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Non-linear vibration of a water drop subjected to high-voltage pulsed electric field in oil: Estimation of stretching deformation and resonance frequency

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HIGHLIGHTS

- Forces acting on a water drop vibrating in a pulsed electric field were analysed.
- Dynamics model of the vibration of the drop was developed.
- Model indicates that the vibration is a non-linear parametric excitation vibration.
- Model predictions were similar to experimental results.
- Vibration waveforms obtained by first-order approximation of the model predictions.

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ABSTRACT

A drop of water subjected to a pulsed electric field in emulsified oil undergoes periodic stretching vibration, which is very effective for promoting the coalescence of the emulsified drops. In this study, the forces that act on a single water drop during its vibration in a pulsed electric field are analysed, and a dynamics model of the vibration of the drop is developed. The expression of the model indicates that the vibration can be described as a non-linear parametric excitation vibration, and comparison of the model predictions with experimental results reveals a good similarity. In addition, a first-order approximation of the predictions of the model is used to obtain the waveforms of the vibration, and the peak of the amplitude–frequency curve reveals the occurrence of resonance. This affords a basis for determining the optimal demulsification frequency of the emulsified oil in the pulsed electric field.

1. Introduction

A high-voltage pulsed electric field is commonly used for the dehydration of crude oil because of the high efficiency and energy-saving that the process affords (Eow and Ghadiri, 2002; Eow et al., 2001; Spielman and Goren, 1970; Colman and Thew, 1980; Lee et al., 2004). A water drop is polarised in the pulsed electric field and vibrates periodically. The vibration, which is referred to as drop vibration, is accompanied by regular stretching deformation of the water drop (Williams, 1989; Eow and Ghadiri, 2003a). If the pulsed electric field, the drop would be completely polarised, and the electrostatic force between different such drops would be very strong, resulting in collision and coalescence of many drops (Eow and Ghadiri, 2003b). This is the primary reason why emulsified oil can be efficiently demulsified and dehydrated by a pulsed electric field.

Many studies have shown that the strength and frequency of the electric field directly affect the vibration of the emulsified drop and the dehydration efficiency (Yan, 1987; Joos and Snaddon, 1985; Rayat and Feyzi, 2011, 2012). There is a particular frequency of a pulsed electric field that optimises the demulsification and dehydration (Eow and Ghadiri, 2003a; Bailes and Larkai, 1982), and the water drops begin to vibrate violently as this frequency is approached (Zhang et al., 2007). However, excessive deformation of the drops causes fracture, which is unfavourable for demulsification (Eow and Ghadiri, 2003b). Zhang et al. (2007) used the linear theory to examine the vibration of an emulsified oil drop exposed to a high-voltage pulsed electric field, and deduced that the optimal demulsification frequency was equal to the natural frequency of the drop. However, some studies have also shown

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that the vibratory forces acting on the emulsified drop were related to the shape of the drop (Gong et al., 2009, 2010; Yang and He, 2011). The vibration of the water drop in a high-voltage pulsed electric field is therefore not linear, and this implies that it would be irrational to solve the drop vibration deformation problem using the linear theory.

In the present study, a non-linear theory is used to investigate the stretching deformation of a water drop exposed to a pulsed electric field. The emphasis is on estimating the stretching deformation and resonance frequency.

2. Model and forces

2.1. Description of vibration

If a single water drop is placed between parallel plate electrodes and high-voltage pulses are applied to the electrodes, the drop would be polarised by the high-level pulse, and then stretched and deformed by the polarisation electrostatic force. The drop takes on a nearly prolate spheroid shape during the stretching. When the pulse falls to a low level, the drop recovers its initial spherical shape by the action of a restoring force. It is then stretched again when the next high-level pulse is released. The drop thus undergoes periodic stretching vibration in the pulsed electric field.

2.2. Forces acting on vibrating drop

This work is mainly on the base of the forces, obtained by Zhang et al. (2007) and Gong et al. (2009), (2010), acting on vibrating drop and the following assumptions are made: (i) The water drop is initially a sphere of radius R; (ii) The drop takes on a prolate spherical shape during the deformation, and the geometric centre remains almost unchanged; (iii) The volume of the drop is unchanged; (iv) The drop does not rotate during the deformation; (v) The effect of gravity is neglect and the fluid is incompressible.

