Vibration characteristic analysis for emulsion droplet excited by chaotic frequency pulsed electric field

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Abstract. In this paper, taking single emulsion droplet as the research object, the vibration characteristics of emulsion droplet in chaotic electric field is explored. The fixed amplitude and equal pulse width chaotic frequency pulsed electric field is constructed by using the Chaotic-Pulse-Position Modulation method, the vibration dynamics model of emulsified oil droplet in chaotic electric field is established, and the chaotic electric field parameters and vibration response of droplet are solved. Results show that the optimal pulse width is 0.009s, the optimal chaotic boundary of pulse electric field frequency is 170 rad/s to 690 rad/s, the droplet is excited into chaotic vibration, and there is resonance. Besides, the droplet vibration in chaotic pulsed electric field is unsteady, but the droplet will enters the steady state vibration from the second same pulse.

1. Introduction
The technology of high voltage pulse electric field demulsification and dewatering is applied in oil exploitation, waste oil recycling and other fields, with the advantages of high efficiency and energy saving [1,2]. A large number of studies have shown that there is an optimal electric field frequency in the pulsed electric field, which drives the droplet resonance and makes the droplet coalescence more efficient [3-5]. However, the droplets size distribution in emulsified oil is large, the commonly used single frequency pulsed electric field cannot meet the optimal condition of all droplets, demulsification frequency, and it is difficult to maximize the effect of pulsed electric field. Liu et al [6] found that the demulsification effect of variable frequency pulsed electric field was better than that of constant frequency pulsed electric field through experiments. Jing et al [7] proposed to apply chaotic pulse field to make all droplets have the opportunity to achieve optimal coalescence by oscillating at their own resonance frequency, which provides inspiration and guidance for the dewatering method of chaotic pulse electric field. This paper use the chaotic mapping theory and nonlinear vibration theory to establish the vibration dynamic model of droplets in oil under the constant amplitude, equal pulse
width and chaotic frequency pulse electric field, explore the vibration dynamic characteristics and provide guidance for the demulsification and dewatering method of chaotic pulse electric field.

2. The vibration dynamic model
The chaotic frequency pulse electric field is constructed by using Chaotic-Pulse-Position-Modulation method [8], and it is the main factor to induce the the chaotic behavior of droplets and the key to study the chaotic electric field vibration of emulsion droplets. Assume all the pulse width is $\tau$ , the amplitude is $E$, the maximum pulse angular frequency is $\omega_{\text{max}}$, and the minimum pulse angular frequency is $\omega_{\text{min}}$, the control range is $\omega_n \in (\omega_{\text{min}}, \omega_{\text{max}})$, the chaotic angular frequency can be expressed as

$$\omega_n = \frac{\omega_{\text{max}} - \omega_{\text{min}}}{(c_i + 1)(\omega_{\text{max}} - \omega_{\text{min}}) / 2 + \omega_{\text{min}}}, n = 1, 2, ...$$

(1)

where $c_i$ is the chaotic value generated by logistic full mapping, $c_n = 1 - 2c^2, n = 1, 2, ..., (c_i \in (-1, 1))$

The constructed electric field can be expressed as

$$E(t) = \begin{cases} E, & 0 \leq t \leq \tau \sum_{j=1}^{n} \frac{2\pi}{\omega_j} \leq t \leq \tau \sum_{j=1}^{n} \frac{2\pi}{\omega_j} \\ 0, & \tau < t < \frac{2\pi}{\omega_j} \sum_{j=1}^{n} \frac{2\pi}{\omega_j} \end{cases}$$

(2)

where $\omega_j$ is the electric field angular frequency of the $i$th iteration, $E$ is the electric field intensity amplitude.

![Figure 1. The principle of chaotic frequency pulsed electric field and Stress the deformation of the right hemisphere of the emulsion droplet.](image)

The vibration of emulsion droplets in chaotic pulse electric field is affected by four forces. These forces are: the chaotic pulse electric field excitation force $F_e$; the resistance of viscous oil $F_r$; the inertia force $F_i$; the interfacial tension of oil-water $F_h$. In the vibration process, the droplet force balance. The force deformation in the right hemisphere of the droplet is shown in figure 1.

