An investigation on the humping ferro-damp induced under non-uniform magnetic field density

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Abstract.
Under non-uniform magnetic field distribution, the humping ferro-damp used to reduce the oscillation of ferro-wave is investigated. Through experimental observation and analytic analysis, the dynamical stability at the so called “humping pool”, enclosed by both centers of permanent magnetisms, is found to be closely dependent on the oscillating frequency, field intensity & the separated distance of magnetisms. Though nodal shift of pool 0.07~0.11 cm, recorded from video-camera suited on self-designed oscillating system, begins to occur as in the deployment of higher ferro-level or lower field strength 0~30 mT, however such the stable response of humping pool, without remarkable change of vibrating amplitude 0.03~0.06 cm, might be under control while oscillating frequency of 0.5~2 Hz is subjected. That could be attributed to the concentrated ferro-viscosity as well as the strongest ferro-magnetization, induced at the humps, initiates a recovering constrain for oscillating pool. Unlike above humping damp accessed, an irregular and random ferro-profile will be generated outside pool region. Such humping deployment, as a manner of shockproof, might be utilized to reduce the seismic damage and that makes damping analysis of seismic study become more practical and approach to the intended demand.

Introduction
With the shock absorbed by ferro-damp without magnetic hysteresis, ferro-fluid, known as promising material used in quakeproof, has gradually attracts public interest. Here the understanding of apparent viscosity vs. ferro-magnetization becomes inevitable if the ferro-property on shockproof is further investigated. Hall etc.[1] initiated a theoretic formula dealing with effective viscosity of water-base ferro-sample where the relative error of viscous increase with field applied will be up to one or two orders of magnitude if Brownian motion and rotating effect are absent. Utilizing Langevin theory with the freedom of ferro-particle as well as directional field taken into account, R.E, Rosensweig [2] not only significantly corrects above deficit but the correlation of ferro-viscosity on asymmetric stress concept could be well formulated. Recently, micro-technology of A.C chip to predict the ferro-property has been widely discussed in biomedical research [3][4][5]. Yet A.C current frequency easily leads to a magnetization lag that makes the access of prompt damping response become impossible. To speed up sampling rate, the technology of MEMS (micro electromechanical system) [6] was considered as an effective way. As a result, the accurateness of resolution could be significantly improved, but relevant discussion of ferro-damp on directional field is still insufficient. Overview from previous mechanical testing instrument, Taylor [7] employed an accelerating system to examine the stability of non-ferro liquid surface. However, the linear motion seems to be unable to meet practical oscillation arisen from earthquake. To compensate above inadequateness, a modified oscillating device on Rayleigh-Taylor theory was developed by Rayleigh [8]. In which, the availability of proposed model estimating surface tension, as a dynamical interfacial boundary, has been undertaken with o-ring
experimental method [9], and ferro-vortex viscosity closely depends on the spatial distribution of magnetic field, instead of a thermal property, was also confirmed [10]. With previous accomplishment accessed from above semi-empirical analysis, advanced application of ferro-damp on seismic problem has arisen our interest and becomes the main objective in this article. Here how to find the nodal position from the ripple resonance of ferro-surface will be clearly discussed using theoretic and experimental approach.

1. Analysis

To successfully formulate the theoretic model and experimental method, several reasonable assumptions should be made beforehand and that will not loss the overall behavior.

1.1 Assumptions

1. The interaction between collinear magnetized particles and Brownian effect arisen from thermal effect are small compared to the external field force and could be neglected.
2. Isotropic ferro-magnetization induced inside ferro-sample will be uniformly distributed and in synchronization with field applied if the size of ferro-particle is in micro-scale considered.
3. The practical magnetization M of ferro-solution, based on Langevin’s theory [1], behaves a linear relationship with magnetization of ferro-particles Ms i.e., M = φMs where φ is ferro-volumetric concentration.

1.2 Governing equations

First, a ferrohydrodynamics (FHD) equation governing one dimensional periodic motion is given in Eqs.(1)−(2). Here symbol \( u \) indicates the oscillating ferro-velocity and \( v \) means the transversal ferro-velocity. And ferro-viscosity \( \mu \) in Eqs.(2), varying with ferro-magnetization is taken as a function of directional magnetic intensity instead of constant value considered [2].

