# Motion of Magnetic Chains in a Vibrating Field

Y-H Li, S-T Sheu, J-M Pai, C-Y Chen

Department of Mechanical Engineering, National Chiao Tung University, Taiwan, Republic of China

## ABSTRACT

This article outlines and illustrates the manipulations and mechanisms of micro magnetic chain by both experiment and simulations. A reversible microchain consisting of superparamagnetic particles whose diameters are about 4.5 micro-meters is formed under a static directional field and manipulated by an additional perpendicular field. We demonstrate the chains appear different behaviors, from rigid body oscillations and bending distortions to rupture failures. The ruptures can be divided into two categories which depend on the breakup position either at center or on two sides. By calculating the induced drag which dominates the distortions and ruptures of the chains, we find that the distortions and ruptures occur at the position between the two particles which sustain significant drag variation.

***Keywords***: **magnetic particles, micro chains, vibrating field**

## 1 INTRODUCTION

Magnetorheological (MR) suspension is an artificial and smart fluid consisting of paramagnetic solid particles suspended in a nonmagnetic solvent. Due to the paramagnetism of these particles, they are useful to make reversible micro devices such as pumps, actuators, and swimmers which can be utilized in micro channel and further applied in advanced biotechnical systems or MEMS.

The dynamics of MR suspensions under rotating magnetic field has been studied extensively in recent years. It has been shown that the field induced magnetic particle chains rotate synchronously with the field but lag behind by a constant phase lag [1,2]. The dependence of the cross-over frequency on the viscosity of the carrier fluid was analyzed by applying a rotating field of constant amplitude on suspensions [3]. Some researches have revealed simulation results of the breakup type of the chains under rotating field with varied Mason number, which is a dimensionless ratio of viscous forces to the dipolar forces [4,5].

To effectively apply the microchains in a micro-electro-mechanical-systems, detailed studies regarding behaviors of the chains are strongly desired. In this paper, we analyze thoroughly the manipulations of the magnetic particle chains subjected to a oscillating field. It has been shown that the chains would evolves from deform to breakup due to the induced drag under an higher oscillating field [6,7]. We calculate the drag acted on each particle of the chains and realize the difference in drag between particles of the chain is the main factor causing the distortion and reupture. The simulation results also reveal that the center of the chains experience maximum shear stress. In addition, the distortion or rupture will occur at the contacting point of the two adjacent particles whose ratios of drag to radius are significantly different.

## 2 EXPERIMENTAL SUTUP

The magnetorheological suspensions used in our experiment are water suspensions of polystyrene (PS) microspheres coated with iron oxide grains. The aqueous suspensions (Dynabeads M-450 Epoxy whose diameters are 4.5 $\mu$ m with a susceptibility of $\chi$ =1.6) possessing superparamagnetic behavior with no hysteresis or magnetic remanence are produced by Invitrogen Life Technologies. This property can be utilized to make reversible magnetic chains.

For aggregating the particles to form chains, we applied an unidirectional magnetic field generated by a pair of coils connecting to a DC power source. As for the oscillating field , we set another perpendicular pair of coils connecting to a AC power supply which can generate sinusoidal electric signals. Fig.1 shows the configuration for developing the overall oscillating field. For realizing the effect of the field strength to the particle chains behaviors, we enhance the strength of the oscillating field by increasing the amplitude with constant frequency and observe the rupturing process of the chains. All the motions of the chains are observed and recorded by an optical microscope. The forces acted on the particles at the breakup moment are estimated via the basic physical equations and calculated by the numerical method, so that we can compare the breakup position between the experimental results and theoretical predictions.

## 3 RESULTS AND DISCUSSIONS

### 3.1 Experimental Results

#### 3.1.1 Vibration

By increasing the oscillating field, the chains appear different behaviors, from rigid body vibrations, bending distortions to breaking failures. Additionally, when the particle chains experience oscillating field, we find that the chains oscillate with the magnetic field but lag behind by a changeable phase lag. Furthermore, the chains of different length might lag behind the field with different phase angles

.

