Quantifying arbitrary-spin-wave-driven domain wall motion, the creep nature of domain wall and the mechanism for domain wall advances

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Abstract
Domain wall motion (DWM) by spin waves (SWs) in different waveforms in a magnetic nanostrip is investigated via micromagnetic simulations. Diversified DWMs are observed. It is found that SW harmonic drives DWM most efficiently and irregular SW may cause abnormal excitation spectrum for DWM in the low-frequency range. We prove that SW harmonic is the basic element when interacting with DW and causes simple creeping motion of DW (i.e. forward propagation of DW accompanied with oscillation) with the same frequency as applied SW harmonic. Under irregular/polychromatic SW, DW makes responses to the energies carried by constituent SW harmonics, instead of overall exhibited torques, and simultaneously conducts multiple creeping motions. This finding enables the analysis for the induced DWM under arbitrary SW. Mapping of SW inside DW reveals that the simple creeping motion is due to real-space expansion and contraction inside DW and the monolithic translation of DW. It is further elucidated that the former relates to the transmitting of spin torques of SW through DW and the latter corresponds to the absorption of spin torques by DW. The overall absorbed spin torques point to direction same as SW propagation and drive DW forward. In addition, the absorption mechanism is evidenced by the well agreement between absorption of SW and averaged velocity of DW.

1. Introduction

In nowadays information society, devices with higher data storage density and faster data processing speed are in ever-growing demands. To meet such demands, controllable domain wall motion (DWM) in magnetic thin film nanowire might provide a feasible future solution. In particular, with modules such as domain wall logic circuits [1], domain wall racetrack memory [2–4] and domain wall-based sensor [5] being conceived in the early time, the manipulation of DWM has attracted considerable interests. Vast investigation has demonstrated prominent DWM under external magnetic field [6–10] and spin-polarized currents [11–16]. However, high field and large injected current can both cause walker breakdown [17]. The scaling problem [18] and Joule heating [19, 20] also appeared to be their respective inevitable drawbacks. For these reasons, new possibilities are still being explored. Recent progress includes making use of voltage [21], temperature gradient [22–28], mechanical stress [29, 30], laser pulses [31], spin waves (SWs) [32–42], etc.

Among them all, the mean of SW holds strong competitiveness and is most widely studied. SW is a collection of precessional motions of magnetic moments around their equilibrium. It has long been considered to possess great potential in transmission and processing of information [43–46] in virtue of its low energy dissipation, ultrafast velocity [47, 48], and the wave nature that enables superposition and phase shift [43]. For its emission, it can be easily stimulated by applying an oscillating field or fast heating to a local region in the sample [49], which helps maintain device scaling. As a driving force for DWM, an abundance of studies also confirmed its validity in
various magnetic structures. In addition, the ability to assist other approaches for improved performance in DWM gives it an extra advantage [50, 51].

On the other hand, the interplay between SW and DW remains interesting in fundamental physics. Although great effort has been made in understanding the basic characteristics of SW-induced DWM in terms of both theoretical analysis [34, 35, 37–39, 41] and micromagnetic simulations [32–36, 40, 42], the precise picture in dynamics was never determined. So far, two major mechanisms were proposed: magnonic spin-transfer torque (STT) [34] and magnonic linear momentum transfer torque (LMTT) [11, 35]. In STT (for a simplified 1D model), linearization on Landau–Lifshitz–Gilbert (LLG) equation gives a solution of reflectionless propagating SW described by a Schrodinger equation. The obtained SW carries a constant magnon current transmitting through DW. Magnons can be viewed as spin-1 bosons with angular momentum $\pm h$ and linear momentum $hk$. As a magnon passes through the DW, its spin is changed by $2h$; according to the conservation of angular momentum, the spin of $2h$ must be transferred to DW, which further results in the backward motion of DW with respect to SW propagation [34, 41]. On the other hand, what concerns the LMTT theory is the conservation law for linear momentum. LMTT was proposed to explain cases with reflection. Reflected magnon reverses its wave vector $k$ in sign. That is, the linear momentum is changed by $2h$. The transfer of linear momentum to DW rewrites the effective field in LLG and causes forward motion of DW [35, 42]. STT and LMTT can only be partially correct due to the fact that SW transmission varies with frequency and the direction and velocity of DWM indeed depend on the SW transmission coefficient through DW [35, 39, 42]. Combining STT and LMTT [35, 42] successfully achieved a qualitative agreement with simulation. However, the effort seemed to fail to reproduce the results on a more quantitative level. Along with other unsolved puzzles such as the creeping motion of DW, the determinant to resection and transmission. Indeed, investigation on absorption by DW as a function of frequency demonstrates good accordance with respect to the averaged velocity of DW (normalized by the power of injected SW), which solidifies the absorption mechanism. As to the influence of LMTT, we believe it does give rise to a propelling...
force which does work to DW. However, it most likely serves to overcome the viscous damping as spins in DW rotate when DW translates forward.

