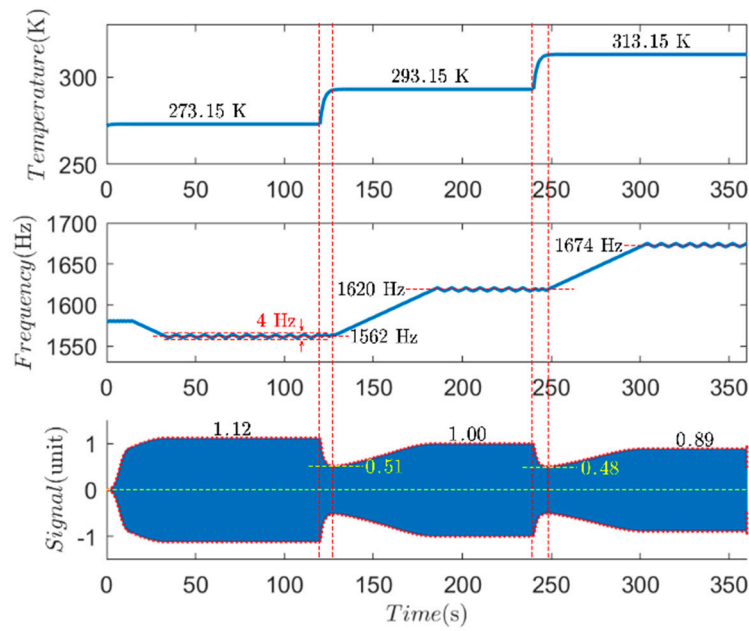


Figure 10. Verification results of the perturbation-observation control strategy.

From the results, it can be observed that the perturbation-observation method achieved the following operating path migration process, as depicted in Figure 11:

- The photoacoustic cell starts from the zero-signal point at 0 and transitions to the operating point 1 corresponding to the initial set frequency at 273.15 K;
- The operating frequency undergoes a negative perturbation, moving the operating point from 1 to the resonance point 2 at 273.15 K, while the operating frequency oscillates around the resonance frequency;
- The temperature changes to 293.15 K, causing the operating point to drop from 2 to point 3 on the amplitude-frequency curve at 293.15 K;
- The operating frequency undergoes a positive perturbation, moving the operating point from 3 to the resonance point 4 at this temperature, and oscillating around it;
- The temperature changes to 313.15 K, causing the operating point to drop from 4 to point 5 on the amplitude-frequency curve at 313.15 K;
- The operating frequency undergoes a positive perturbation, moving the operating point from 5 to the resonance point 6 at this temperature, and oscillating around it.

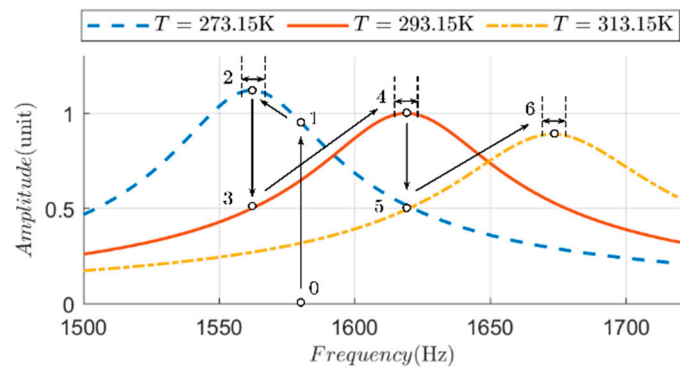


Figure 11. Migration of the photoacoustic cell operating path.

5. Conclusions

The aforementioned results demonstrate that the perturbation-observation method enables automatic tracking of the photoacoustic cell's resonance point in response to temperature variations. However, for this method to be practically implemented, several key challenges must be addressed:

- (1) The frequency resolution of the signal generator controlling laser wavelength modulation imposes a lower limit on the frequency perturbation step length;
- (2) The voltage signal output from the microphone, which measures the acoustic signal, may be overwhelmed by noise, necessitating appropriate filtering of the electrical signal if such interference occurs;
- (3) When the initial frequency deviates significantly from the resonance frequency under operating temperature conditions, a larger frequency perturbation step is desirable to expedite the convergence of the working frequency toward the resonance frequency; conversely, once the working frequency approaches the resonance frequency, a smaller step is preferable to minimize signal fluctuations. Resolving this inherent trade-off requires optimization of the step values based on specific operational scenarios;
- (4) The implementation of perturbation-observation control encompasses multiple physical relaxation processes and transitional phases within the measurement system's circuitry, demanding meticulous tuning of the controller's timing sequence.

Author Contributions: Conceptualization, H.N.; methodology, J.W.; software, X.W.; validation, J.S.; formal analysis, Z.W.; investigation, L.H.; data curation, H.N.; writing—original draft preparation, H.N.; writing—review and editing, Z.W. and J.W.; supervision, Q.Z.; All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by State Grid Corporation of China Science and Technology Project, grant number 520940240010.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare no conflicts of interest. Authors Heli Ni, Xinye Wu and Lin He were employed by State Grid Shanghai Electric Power Research Institute. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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