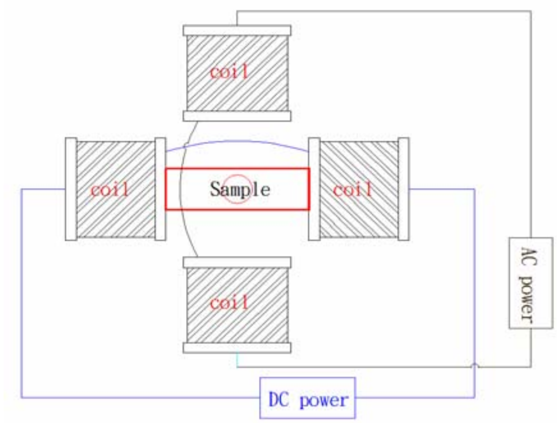


Figure 1. Schematic diagram of oscillating magnetic field configuration.

Fig. 2 shows the sequential images of the chain of 8 particles (denoted as P8) vibrates with the oscillating field of amplitude 48.02 Oe within one period. We find that the chain vibrates as a rigid body and almost synchronously with the magnetic field, lagging behind by a slight phase angle. To study the chain deformation, we used the chain of 15 particles to demonstrate the bending distortion behavior under the same field strength of 48.02 Oe. Fig. 3 depicts the sequence of the distorting process of the chain. Obviously, the lagging angle of the chain with respect to the field is larger than 8-particle one.

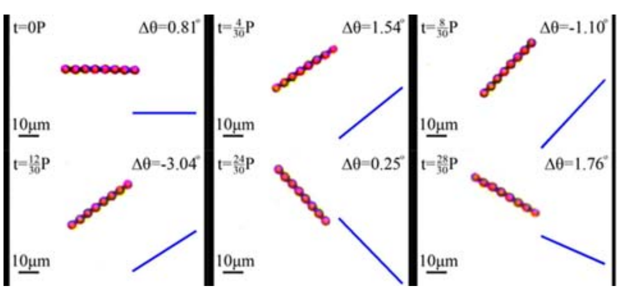


Figure 2. Sequential images of a chain consisting of 8 particles (denoted as P8) under a oscillating magnetic field of 48.02 Oe and a frequency of f=1Hz. The chain was formed by a uniform directional magnetic field of 52.18 Oe. The blue solid line indicates the direction and magnitude of the magnetic field.

### 3.1.2 Rupture

In order to study the rupture behaviors of the magnetic particle chains, we increased the amplitude of the oscillatingting field until the breaking failure occurred. Based on our experimental results, the ruptures can be classified into two categories by the rupture position, one is breaking at center of the chains which can be named as brittle rupture, the other one is breaking from two sides or can be categorized as plastic rupture.

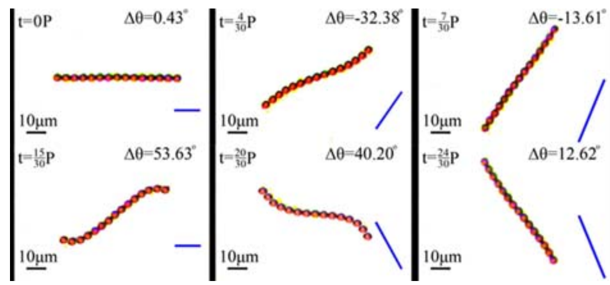


Figure 3. Sequential images of a P15 chain under a oscillating magnetic field of 48.02 Oe and a frequency of f=1Hz. The chain was formed by a uniform directional magnetic field of 17 Oe.

Fig. 4 and 5 show the sequential images of oscillating chains consisting of 15 and 20 particles evolve from bending distortion to breaking failures on sides, respectively. In fig. 4, at the time of t=16/30P, the chain breaks into three smaller chains, the three chains might oscillate with the field but lag behind by different phase angles which depend on the length of the chain. In fig. 5, at the time of t=20/30P, the chain bends to S-shape and oscillate with the field but lag behind a significant phase lag which caused the chain to reverse direction to align with the original oscillate field.

