# The Effect of Time-Varying Magnetic Field on Magnetic Nano-Thickness

**Pimonpan Sompet and Yongyut Laosiritaworn***

*Department of Physics, Faculty of Science, Chiang Mai University, Chiang Mai 50200, Thailand*

**Corresponding author. E-mail: yongyut@science.cmu.ac.th*

## ABSTRACT

***We report the results of Monte Carlo simulations on Ising nano-thickness films, i.e., an ultra-thin-film under the effect of time-varying magnetic fields in both sinusoidal and triangular patterns. The study was performed using the Metropolis spin-flip algorithm to investigate how the hysteresis loop-area of Ising spins depends on the frequency of the external time-dependent magnetic field in a ferromagnetic phase. From our results, it is found that the response of the system from both sinusoidal magnetic field and triangular magnetic field are of a similar trend. In terms of the frequency dependence, at low frequencies, the hysteresis loop-area increases with the increase of the frequency of the external magnetic field because the effective delay, i.e., the phase lag, increases. On the other hand, at high frequencies, the hysteresis loop-area decreases with increasing frequency due to that the effective delay is moving away from its optimum point, i.e., π/2. These results qualitatively agree well with experiments.***

**Key words:** Nanostructure, Magnetic ultra-thin-film, Ising model, Monte Carlo, Hysteresis, Time-varying field

## INTRODUCTION

When an interacting many-body system, such as a magnet, is driven in time by an external perturbation, such as a time-varying magnetic field, the system cannot respond instantaneously due to a relaxation delay. As a result, the magnetization will lag behind the applied field, and this gives a nonzero area of the hysteresis loop (magnetization-field loop). The response of such a system under a time-dependent field leads to many novel physical phenomena intriguing physics and important technical applications (Johnson et al., 1996). Considerable points in hysteresis loop are coercivity and remanence which are interesting in terms of physical designs as they are important parameters to make an efficient transformer or a high-capacity magnetic recording media (memory). Consequently, in this study, we tried to model this dynamic magnetic behavior in magnetic thin-films with a thickness lies in nanometer-range, i.e., very thin films, which is the key factor to obtain a high-density memory application.

In modelling such a thin-film structure, we considered the use of Ising model since both theoretical (Binder and Hohenberg, 1974; Bander and Mills, 1988) and experimental (Li and Baberschke, 1992; Elmers et al., 1994; Dunlavy and Venus, 2004) investigations confirmed that the magnetic behavior in nano-thickness ferromagnetic-films is an Ising-like. In literatures, there are considerable number of studies on magnetic thin-film system and its perturbation. Nevertheless, most studies concentrated on the effect of sinusoidal magnetic field to the dynamic hysteresis properties which depends on temperature $T$ of system, amplitude $h_0$ and frequency $f$ of applied field. A very good review was given by Chakrabarti and

Acharyya (1999). On the other hand, there are also many other patterns of magnetic field that are used widely at present. In this work, we tried to study the dynamic behavior of the hysteresis loops that are perturbed by both a sinusoidal magnetic field and another kind of the field, i.e., a triangular magnetic. The objective is to investigate how the dynamic behaviors react to different patterns of the applied fields in ultra-thin-films structure. As a prototype, we considered the two-dimensional square lattice system. The study was firstly done by investigating how the hysteresis loop depends on a frequency of triangular magnetic field and sinusoidal magnetic field (at fixed $h_0$ and $T$) by using the Ising model and Monte Carlo simulations. After that, the procedures were repeated at other temperatures in the range of $k_BT/J$ = 2 to 3 with a step of 0.2. Finally, the results were analyzed and compared with the previous study.