Considering that the stretching deformation of the drop is symmetrical, comprising the deformation of two hemispheres, the right hemisphere is investigated. The geometric centre of the drop is used as the origin of the coordinates. Assuming that the major and minor semi-axes of the drop are a and b during a transient vibration, the deformation velocities are denoted by $\dot{a}$ and$\dot{b}$, respectively. The Cartesian coordinate system is shown in Fig. 1. At this moment, the drop is under the action of the inertial force (F_i), vibration resistance (F_r), restoring force of the vibration (F_h), and the excitation force of the electric field (F_e).

2.2.1. Inertial force of vibration

In Fig. 1, if the right hemisphere of the drop is not deformed, the centre of mass is located at $(0.375R, 0, 0)$. After deformation of the drop, the displacement of the mass centre along the x-axis is $0.375(a-R)$. The inertial force of the drop vibration is therefore as follows (Zhang et al., 2007):

$$F_i = \frac{1}{4}\pi\rho R^4 \frac{d^2\chi}{dt^2} \tag{1}$$

2.2.2. Vibration resistance

During the stretching, the drop is affected by the vertical stress and shear force, which constitute the resistance of the surrounding oil to the vibration (Lamb and You, 1991). The diameter of the drop is very small, and the velocity of the stretching deformation is low; hence, the low-Reynolds-number fluid theory can be used to solve the problem of the vibration resistance (Happel and Brenner, 1983). The external oil flow caused by the deformation of the drop is a symmetrical Stokes flow (Yan, 2002). With the assumption of

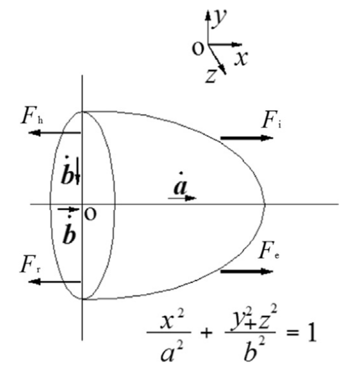

Fig. 1. Forces acting on the right hemisphere of a prolate spherical drop at an instance during its vibration. The major and minor semi-axes of the prolate spherical drop are respectively a and b, and the corresponding deformation velocities are $\dot{a}$ and $\dot{b}$.

ignoring the induced flow circulation inside the drop, the resistance of the surrounding oil to the right hemisphere of the drop is given by (Gong et al., 2009)

$$F_r = \pi\mu(1+\chi)^{-1/2} R^2 K \cdot \frac{d\chi}{dt} \tag{2}$$

where

$$K = -4\left[(1+\chi)^{3/2} - (1+\chi)^{-3/2}\right] \cdot \frac{(\tau_0^2-1)\left[3(\tau_0^3-\tau_0)\left(3\tau_0 \ln\frac{\tau_0^2}{\tau_0^2-1} - 2a\coth\tau_0\right) - 3\tau_0^2+2\right]}{3(\tau_0^3-\tau_0)a\coth\tau_0 - 3\tau_0^2 - 4} \tag{3}$$

and

$$\tau_0 = \left[1-(1+\chi)^{-3}\right]^{-1/2} \tag{4}$$

2.2.3. Restoring force of vibration

In Fig. 1, the drop is stretched by the high-level pulse. When the electric field is removed, the drop recovers its original spherical shape owing to the interfacial tension between the drop and the surrounding oil (Mousavichoubeh et al., 2011). In the initial condition, the internal pressure of the drop and the interfacial tension are balanced. However, the deformation of the drop creates an imbalance, at which point the restoring force of the vibration of the drop is equivalent to the difference between the interfacial tension and the internal pressure. The expression of the restoring force is as follows (Zhang et al., 2007):

$$F_h = 2\pi\gamma R \frac{\chi}{\left[(1+\chi)^{1/2}+1\right](1+\chi)} \tag{5}$$

2.2.4. Excitation force of vibration

The polarisation of the drop by the high-voltage pulsed electric field creates two types of polar charges at the left and right hemisphere of the drop, resulting in the generation of an electrostatic force (Hu et al., 2001). At the low electric frequency, the electrostatic force is then transformed into the excitation force of the vibration, which is given by (Gong et al., 2010)

$$F_e = \pi\varepsilon_0\varepsilon_2 R^2 E^2(t) \frac{\lambda^{-2/3}}{1-\lambda^2}\left(1+\frac{2\ln\lambda}{\lambda^{-2}-1}\right)\frac{1}{N(\lambda)} \tag{6}$$

$$N(\lambda) = -\frac{1}{\lambda^2-1}\left[1-\left(\frac{\lambda^2}{\lambda^2-1}\right)^{1/2}\ln\left(\lambda+\left(\lambda^2-1\right)^{1/2}\right)\right] \tag{7}$$

$$\lambda = a/b = (1+\chi)^{3/2} \tag{8}$$