Fig. 6 indicates the brittle rupture of a chain consisting of 16 particles under oscillating field. The rupture with no apparent deformation occurred at the time of t =4/30P just right after the start oscillating motion.

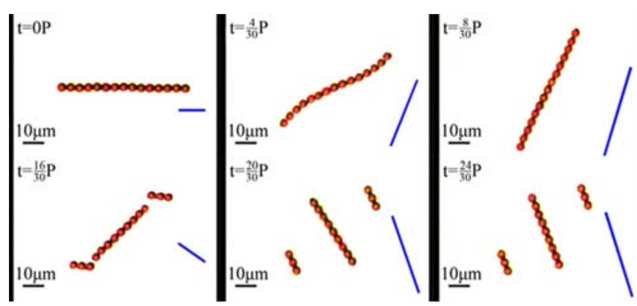


Figure 4.Sequential images of a P15 chain evolves from bending distortion to breaking failures on two sides under a oscillating magnetic field of 56.25 Oe and a frequency of f=1Hz.

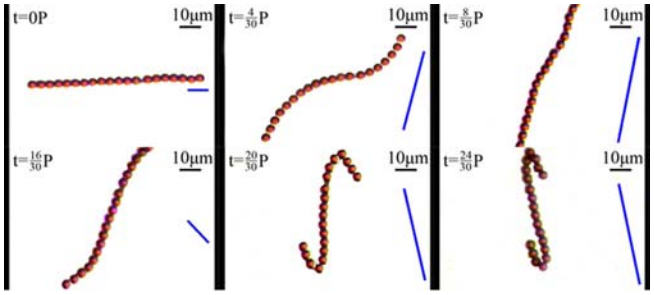


Figure 5. Sequential images of a P20 chain evolves from bending distortion to breaking failures on two sides under a oscillating magnetic field of amplitude 87.25 Oe and a frequency of f=1Hz.

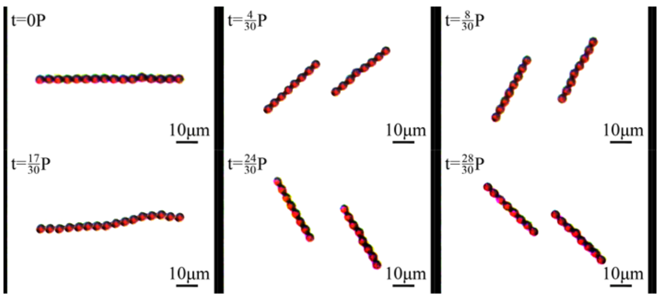


Figure 6. Sequential images of a P16 chain break at center.

## 3.2 Numerical Simulations

In order to investigate the forces act on the oscillating chains, dynamics simulation are conducted by commercial software FLUENT. Fig.7 shows the 3D meshes for calculating the induced drag of particles under the identical conditions to the experiments. The simulations results are utilized for dynamics analysis on next section.

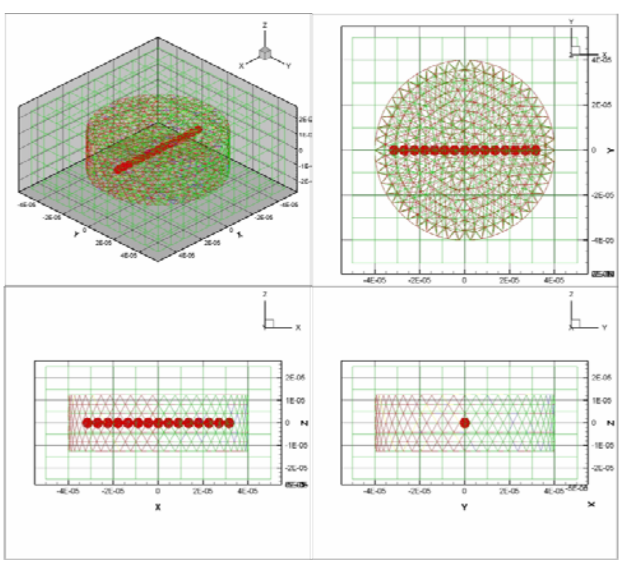

Figure 7. Schemes of the calculation grids for simulating drag acted on a chain consisting of 15 particles.