## MATERIALS AND METHODS

### The model

In this study, we used Monte Carlo simulations to investigate the dynamic behavior of the Ising spins under an influence of time-dependent magnetic fields, i.e., sinusoidal and triangular patterns. In the model, there contains ferromagnetic interaction Ising spins where each spin is associated with up/down (or ±1) spin state and only nearest-neighbor ferromagnetic coupling's are taken into account. The Ising Hamiltonian is given by

$$H = -J \sum_{<i,j>} s_i s_j - h(t) \sum_i s_i \qquad (1)$$

where $J$ is the exchange interaction, $s_i$ (= ±1) represents the Ising spin variable at site $i$, $<\ldots>$ denotes that only the nearest-neighbor pairs are useful to the sum. The magnetic field

$$h(t) = h_0 \sin 2\pi f t$$

is an external sinusoidal magnetic field, whereas

$$\begin{aligned} h(t) &= 4h_0 ft; & 0 \leq t < \tfrac{1}{4}\ \text{period} \\ &= 2h_0 - 4h_0 ft; & \tfrac{1}{4}\ \text{period} \leq t < \tfrac{3}{4}\ \text{period} \\ &= -4h_0 + 4h_0 ft; & \tfrac{3}{4}\ \text{period} \leq t < \text{period} \end{aligned}$$

is an external triangular magnetic field, where $f$ refers to the field's frequency. Generally, $J$ = 1 can be set which leads to that both the Hamiltonian $H$ and the field $h$ are defined in a unit of $J$. In the same way, the unit of the temperature $T$ is $J/k_B$.

### Monte Carlo Simulation

In the study, the Ising model was prepared on lattice sizes of 20x20 spins and the periodic boundary condition was used on all edges. The magnetic configuration was assigned to start from the ferromagnetic ground-state that all spins are pointing up (+1). Then, the Ising system in an external dynamic magnetic field was updated as a function of time by means of the Monte Carlo method and the Metropolis single spin flip dynamics (Metropolis et al., 1953). The spin state ($s_i$) at site $i$ and time $t$ is updated with a probability proportional to

$$\mathrm{esp}\left[-\frac{1}{k_BT}\Delta E_i(t)\right], \qquad (2)$$

where

$$\Delta E_i(t) = 2s_i\left[\quad {}_j s_j\,(t) + h(t)\right], \tag{3}$$

is the change in energy due to a spin-flip at site *i* which is provided from Ising Hamiltonian. The spin at this site is flipped if the change in energy of the flipping spins is less than zero, or a uniform random number [0, 1] is less than the probability in Eq. (2). The unit time step is defined in terms of one full scan of all sites of the Ising lattice that is 1 Monte Carlo step per site (mcs). From the configuration of Ising spins at time *t*, we calculated the response magnetization per site to the magnetic field at time *t* as

$$m(t) = \frac{1}{\mathrm{N}}\ {}_{i}\ s_i\,(t), \tag{4}$$

where N is the total number of spins in Ising lattice (in this study *N* is 400 or 20x20) and ${}_i s_i\,(t)$ is the summation of spin (±1) at all sites in the entire lattice. From the response magnetization per site (*m*), the plot of *m* as a function of external magnetic field (*h*) defines the hysteresis loops. Next, we considered the hysteresis loop-area

$$A = \oint m\,dh \tag{5}$$

to investigate how the area responds to the pattern and frequency of the magnetic fields.

## RESULTS AND DISCUSSION

From our studies, on the effect of magnetic field frequency to the hysteresis loop, we found that the hysteresis shape changes as varying the frequency. Figure 1 presents the simulated hysteresis loops that were forced by the sinusoidal magnetic field and the triangular magnetic field at a series of the frequencies *f* at a fixed amplitude of the magnetic field, i.e., $h_0 = 1.0\ J$ and temperature $T = 2.0\ J/k_B$. The significant effect of frequencies on the shape and pattern of hysteresis is demonstrated. For example, considering a very low frequency (e.g., $f$ = 0.002 mcs$^{-1}$), the hysteresis loop takes a thin rhombic pattern and becomes saturated before the field reaches $+h_0$. As being evident, the coercivity $h_c$ and the remanence $m_r$ are small. This is because the low frequency results in a high period and the magnetic spins have a sufficient time to follow the field. Consequently, this results in a small lagging between the magnetization and the field direction. Hence, the hysteresis loop is small in this case and provides a small magnitude of $h_c$ and $m_r$. However, as frequency increases (e.g., at $f$ 0.007 mcs$^{-1}$), the simulation loop takes a fat rhombic, expanding along both *m* and *h* axes and both $h_c$ and $m_r$ increase. This is due to that the higher frequency reduces the field period, so it is more difficult for the magnetic spins to follow the field. Therefore, this significantly increases the time-delay (lagging) between the magnetization and the field, giving a bigger loop of the hysteresis. However, the increase of the hysteresis area is proportional to the magnetization-field time-delay until an optimal point, i.e. $\pi/2$, is reached. At this optimum point, the coercivity of the field gets its maximum magnitude, i.e., $h_c \sim \pm h_0$. Alternatively, as frequency further increases, i.e., at $f > 0.02$ mcs$^{-1}$, the loop is no longer saturated. At this high frequency, the symmetry of hysteresis loop is broken and the shape of hysteresis loops shrink. For example at $f = 0.2$ mcs$^{-1}$, the position of hysteresis loop lies only in a positive magnetization-region and the shape of loop is like a thin ellipse. The description of this phenomenon is that the magnetic field switching is too fast to be followed by the magnetic spins.