2. Model and method

The configuration we construct and use is shown in Figure 1. It is 5600 nm long, 40 nm wide and 5 nm thick. In its initial state, a head-to-head TW is placed at the center and relaxed to stable.

The time evolving dynamics of the system is governed by the LLG equation [54, 55] which is embedded in our code

$$\frac{dM}{dx} = -\gamma M \times H_{\text{eff}} + \frac{\alpha}{M_s} M \times \frac{\partial M}{\partial t}. \tag{1}$$

Here, $M$ is the local magnetization vector; $M_s = |M|$ is the saturation magnetization; $H_{\text{eff}}$ is the effective field attributes to four interactions including exchange interaction, Zeeman interaction, magnetocrystalline anisotropy, and dipole-dipole interaction; $\gamma (=\mu_0 \gamma m_s)$ is the gyromagnetic ratio; And $\alpha$ is the so-called Gilbert damping constant.

For the simulations, we select the cell size of $4 \times 4 \times 5 \text{ nm}^3$ and adopt the material parameters corresponding to Py given its excellent conductivity for DW motion [7, 56]: saturation magnetization $M_s = 8.6 \times 10^5 \text{ A m}^{-1}$, exchange stiffness $A = 1.3 \times 10^{-11} \text{ J m}^{-1}$, damping constant $\alpha = 0.01$. The magnetocrystalline anisotropy $K$ is assumed to be 0 due to its negligible value. To model a wire with infinitely long length as well as to avoid possible distortion during simulation, the left-end and right-end edges are artificially pinned. In addition, in order to minimize the reflection of SW from two ends, each end within 100 nm long is implemented with the absorbing boundary condition of gradually increasing $\alpha$ as approaching the edge [36, 40]. To excite SWs in different waveforms, three types of signals (sinusoidal-, square-, and triangular microwave $H$ fields) are utilized. We apply one signal in one experiment, and in each case, the signal is applied along y-direction to a local area ($4 \times 40 \times 5 \text{ nm}^3$) [49] at 1600 nm away from TW center, see Figure 1. The excitation of SWs within such narrow area ensures that the excited SWs are to be with the same phase so as to avoid interference. Note that area with a width of 4 nm contains only 1 column of spins. The three signals are tuned to be with uniform power input so as to compare their efficiencies in driving DWM. For simplicity, in section 3, we will denote cases with an injection of sinusoidal ac field, square ac field and triangular ac field as case SI, case SQ and case TR, respectively.

3. Results and discussion

Figure 2 shows the displacements of DW as a function of simulating time at several representative frequencies for three cases. It is obvious that the induced DWM after SW arrives strongly depends on the frequency of SW for all cases. Note that explicit frequency of excited SW is consistent with the applied field regardless of field types. Explicit frequency is defined as the frequency calculated based on the periodicity of the explicit appearance of SW. Comparison between DW displacements in three cases at each frequency also indicates the different function of frequency dependence of DWM when subjected to different SWs. As seen, for high frequencies 18.5 and 20.5 GHz, the slopes of DW displacement in case SQ are of obviously lowered values compared with that of the other two cases. On the contrary, for low frequencies 2.65 and 4.5 GHz, sizeable displacements only occur under square ac $H$ field (see figure 2(b)), whereas in case SI and TR, we observe completely no DWM (see figures 2(a), (c)).