Under a certain instantaneous condition, the semi-axis elongation of the droplet is $\delta = a - R$, let $\chi = \frac{\delta}{R}$, the dynamic model expression of the droplet in the oil in the chaotic frequency pulse electric field is [9]

$$\frac{d^2 \chi}{dt^2} + A\varphi(\chi) \frac{d\chi}{dt} + Bf(\chi) = Gc(t)e(\chi)$$

(3)
where \( A = \frac{4\mu}{R^2\rho} \); \( B = \frac{8\lambda}{R^2\rho} \); \( G = \frac{4\varepsilon_0\varepsilon_r E^2}{R^2\rho} \) are the constant of each forced terms; \( \varphi(\chi), f(\chi) \) and \( e(\chi) \) are nonlinear function terms of each forced terms; \( c(t) \) is chaotic signal generating function,

\[
c(t) = \begin{cases} 
1, & 0 \leq t < \tau, \\
1, & \tau \leq t \leq \frac{2\pi}{\omega}, \\
0, & \frac{2\pi}{\omega} < t < \frac{2\pi}{\omega_1}, \\
& \sum_{i=1}^{n} \frac{2\pi}{\omega_i}, \\
& \sum_{i=1}^{n} \frac{2\pi}{\omega_i} + \tau < t < \sum_{i=1}^{n+1} \frac{2\pi}{\omega_i}, \\
& n = 1, 2, \cdots
\end{cases}
\]

3. Chaotic electric field parameters

Setting physical parameters of emulsified oil are as follows: the droplet’s radius is \( R = 0.6 \times 10^{-3} \) m; the viscosity of oil is \( \mu = 47.2 \times 10^{-3} \) Pa·s, the relative dielectric constant is \( \varepsilon_r = 5 \), the interfacial tension of oil-water is \( \gamma = 5 \times 10^{-3} \) N·m⁻¹, and the electric field intensity is \( E = 3 \times 10^5 \) V·m⁻¹, the initial vibration velocity of droplet is \( \chi' = 0 \), the initial vibration displacement is \( \chi_i = 0.0001 \), and the initial chaos value is \( c_i = 0.35 \). the simulation time from 0s to 1s, solving the model by adaptive step Runge-Kutta algorithm ode45.

It is necessary to determine the optimal parameters of the electric field before solving the droplet vibration. Figure 2 shows the vibration response of emulsion droplet in constant current electric field and single pulse electric field. The optimal pulse width is determined as the time for the droplet to reach the maximum deformation, so the pulse width is \( \tau = 0.009 \) s. It can be seen from the response curve of single pulse electric field that the amplitude continues to be 0 when the response time is 0.037 s, Thus minimum pulse period is \( T_{\min} = 0.009 \) s, maximum period \( T_{\max} = 0.037 \) s, the frequency of pulse electric field satisfies the condition: \( \omega \in \left( \frac{2\pi}{T_{\max}}, \frac{2\pi}{T_{\min}} \right) \), thus define \( \omega_{\min} = 170 \) rad·s⁻¹, \( \omega_{\max} = 690 \) rad·s⁻¹.

![Figure 2. The vibration response of emulsion droplet in electric field.](image1)

![Figure 3. Vibration displacement.](image2)
4. Results and analysis

4.1. Dynamic analysis of droplet vibration
The vibration displacement in chaotic pulse electric field is shown in figure 3. It can be seen that the vibration of the droplet is non-periodic, and there is resonance. The vibration phase trajectory [10] is shown in figure 4, it can be seen that the trajectory curve of droplet vibration is infinitely winding, folding and never repeating, it can be judged that the vibration of emulsion droplets in chaotic electric field is chaotic vibration.

![Figure 4. Vibration Phase trajectory.](image1)

![Figure 5. Different initial vibration displacement.](image2)

4.2. Influence of initial vibration value
The frequency in the pulsed electric field is chaotic, the electric field can be regarded as composed of several single pulses with the same amplitude and pulse width. When the vibration state of the droplet reaches the corresponding value after the action of the previous pulse, it becomes the initial value of the latter pulse, that is to say, the vibration state of the droplet is different when the single pulse starts to act, and the vibration has not yet reached the steady state. Therefore, it is necessary to study the vibration state of the droplet under different initial conditions.

The vibration responses of droplets with different initial vibration displacement in the periodic pulsed electric field with resonant frequency are shown in figure 5. It can be seen that the initial vibration displacement has a great influence on the first amplitude. In addition, the droplet enters into steady vibration from the second period.

5. Conclusion
In this paper, a single droplet chaotic frequency pulse electric field vibration dynamic model is constructed, and the electric field parameters are analyzed and selected. Finally, the model is solved and dynamic analysis is carried out, and the following conclusions are obtained. The chaotic frequency pulse electric field can excite the droplets into chaotic vibration, and there is resonance phenomenon at the optimal electric field parameters. Under the same frequency, the droplet vibration will enter the steady state after the second same pulse. Therefore, in the subsequent study, the chaotic pulse group electric field, each group is composed of two adjacent same pulses, can be used to excite the droplet, so that the electric field has both chaotic and periodic characteristics, which makes the vibration of the droplet can reach the steady state at the resonance frequency, so as to improve the stability of the droplet vibration in the chaotic electric field.
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