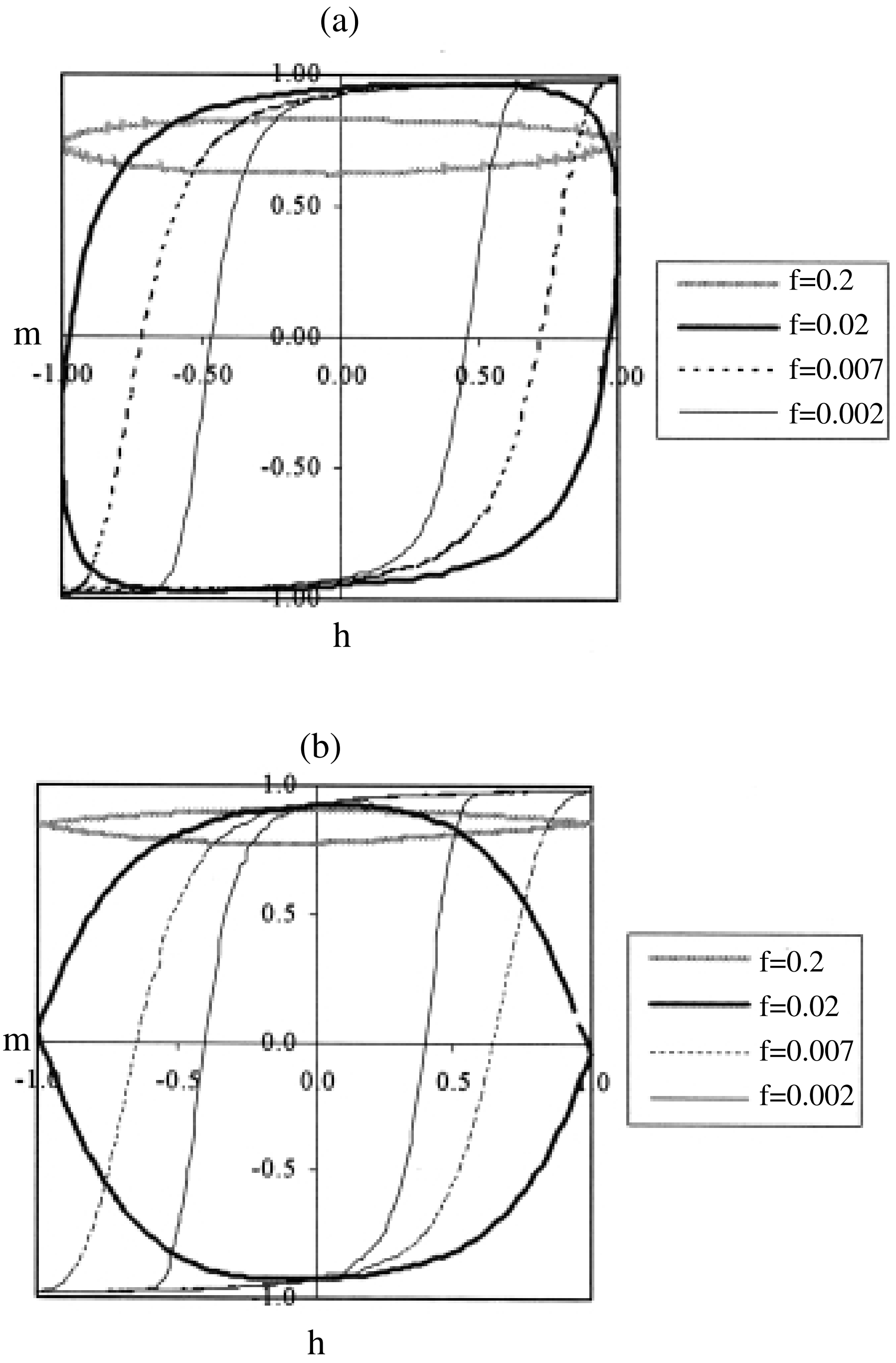



**Figure 1.** Simulated hysteresis loops being driven by (a) sinusoidal magnetic field and (b) triangular magnetic field at various frequencies $f$ (in the mcs$^{-1}$ unit) but fixed amplitude of the external magnetic field ($h_0$ = 1.0 $J$) and a fixed temperature T = 2.0 $J/k_B$.

Figure 2 summarizes how the hysteresis loop-area A responds to the increase of frequency $f$ from a low-f region to a high-f region. As mentioned earlier, at low frequencies, the phase lag between $f$ and $h$ increases towards $\pi/2$ with increasing $f$ and the loop-area gets increasing. However, at