In figure 3, we explicitly demonstrate the frequency dependence of DWM (i.e. $v_{\text{DW}}$-versus-$f_{\text{SW}}$ relation) for each case over a wide range of frequencies from 1 to 42 GHz. $v_{\text{DW}}$ is the averaged velocity estimated in early time.
interval 6–10 ns, and $f_{SW}$ is the explicit frequency of SW. Resonant effect commonly exists as we identify three resonant peaks (13.5, 18.5, and 20.5 GHz) for all cases. The relative $\nu_{DW}$ value in between three cases for such medium frequencies is found to be in relation: $\nu_{DW}$ (case SI) $> \nu_{DW}$ (case TR) $> \nu_{DW}$ (case SQ). The problem of such resonant effect currently remains unresolved. Its possible origin may ascribe to SW-induced stray field and/or DW normal modes. In former theory, the traveling SW within DW causes surface magnetic charge on DW boundaries and further gives a dynamic stray field which acts as a potential barrier and leads to SW reflection [39, 57]. With such stray field taken into consideration, calculation has shown resonance of reflection that can justly reflect the resonant effect in DWM [39]. Note that it has been previously established that domain wall velocity strongly depends on transmission $T$/reflection coefficient $R$ of SW [35] (here, $R = 1 - T$). In the latter theory, resonance in DWM (or resonance reflection of SW) is related to DW ferromagnetic resonance. The correspondence has been demonstrated in [32, 39] and our early work [58]. When the frequency of propagating SW is coincident with that of DW normal modes, the SW-induced DW ferromagnetic resonance occurs, which gives SW resonance reflection (or resonance in DWM). A comprehensive analytical work that can give quantitative explanation for the resonant effect in DWM is currently in absence because of the lack of knowledge for the precise physical picture.

At low frequencies, expected prohibited band is observed in case SI as SW harmonics of such frequencies are strongly spatially localized. Note that by the observation of this study, sinusoidal ac $H$ field excites well-sine-shaped SW (i.e. SW harmonic) while square- and triangular ac $H$ fields excite SWs in diverse irregular waveforms. The localization of SW harmonics stems from two causes. First, quantization of in-plane components of SW wave vector due to lateral width confinement of thin film rectangular magnetic element leads to quantized SW eigenmodes, i.e. only SW harmonics at certain quantized frequencies can exist [44, 59, 60]. Secondly, possibly allowed low-frequency modes can only exist in limited internal field range, which further

Figure 2. Displacements of DW as a function of time at several representative frequencies (2.65, 4.5, 18.5 and 20.5 GHz) under (a). Sinusoidal ac $H$ field. (b). Square ac $H$ field. (c). Triangular ac $H$ field.

Figure 3. The averaged velocity of DW as a function of explicit SW frequency in the range of 1–42 GHz under three different ac $H$ fields. Three dominant peaks (13.5, 18.5 and 20.5 GHz) are identified. The largest DW velocity is estimated to be 17.49 m s$^{-1}$ at 13.5 GHz. Abnormal excitation spectrum with four minor peaks (2.65, 4.5, 6.1, and 6.8 GHz) is observed for case SQ.
indicates existence within limited space inside magnetic nanostripe. Reflection of SWs from areas with zero internal field and event of second turning of SWs due to the inhomogeneous field in nanostripe lead to the formation of potential well which localizes propagating SW eigenmodes [44, 60].

The threshold frequency of the prohibited band for SW harmonics is found to be \( \sim 8 \) GHz, which explains the flat displacement of DW at 2.65 and 4.5 GHz shown in figure 2(a). The propagation of SW harmonic of 4.5 GHz along the nanostripe is shown in figure 4 in comparison with that of SW harmonics of 13.5 and 38 GHz. As seen, the excited SW harmonic of 4.5 GHz rapidly decays near the very source. The same prohibited band is also observed in case TR and, interestingly, case SQ displays an abnormal minor excitation spectrum for DWM with four peaks (2.65, 4.5, 6.1 and 6.8 GHz), see figure 3.

To understand the induced DWM by irregular SWs in case SQ and case TR, we investigate the SW being generated at the source and the arrived SW to the left boundary of DW in these two cases. Considering the particular abnormity found in case SQ, we show its subcase that corresponds to its first minor peak (2.65 GHz) for demonstration. Applied signal (figure 5(a)) and the generated SW (figure 5(b)) have the same explicit frequency, as mentioned, but clearly different appearance. Carrying out FFT demonstrates exactly same discrete series (see figures 5(d), (e)), which implies that such irregular SW is generated as a superposition of the many SW harmonics excited by corresponding field harmonics that form applied polychromatic field. Comparison between generated SW and arrived SW to the left boundary of DW continuously shows consistent harmonic series except for 2.65 and 7.95 GHz (see figures 5(f), (e)). The extinction of harmonics of 2.65 and 7.95 GHz is due to the fact that they are located in the prohibited band and are strongly localized in space near the source, as mentioned. Therefore, we conclude that SW harmonics serve as the basic elements for SWs with respect to either its generation or propagation. Note that carrying out similar analysis to case TR manifests the same. Concerning the altered appearance of SW during generation and propagation, we consider it stems from the frequency dependence of both SW harmonic excitation efficiency and SW harmonic attenuation property, see figure 6.