Based on our experimental results, the rupture of the oscillating chains would always occurred within the duration of half a period (denoted as P/2). We divide the oscillating process from starting (t=0) through half a period (t=P/2) into four stages as shown in fig. 8. Fig.9 indicates the center of the chain sustains the maximum shear stress caused by hydrodymanics drag throughout the oscillating.

At first stage (t=0), the bonding force is weakest due to there in no radial component of induced dipolar force generated by the oscillating field. If the overall radial dipolar force could not sustain the shear stress caused by hydrodymanics drag, the rupture would occur at the center just at moment near t=0. This explanation shows good agreement with the experimental results shown in fig. 6.

When the oscillating chain goes through the second stage (0<t<P/4), the chain experiences a decelerated process, in which the hydrodynamics drag declined and the radial component of dipolar force increased. If the chain did not break at the first phase(t=0P), it would not rupture within this stable stage either. This is the reason for there is no rupture occur within second stage.

At the third stage (t= P/4), the chain obtains the maximum radial dipolar force but no hydrodynamics drag due to stagnation, which results in the maximum bonding force existing in the chain. The maximum bonding force means the structure of the chain is so strong that lead the chain to be a rigid body.

When the oscillating chain gets into the fourth stage (P/4<t<P/2), the chain experiences a accelerated process, in which the hydrodynamics drag increaased, but the radial dipolar force declined which is contrary to the second stage. That means rupture would occur at this unstable stage.

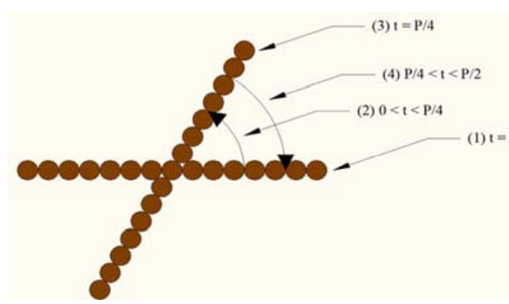


Figure 8. Scheme of the four stages of the oscillating motion.

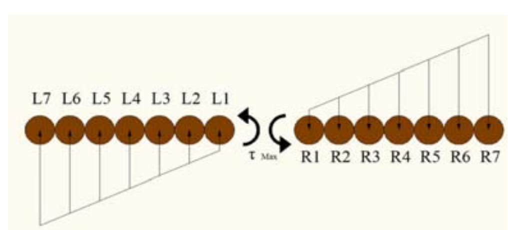


Figure 9. Illustration for indicating the center of the chain bear the maximum shear stress caused by induced drag.

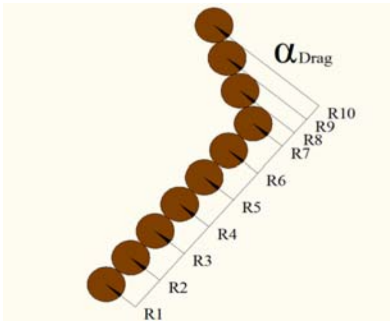


Figure 10. Schematic representation of increasing angular acceleration inducing drag variation.