high frequencies, the area decreases as f increases because the effective delay becomes very great since the magnetization cannot respond to such high switching field. Our results in Figure 2 qualitatively agree well with the previous experimental result in Figure 3 (Jiang et al., 1995).

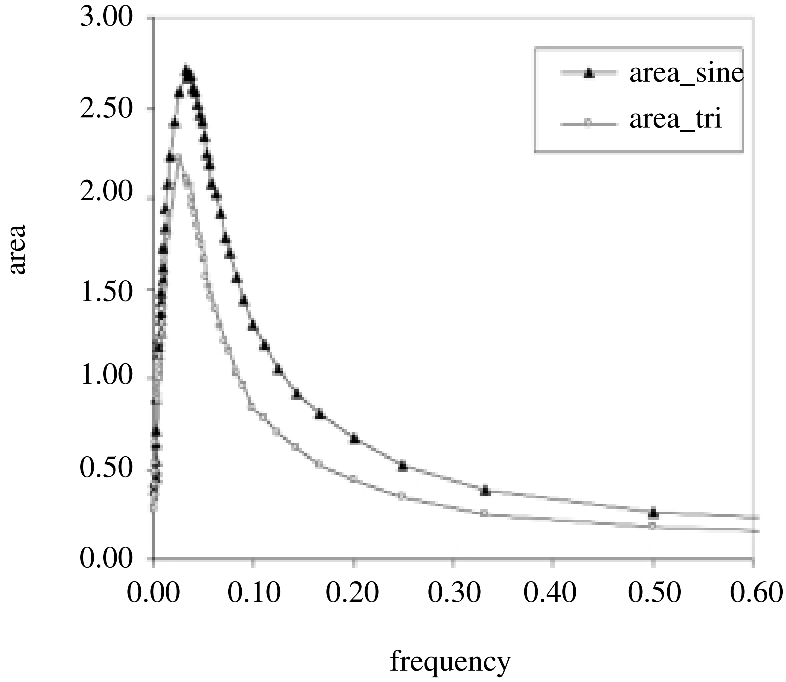



**Figure 2.** Simulated area of hysteresis loop A being driven by the sinusoidal magnetic field (– ▲ –: area_sine) and the triangular magnetic field (– □ –: area_tri) as a function of frequency $f$ plotted at a fixed amplitude ($h_0$ = 1 $J$) and a fixed temperature (T = 2.6 $J/k_B$).