With the conclusion drawn from figure 5, we may take a leap forward and tentatively assume SW harmonics serve as fundamental elements when interacting with DW as well. Note that we will verify it later in this paper. Based on this assumption, it further implies that the obtained DWM by SW can be sufficiently analyzed in terms of harmonics and superposition. Expanding the three signals of uniform power input into Fourier series gives us the following expressions:

\[
\text{Case SI: } H(t) = H_0 \cos \omega t
\]

\[
\text{Case SQ: } H(t) = 2\sqrt{2} \pi H_0 \left( \cos \omega t - \frac{1}{3} \cos 3\omega t + \frac{1}{5} \cos 5\omega t - \frac{1}{7} \cos 7\omega t + \ldots \right)
\]

\[
\text{Case TR: } H(t) = \frac{4\sqrt{2}}{\pi} H_0 \left( \cos \omega t + \frac{1}{3^2} \cos 3\omega t + \frac{1}{5^2} \cos 5\omega t + \frac{1}{7^2} \cos 7\omega t + \ldots \right).
\]

For an arbitrary frequency \( \omega_0 \), the power distribution with respect to constituent harmonics can be easily calculated through relation \( P(\cos n\omega_0) \propto (\text{Coefficient}(\cos n\omega_0))^2, n = 1, 3, 5, \ldots \). Hence, the 1st constituent harmonic \( \cos \omega_0t \) of the triangular signal is known to alone possesses 98.55% of the entire injected power. On the other hand, for the square signal, its 1st constituent harmonic possesses 81.06% of injected power. And as much as 18.94% of the distributed power is possessed by the higher orders. Nevertheless, considering that, for \( \omega_0 \) above the prohibited band, higher order harmonics have little effect on driving DWM (see the black curve in figure 3), the 1st harmonics in both case SQ and case TR contribute to DWM dominantly. Based on the powers that 1st
harmonics possess, the observed DWMs in case SQ and TR are indeed in expected proportion to the ones in case SI above the prohibited band. Regarding the abnormal excitation spectrum for DWM in the low-frequency range ($\omega_0 < 8$ GHz) in case SQ (see the red curve in figure 3), we show that it, in turn, can be ascribed to the

Figure 5. (a). Injected 2.65 GHz square ac field. (b). Generated SW at the source. (c). Arrived SW at the left boundary of DW (left 50th lattice point from center). (d)–(f) show the corresponding fast Fourier transform (FFT) spectra for (a)–(c).

Figure 6. (a). Excited harmonic SWs' amplitudes as a function of frequency under uniform power input. (b). Attenuation length of harmonic SWs as a function of frequency. Attenuation length $\Lambda$ is obtained by exponential fitting based on the envelope of $M_y(x)$ using $A \exp(-x/\Lambda)$. $A$ is the amplitude of SW at $x = 0$. 
conduct FFT. Note that net displacement is a linear function of time with a slope equivalent to the averaged
constituent higher order harmonics. At such low frequencies, as mentioned, the 1st harmonic \( \cos \omega_0 t \) is prohibited. However, constituent triploid and pentaploid harmonics may be allowed to travel and reach the location of DW and further cause notable DWM due to the considerable power they possess. Indeed, one can easily realize that the three minor peaks (4.5, 6.1, 6.8, see red curve in figure 3) rise from the three dominant peaks we previously identified (13.5 GHz \((=3 \times 4.5 \text{ GHz})\), 18.5 GHz \((=3 \times 6.1 \text{ GHz})\), 20.5 GHz \((=3 \times 6.8 \text{ GHz})\)) as the latters serve as their triploid harmonics. Similarly, the peak of 2.65 GHz can be attributed to its pentaploid harmonic which is of 13.5 GHz. In figure 7, we show the excellent agreement between simulated DWM and the DWM by analytical calculation for case SQ. Calculated DW velocity is obtained based on the acquired profile of \( v_{\text{DW}} \)-versus-\( f_{\text{SW}} \) of case SI (see the black curve in figure 3) and power distribution determined by equation (5). The explicit expression is listed as follow:

\[
v_{\text{SQ}}(\omega) = \sum_{i=0}^{n} \frac{P_{\text{SQ}}((2n+1)\omega)}{P_{\text{SQ, total}}} \cdot v_{\text{SQ}}((2n+1)\omega),
\]

where \( v_{\text{SQ}}(\omega) \) is the desired velocity at frequency \( \omega \) in case SQ, \( P_{\text{SQ}}((2n+1)\omega) \) is the power possessed by high order \( \cos((2n+1)\omega) \) in case SQ, \( P_{\text{SQ, total}} \) is the total power of the injected signal in case SQ, and \( v_{\text{SQ}}((2n+1)\omega) \) is the adopted value of velocity at \((2n+1)\omega \) in case SI (see figure 3, black curve). Above described analysis and equation (5) for calculation of DWM require no precondition and therefore apply to all situations as long as the constituent harmonics of SW spectrum is known. Thus far, we have enabled the calculation for arbitrary-SW-driven DWM.

In order to get a glimpse of how DW interacts with incoming SW, in figure 8, we record the arrived SWs to the left boundary of DW (red lines) and the consequent DW displacements (blue lines) for cases under SW harmonic (figure 8(a)) and square-field-stimulated SWs (figures 8(b), (c)). Under SW harmonic, DW demonstrates monotonously oscillatory behavior under the injected SW. The frequency of DW oscillation is found to be the same as that of injected SW. Such oscillatory motion of DW has been reported in our previous work [58] as well as in works carried out by others [40]. By eliminating the delay, we observe very good accuracy between \( M_r \) and DW displacement (see inset in figure 8(a)), which likely suggests that DW reacts to the precession torques carried by SW and do motion back and forth. Our investigation based on a case with an injection of square-field-stimulated SW of 2.65 GHz (figure 8(b)), however, indicates otherwise. Although the injected SW and the corresponding DWM still have the same periodicity, the ups and downs in DWM do not match with that of recorded \( M_r \) profile accordingly (see attached inset). A more clear contrast is shown in the inset of figure 8(c) where 4.5 GHz square-field-stimulated SW is injected. We thus conclude that precession torques carried by injected SWs and induced DW motion are not in universal correlation. Ignoring the oscillatory behavior of DW, DW exhibits net advances with constant speed, which is a common phenomenon for all cases.

To gain a better understanding of the intricate DW displacement profile under polychromatic SW, we subtract the net displacement reported above from the recorded DW displacement and obtain the DW local oscillation profile. Such profile keeps the oscillatory characteristic of actual DW displacement and allows us to conduct FFT. Note that net displacement is a linear function of time with a slope equivalent to the averaged
velocity. The produced DW local oscillation profile for a case with an injection of 2.65 GHz polychromatic SW is shown in figure 9(a) (see the black line). As seen, the ups and downs in the profile all synchronize the ones in recorded DW displacement (blue line), which manifests successful manipulation. Subsequent FFT spectra for the above DW local oscillation profile and the injected polychromatic SW are shown in figure 9(b). The apparently overlapped series of peaks in two FFT spectra indicates that DW displacement by a polychromatic SW is the result of the superposition of multiple simple creeping motions of DW caused by constituent SW harmonics, which just verifies the assumption we made earlier. In view of the successful explanation for the frequency dependence of DWM based on power, we thus conclude that, in regards to the interaction between DW and polychromatic SW, DW makes responses to the energies carried by each individual SW harmonics and simultaneously do multiple simple creeping motions. In figure 9(b), one may additionally find that the relative amplitude in between peaks in FFT spectrum of DW local oscillation is different from that of FFT of injected SW, in particular for 13.25 and 18.55 GHz. This can attribute to the frequency dependence of DW local oscillation.
Mx varies with oscillating frequency which is the same as that of injected SW harmonic. The oscillating amplitude, however, is constant net velocity that there exists monotonous phase shift differences in phase and amplitude in local oscillation, the early reported process of spin-wave phase shift accumulation across DW frequency dependence is also the reason why we trace the locations of multiple states: to know what happens inside DW requires the status of all parts. For the TW in this study, we simultaneously carry out further study towards this problem.