\[
\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = - \frac{1}{\rho} \frac{\partial P}{\partial x} + v \left( \frac{\partial u}{\partial x^2} + \frac{\partial u}{\partial y^2} \right) \quad \mu = \frac{\mu_0}{\rho} \left( 1 + \frac{3}{2} \phi \frac{1}{2} \alpha F(\alpha) \right) \quad \mu = \mu_0 \left( 1 + \frac{3}{2} \phi \frac{1}{2} \alpha F(\alpha) \right)
\]

where

\[
F(\alpha) = \frac{\cosh \alpha - 1}{\alpha} = \frac{d}{d\alpha} \ln \left( \frac{\sinh \alpha}{\alpha} \right) \quad \alpha = \frac{\mu_0 M_s H \sqrt{\varphi}}{KT}
\]

Langevin function \( F(\alpha) \) and argument \( \alpha \), referred to [2], are defined below. Symbols of \( \mu_0 M_s \), \( H \), and \( \sqrt{\varphi} \) indicate ferro-permeability, magnetization of ferro-particle, field intensity and particle volume respectively. \( K \) and \( T \) are plank’s constant and absolute temperature.

To access the steady recycling model, a quasic-steady transformation by transferring the inertial coordinate \( (x,t) \) to relative coordinate \( (x',t) \), subjected to slider, should be made and relevant transforms will be yielded in Eqs.(3) where \( U \) is the time-oscillating velocity of slider, \( U_o \) is maximum oscillating velocity and \( u' \) expresses the axial flow velocity relative to \( U_o \).

\[
u = U + u' \\
x = x' + \int u dt \\
\frac{\partial}{\partial t} - \frac{\partial}{\partial x'} - u \frac{\partial}{\partial x'} + U = U_o e^{i\nu t}
\]

After substituting Eqs.(3) into Eqs.(1), a steady oscillating model in Poiseuille formulation with boundary equations could be carried out in Eqs.(3) where \( \varphi \) is the length of testing device.
\[ \frac{\partial^2 u'}{\partial x'^2} + \frac{\partial^2 u'}{\partial y'^2} = \frac{i\omega U_0}{v} e^{i\omega t} \]

\[
\begin{aligned}
B.C.: \quad & u'(0, y, t) = 0 \\ & u'(t, 0, t) = 0 \\ & u'(x', 0, t) = 0 \\ & u'(x', \delta, t) = U(x') e^{i\omega t}
\end{aligned}
\]

Invoking separation method, Eqs.(4) and (5) give analytic solutions of axial and transversal surficial ferro-velocity \( u' \), \( v \).

\[
\left( \frac{2\omega U_0}{v n(n)} \right)^2 \left[ 1 - (-1)^n \right] \sin \frac{n\pi x}{\ell} + \frac{\omega U_0 x'^2}{2v} - \frac{\omega U_0 \ell x}{2v} \right] e^{i(\omega t + \frac{\pi}{2})}
\]

\[
\left( \frac{2\omega U_0}{v n(n)} \right)^2 \left[ 1 - (-1)^n \right] \cos \frac{n\pi x}{\ell} - \frac{\omega U_0 x'^2}{2v} - \frac{\omega U_0 \ell x}{2v} \right] e^{i(\omega t + \frac{\pi}{2})}
\]

Using the kinematic relation of standing wave traveling on the interface given below, corresponding wave amplitude \( \delta \) vs. axial position \( x' \), after further integration, might be successfully developed in Eqs.(6).

\[
\frac{\partial \delta}{\partial t} = -v
\]

\[
\delta = \left( \frac{2\omega R^2}{v n(n)} \right)^2 \left[ 1 - (-1)^n \right] \sin \frac{n\pi x'}{\ell} + \frac{\omega R x}{2v} - \frac{\omega R x}{2v} \right] e^{i(\omega t + \frac{\pi}{2})}
\]

2. Experimental analysis

In Fig.1, a self-design testing system constituted by DC power supply, video camera, slider and ferro-sample etc. is set up. That features a special characteristic of smaller size, economical utility and efficient operation. While the power is transmitted, periodic motion of slider induced by DC motor will start working. After the steady oscillation has been reached, the view of wave traveling on ferro-surface could be pictured by camera and transferred to PC immediately.