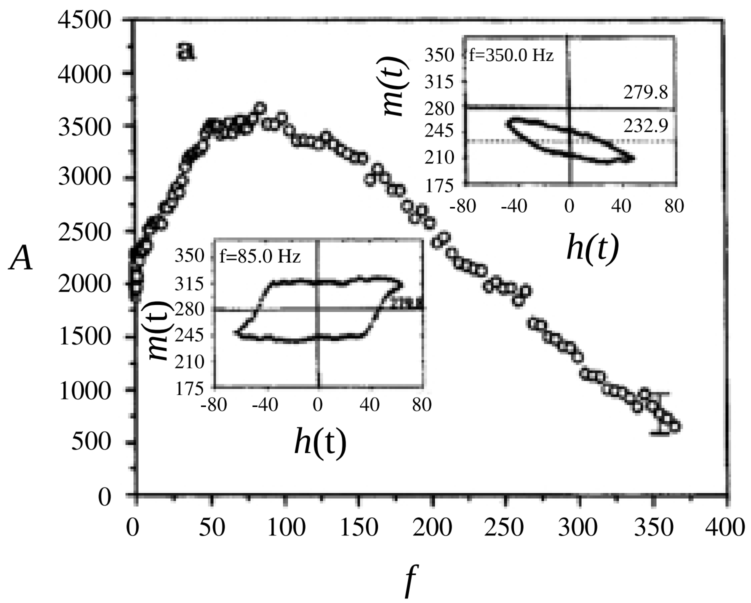
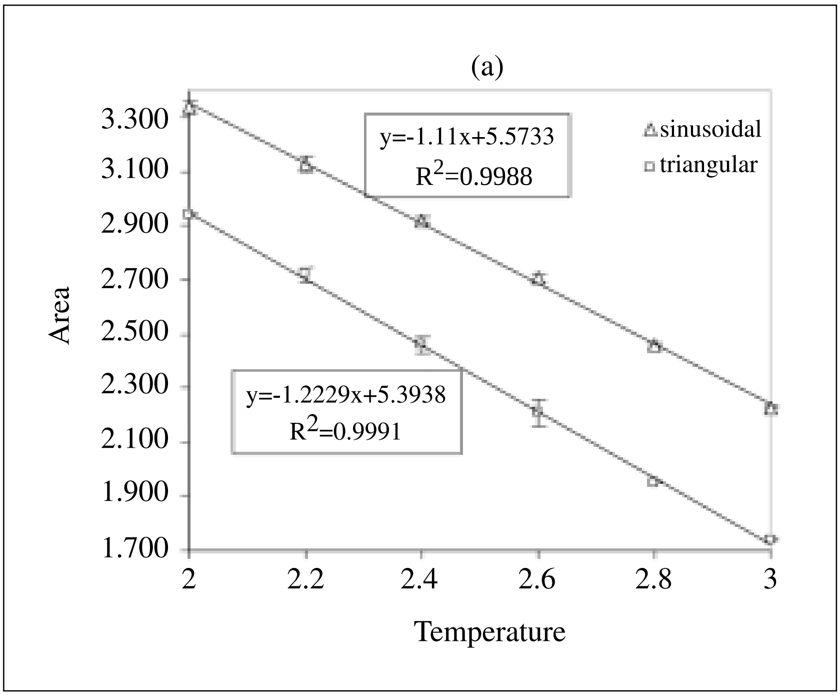



**Figure 3.** After Jiang et al., (1995), experimental results on the dynamic hysteresis loop-area as a function of frequency at a fixed ac current of 0.4 Amp. The direction of the magnetic field is parallel to the film plane. The insets show plots of m-h loop for the following particular values of the field amplitudes $h_0$ : (i) $h_0$ = 48.0 Oe (top inset) and (ii) $h_0$ = 63.0 Oe (bottom inset).

As can be seen in Figure 2, in comparison between the sinusoidal and the triangular magnetic field at a same frequency, the area *A* of hysteresis loop being driven by the sinusoidal field has a greater magnitude than the other. Moreover, the frequency at maximum area of sinusoidal field is higher than that from the triangular field. This is expected since there is more energy from the sinusoidal field that gives to the magnet in one period (at fixed $h_0$ and *T*).