Remarkably, we observe vivid creeping motions for all motions caused by constituent SW harmonics, the left unknown physics regarding the interaction between DW and SW then simply lie in understanding such simple creeping motion. Simple creeping motion likewise is the fundamental of states. Recorded creeping motions exhibit uniform distributions of states in which spins are pointed to x + and x −, respectively. The spacing that correspond to intervals Mx(6, 9), Mx(3, 6), Mx(0, 3), Mx(−3, 0), Mx(−6, −3), Mx(−9, −6), respectively. (d) Estimated DW width Δ as a function of time (= the spacing of interval Mx(−9.9, 9.9)). (b)-(d) are plotted within time interval 11.35–11.71 ns and are obtained based on a case with an injection of SW harmonic of 15 GHz.

As we determine that DW movement by arbitrary SW is just a superposition of multiple simple creeping motions caused by constituent SW harmonics, the left unknown physics regarding the interaction between DW and SW then simply lie in understanding such simple creeping motion. Simple creeping motion likewise is the summation of net displacement and local oscillation, as discussed. The spin–wave-driven net displacement of DW, which relates to the averaged velocity of DW, has been vastly investigated by an abundance of previous researches since it is of key interest in technological application. However, the DW local oscillation specifically related to SW as a newly discovered phenomenon has not yet been studied and explained. In the following, we carry out further study towards this problem.

In simulation, the recorded DW displacement is in fact obtained by locating the position of state Mx = 0 during simulation as we know that, in walker profile, state Mx = 0 corresponds to the center of DW. However, to know what happens inside DW requires the status of all parts. For the TW in this study, we simultaneously trace the locations of multiple states: Mx = −9, −6, −3, 0, 3, 6, 9 (see figure 10(a)). Note that Mx = 10 and Mx = −10 correspond to states in which spins are pointed to x+ and x−, respectively. The spacing of interval Mx(−10, 10) represents the DW width Δ. Figure 10(b) shows the displacements of each monitored Mx as a function of time within time interval 11.35–11.71 ns for a case with an injection of SW harmonic of 15 GHz. Remarkably, we observe vivid creeping motions for all Mx states. Recorded creeping motions exhibit uniform oscillating frequency which is the same as that of injected SW harmonic. The oscillating amplitude, however, varies with Mx. As seen, it increases as position changes from DW center to edge. Meanwhile, a close look tells that there exists monotonous phase shift P(Mx) as we increase Mx. This phenomenon in point of fact visualizes the early reported process of spin–wave phase shift accumulation across DW [39, 40, 58]. Despite all these differences in phase and amplitude in local oscillation, Mx's demonstrate parallel net translation indicated by the constant net velocity vnet which suggests it is a property of DW as unity.

(see inset in figure 9(b)) where SW harmonic of 18.55 GHz clearly causes larger local oscillation of DW. Such frequency dependence is also the reason why we find desynchronization in figures 8(b), (c).

Figure 10. (a). The Mx profile of the transverse wall studied in this paper. Δ indicates the DW width. The colored dash lines are used to mark the states Mx = −9 (blue), −6 (sky blue), −3 (light green), 0 (yellow), 3 (orange), 6 (brown), 9 (red). (b). Recorded displacement of states Mx = −9, −6, −3, 0, 3, 6, 9. P(Mx) indicates the phase of local oscillation as a function of Mx inside DW. vnet indicates the constant net velocity of Mx. The oscillating frequency is found to be the same as that of injected SW harmonic. (c). The spacing that correspond to intervals Mx(6, 9), Mx(3, 6), Mx(0, 3), Mx(−3, 0), Mx(−6, −3), Mx(−9, −6), respectively. (d). Estimated DW width Δ as a function of time (= the spacing of interval Mx(−9.9, 9.9)).
In figure 10(c), we show the spacing of each segmented $M_s$ interval produced from figure 10(b). Clear local expansions and contractions inside DW are observed. The magnitude and phase of such expansion and contraction also vary as one may expect. The obvious differences between the spacing of $M_s(6, 9)$ and that of $M_s(-9, -6)$ due to monotonous phase shift $P(M_s)$ and commonly existing SW attenuation indicate the breaking of symmetry, which means that the walker profile is no longer sustained. Finally, out of interest for the length of the entire DW, we present the approximated DW width estimated by measuring the spacing of $M_s(-9.9, 9.9)$ in figure 10(d). Thus far, two conclusions can be drawn: (i). DW cannot be simply taken as a rigid object; (ii). Local oscillation of $M_s$ can be equivalently viewed as a result of local expansion and contraction inside DW. Note again that the frequency of local oscillation as well as that of expansion and contraction inside DW is consistent with injected SW harmonic. It is important to point out that the above described pattern is commonly observed for all frequencies. Thus, such pattern may be considered as the intrinsic pattern when SW harmonic interacts with a TW. The specific parameters including net velocity and local oscillation amplitude, however, strongly depend on frequency (see figure 3 black line, figure 9(b) inset).