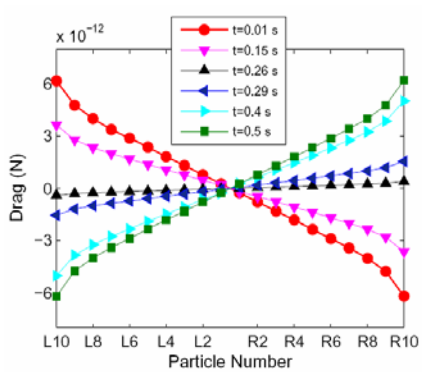


Figure 11. Hydrodynamics drag acted on each particle of a P20 chain within half period (t=0.5s).

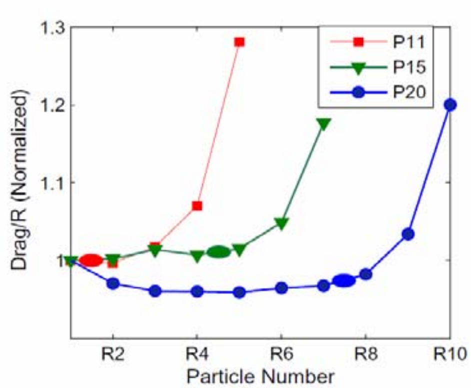


Figure 12. Schematic representation of comparison of normalized drags acted on three chains of different lengths at rupture moment. The oval-shaped points indicate the rupture position of the chains.

It is known that when the drag acts on the chain, each particle will obtain a angular acceleration adverse to its oscillating orientation as depicted in fig.10. When the accelerations of the two adjacent particles are different, one particle of the two will slip from the other. For obtaining the angular acceleration of each particle, we have claculated the drag acted on the chain by simualtion. Fig. 11 shows the simulation results of drag acted on a chain consisting of 20 particles. We find that the outer particles experience more significant drag than the inner ones all the time, which means the particle at the center always bearing maximum shear stress caused by the drag. Besides, the linear curve is similar to the shape of the chain which oscillates as rigid body. Those findings reveals that if the chain oscillate as a rigid body, there will be a linear relationship between the drag acted on the Nth particle and the radius (denoted as R) which represents the distance from the center of the chian to the Nth particle. Based on above theory, we compare the normalized ratio of drag to radius (denoted as Drag/R) with several chains of different particles at the distorting or the rupture moment. The results as shown in fig. 12 indicate that the rupture or distortion occurr at the position between the two particles whose Drag/R were significantly different. Those findings correspond with our experimental results.

## 4 CONCLUSIONS

In this paper, we conducted an intensive experimental study on the manipulations of the magnetic particle chains under oscillating magnetic fields. Different types of oscillating behaviors of the chains are detailed recorded.. Depending on the oscillating stage, the rupture of the chain can be classified into two categories, which are brittle rupture and plastic rupture. The brittle rupture occurs at the center of the chain when the oscillating just begin. The plastic one breaks from two sides occuring at the time just after the reverse motion of the chain. The rupture predictions from the simulation results of the drag show good agreement with experiments.

## ACKNOWLEDGEMENT


This research is supported by the National Science Council in Taiwan through Grant NSC 99-2221-E-009-057-MY3.


## REFERENCES


[1] S. Melle, G. G. Fuller, M. A. Rubio, Phys. Rev. E 61(4): 4111–4117, 2000.
[2] S. Melle, James E. Martin, J. Chem Phys. 118, 21:9875, 2003.
[3] S. Melle, O. G. Calderon, G. G. Fuller, M. A. Rubio, J. Colloid Interface Sci., 2001.
[4] T. G. Kang, M. A. Hulsen, P. D. Anderson, J. M. J. d. Toonder, H. E. H. Meijer, Phys. Rev. E 76, 066303, 2007.
[5] S. Melle, O. G. Calderon, M. A. Rubio, G. G. Fuller, Phys. Rev. E 68, 041503 ,2003.
[6] YH. Li, ST. Sheu, JM. Pai, CY. Chen, J. Appl. Phys., 111: 07A924, 2012.
[7] YH. Li, CY. Chen, ST. Sheu, JM. Pai, Microfluidics and Nanofluidics, in press. ( DOI 10.1007/s10404-012-0974-y)