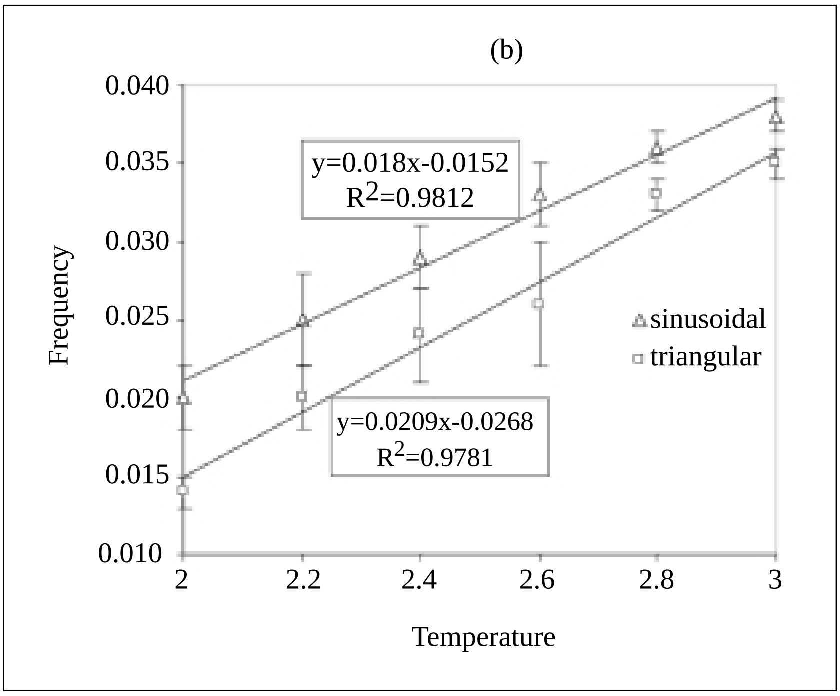




**Figure 4.** (a) Maximum area of hysteresis loop and (b) the frequency at the maximum area of the Ising system being driven by the sinusoidal magnetic field and the triangular magnetic field as a function of temperature plotted at a fixed amplitude $h_0$ = 8 J. Solid lines are the linear fits to the results.

It is also of interest to consider how these dynamic systems depend on temperatures. Therefore, we repeated the simulation procedures for a range of temperature from $T$ = 2 to 3 $J/k_B$ with a step of 0.2. Figure 4 shows an example of the temperature-dependent results by presenting the maximum area of hysteresis and the frequency at this maximum area which interestingly the linear relationships with temperatures are found. The maximum area decreases with increasing temperature due to that the higher thermal fluctuation reduces the magnetization magnitudes. On the other hand, the frequency at the maximum area increases with increasing temperatures. This is because the thermal energy and thermal fluctuation partly compensates the exchange coupling between magnetic spins. As a result, the spins use less effort to follow the field which decreases the phase lag between $m$ and $h$. Thus, this postpones the phase-lag optimum-point, i.e., $\pi/2$, to a higher frequency.

## CONCLUSION

In this study, we used Monte Carlo simulations to study the hysteresis behaviors of magnetic ultra-thin-film that is driven in time-dependent magnetic field. We considered the shape, area and pattern of the loop that responded to frequency and pattern of external magnetic field and temperature of the system. From our studies, we have found that the delay of the response magnetization to the field determines the hysteresis behaviors. The hysteresis loop-area increases as frequency increases at low frequencies, but the area decreases as frequency increases at high frequencies. On the other hand, with increasing temperature (and hence the thermal fluctuation), the effective delay of the response magnetization to the field decreases which reduces the hysteresis loop-area, and this shifts the frequency at the maximum area to a higher value. By comparing the detailed behaviors between the sinusoidal and the triangular magnetic field, the qualitative behaviors are of a similar trend. However, since there is a higher energy from sinusoidal magnetic field giving to the magnetic spins in one period, the area of the hysteresis retrieved from the sinusoidal field is greater than that from the triangular field.

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