A complemented pattern of figure 10(b) with plotted curves for all $M_s$ within interval $M_s(-10, 10)$ can be viewed as a thorough mapping of SW inside DW. In order to study the property of oscillation, in figure 11(a), we show the abstractive schematic illustration of spin states at several positions near DW center within one period of SW propagation based on the mapping (figure 10(b)) with the factors of net translation $v_{\text{net}}$ and phase shift $PM_x$ removed. It can be easily realized that the oscillatory motion of state $M_x = 0$ (see yellow dash line) is merely a process of upward-spin state periodically changing position from one location to another. The obvious spatial confinement (see the black dash–dot line) of the upward-spin state can be understood in term of the gradient of $M_x$ in DW (see figure 10(a)) and the limited perturbative precession of each spin. However, its sinusoidal trajectory can only be ascribed to the intrinsic pattern (see figure 10(b)) itself as it represents the interaction between SW and DW. It is important to point out that it is the transmitting of precession torque that results in the back and forth migration of state $M_x = 0$ as explained as follow. As we draw an arbitrary vertical line intersecting figure 10(b), we find maintained hierarchy from $M_x = -10$ to $M_x = 10$. Transient transfer of torque (see hollowed arrows) to spin at specific position changes its $M_s$ value up and down periodically. Due to the hierarchy, the $M_x$ state of value at equilibrium (e.g. $M_x = 0$) is then expected to conduct back and forth migration in space. This process exactly justifies the correlation we found between injected SW harmonic and corresponding DW creeping motion in figure 8(a).

In consideration of net translation, the corresponding schematic is depicted in figure 11(b). Note that each plotted spin indicates the spin state at its located coordinate. The grayed spin states correspond to exactly the ones in figure 11(a) but with adjusted locations due to translation. Translation as a function of time is indicated by the double-headed arrows. The colored spins show the spin states at the fixed position ($x = 0$) along with time. With small perturbative precession of spin and approximately unchanged DW profile, the linear relation between the gained angular momentum of spin due to translation and the translation itself—length of the double-headed arrows is rather straightforward; in other words, the net advance of spin states in DW is a result of absorption of angular momentum of spins in DW. In view of uniform net velocity $v_{\text{net}}$ shared by all spin states.
and the symmetry of walker profile, the net absorption of angular momentum by DW points to positive x-direction and is with a constant rate.

Above findings suggests the same STT mechanism that drives DW as in [34]. However, the direction of transferred torque is completely reversed and it causes forward motion of DW. Indeed, unlike object in empty space, for the motion of a head-to-head TW in ferromagnetic medium, in our opinion, the transfer of angular momentum to DW is a fundamentally inevitable process, which under no circumstances can LMTT explain. Such transfer necessarily consumes a certain portion of SW in addition to retransmission gives negative-x-direction magnonic STT which causes backward DWM and reflection can never give positive-x-direction magnonic STT since the amplitude of reflected SW can never be greater than incoming SW.

To evidence the above absorption mechanism that explains the net displacement of DW, we for the first time measure the absorption of SW in the region containing DW within frequency range 11–24 GHz which includes three resonant peaks (see red dot line in figure 12). In comparison with the averaged velocity of DW (normalized by the power of arrived SW to the left boundary of DW) (see blue dot line), it indeed demonstrates well agreement.