Fig.1. The sketch of dynamical testing device

Fig.2. The photograph of humping ferro-surface at the center of magnetism
3. Results and Discussion

Initially, let’s examine the profile of ferro-surface. Here the peak of concaved ferro-surface, as dash line sketched in Fig.2, indicates ferro-hump, just located above the center of permanent magnetism, where the strongest magnetic field intensity will be expected to induce the intensified ferro-magnetization to form ferro-hump due to magnetic attraction. Oppositely, the wave trough, shown in Fig.3, tells the ferro-sample here will be drawn out owing to the weakest field strength will be convinced at the contacted interface of both magnetisms. Thus the humping pool could be recognized at the region surrounded by both wave crests. Next we will forward to discuss how the theoretic ferro-viscosity, in Fig.4, varies with field enforced. According to the definition of modified Langevin theorem in Eqs.(2), the estimated ferro-viscosity, for volumetric concentration $\psi = 0.4$ at 25°C, shows a rapid increase, $0.003 \text{ (N-S)/m}^2 \sim 0.0047 \text{ (N-S)/m}^2$, within the interval of magnetic intensity $0\sim30$ mT. Here apparent viscosity arised from the coupling effect of ferro-magnetization $M_s$ and field intensity $H$,will be effectively initiated as the quick magnetization starts between field $12 \sim 18$ mT, and then the value exhibits a slow growth as the additional field is extended due to ferro-magnetization of sample approaches to saturated state [9].

Subsequently, we will forward to observe the surficial vibration of humping pool a well as nodal shift. Here nodes are defined as these particular points always having zero amplitude during oscillation i.e., effective seismic-proof will be predicted here. In Fig.5~ Fig 6, ferro-sample with depth of 0.3~0.5 cm in testing vessel is subjected to magnetic flux 15~30 mT & periodic frequency 0.8~2 Hz, and initial ferro-surface under field applied is indexed in yellow while kinematical interface is then marked in white. Origin coordinated in these photographs is scheduled at contact spot of magnetism 1 and magnetism 2, and nodal shift is defined as the x coordinate of nodal position deviating from the origin. Images from above photos show that the rigorous vibration found at the region outside humping pool, situated at the left side of white vertical line, will be evolved as in the conditions of higher interface 0.5cm under the enforcement of lower field intensity 15 mT (see Fig.5). However, the confined fluctuation appears inside the humping pool situated at the right side of white vertical line. Additionally, the nodal point is in right shift about 0.4 cm. Dissimilar to above results, Fig.6 reveals that surficial fluctuation might be effectively controlled throughout the region above the magnetism for shallow ferro-surface considered, and the nodal deviation is only 0.1 cm. That attributes to the strong ferro-viscous drag for shallow ferro-sample, induced by the higher field intensity, further restricts ferro-oscillation, and which also possess more potential in absorbing dynamical energy to constrain the corresponding amplitude.
Finally, our discussion will turn to quantity analysis of damping effect displayed in Fig.7~Fig.8. In Fig.7, nodal shifts for ferro-surface with height of 0.3 and 0.5 cm are found to be “frozen”, that is, individual deviation is independent to the periodic rate of 0.5~1.8 Hz. However, the shifting magnitude is found to be about 0.1 cm for liquid with depth 0.3 cm, and the value will be increased to 0.4 cm for liquid depth of 0.5 cm. That means the obvious shift, occurs at higher ferro-surface, is primarily caused by the weaker magnetic restriction. Otherwise, the deviation will be further restricted as in the stronger field intensity, 30 mT, imposed, which carried out the shifting value 0.05 cm. Corresponding to above conditions, individual amplitude 0.01~0.06 cm for ferro-surface of 0.5 cm at 15 mT, 0.001~0.05 cm for ferro-surface of 0.3 cm at 15 mT, and 0.001~0.028 cm for ferro-surface of 0.3 cm at 30 mT will be experienced in Fig.8 as the working periodic frequency is fallen within 0.5~1.8 Hz. Base on above distributions, all reveal that the amplification of amplitude will come out as oscillating frequency increases from 0.5~1.8 Hz, and the smallest amplitude occurs at ferro-surface of 0.3 cm subjected to 30 mT. That implies most of dynamical energy will be dissipated by viscous absorption i.e., shaking effect could be effectively avoided. That is also consistent with the quality analysis of Eqs.(6) where the amplitude δ exhibits a linear proportional to the periodic rate ω as well as oscillating velocity U₀, but is found to be inversed to induced viscosity.
4. Conclusions

Summary from above discussion, the humping ferro-damp, as a function of magnetic variable instead of thermal property, has a direct influence on the ferro-damp. With the reversal ferro-magnetization induced by field intensity, using variable viscosity to regulate damping effect becomes a feasible manner in reducing the shaking quake. Although the progressive fluctuating amplitude appears as in the increase of oscillating frequency, further restriction will be expected under the usage of strong field intensity or denser ferro-concentration. In addition, the shift of humping pool is also found to be irrelevant to periodic rate which will provides a realistic way to achieve the effect of quakeproof.

5. References