One may question how can absorption of SW give forward motion of DW since the incoming SW from left side carries negative-direction angular momentum. However, the transfer of angular momentum from SW to DW does not depend on the type of angular momentum that SW carries. It is possible for the absorbed portion of SW/excitations/magnons which carries negative-direction angular momentum to transfer positive-direction angular momentum to DW while itself becomes more negative in x-direction angular momentum. Note that magnons enable annihilation and recreation, as long as the conservation law is obeyed. For example, in [34], the x-direction angular momentum/magnons changes from, e.g. $-a$ (carried by incoming SW from the left side) to $+a$ (when SW all transmitted to the right side). It can be viewed as two processes: $-a$ to 0 and 0 to $a$. The latter process is an example of recreation.

Energy-wise, above process is also allowed. A gain of negative-direction angular momentum in the absorbed SW/excitations needs not to increase the energy of the absorbed SW, i.e. the energy can still be conserved. Note that, inside DW, the scenario of SW/excitation should not be pictured as the incoming SW at the left side. Inside the static DW (in this case, it is a head-to-head TW with walker profile), one can notice that the spins gradually become perpendicular with respect to the longitudinal axis as approaching the middle. Spins near the middle are able to have relatively large x-direction angular momentum while being with limited excitation amplitude. Therefore, it is possible to have a state of SW/excitation in DW to carry enlarged negative-direction angular momentum while conserving the absorbed energy. And eventually, such state can be damped naturally.

The conservation of the energy for the absorbed SW/excitation by DW also acts as a boundary condition, which confines the SW/excitation pattern inside DW, i.e. the SW/excitation pattern inside DW cannot be random. (Note that we did observe unified pattern of SW in DW under propagation of SW harmonic of arbitrary frequency.) Assume a fixed pattern of SW/excitation in DW, when one increases the absorbed energy, it would indicate an accordingly increased amplitude of the excitations of the spins in DW, which further imply an
accordingly increased negative-direction angular momentum gain in SW due to the transfer of positive-direction angular momentum to DW. Since the negative-direction angular momentum gain in SW is equal to the transfer of positive-direction angular momentum to DW, and the transfer of positive-direction angular momentum is proportional to the forward movement of DW, we expect good accordance between the absorption of SW and DW forward velocity as exactly we obtained in figure 12.

It is worthwhile to mention that, by observation of this study, we also find accordance between the averaged velocity of DW and reflection with respect to peak positions, which exhibits consistency to studies that report strong reflection dependence of DWM and support LMTT [35, 39, 42]. However, as mentioned, the theory of LMTT should not be able to yield the required STT. As to the influence of LMTT, we believe the impinge of magnons to DW does give rise to a propelling force which does work to DW once DW moves forward. From this perspective, LMTT may also be the inducement for the absorption of SW. Meanwhile, the work done by LMTT serves to overcome the viscous damping as spins in DW rotate when DW translates forward.

4. Conclusions

In conclusion, we carried out an investigation of the induced DWM by SWs in a magnetic nanostripe by the mean of micromagnetic simulation. Simulated results exhibit diversification in DWM when subjected to SWs in different waveforms. The observed DWM by arbitrary SW can be successfully explained via Fourier analysis in terms of power distribution as SW harmonic is proved to be the necessary basic element when interacting with DW. SW harmonic causes simple creeping motion of DW. It is made clear that, with an injection of arbitrary SW, DW makes responses to the energies carried by constituent SW harmonics, instead of overall exhibited torques, and simultaneously conducts multiple creeping motions.

We point out that the observed DWM reflects the migratory trajectory of state $M_x = 0$. Mapping of SW inside DW illustrates that the creeping behavior is shared by all $M_x$ inside DW with uniform net translation and frequency but different local oscillation amplitude and phase when under SW harmonic, which suggests the process of local expansions and contractions inside DW along with monolithic advances. The obvious discrepancy in local expansion and contraction indicates that the walker profile cannot be sustained. The frequency of creeping motion of $M_x$ as well as of local expansion and contraction is found consistent with that of applied SW harmonic.

Finally, we elucidate that the local back-and-forth oscillation and net translation of $M_x$ correspond to processes of transmitting of angular momentum of SW through DW and absorption of angular momentum by spins in DW, respectively. The steady forward movement of DW suggests a constant absorption of spin angular momentum by DW with direction same as SW propagation. The proposed absorption mechanism is further evidenced by the well agreement between absorption of SW and averaged velocity of DW (normalized by power injected SW).

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