Resonant translational, breathing and twisting modes of pinned transverse magnetic domain walls

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We study resonant translational, breathing and twisting modes of transverse magnetic domain walls pinned at notches in a ferromagnetic nanostrip. The translational mode’s eigenfrequency remains non-zero as long as the domain wall is pinned, approaching zero as the notch depth goes to zero or when the applied field approaches the depinning field. However, the breathing and twisting modes, which exhibit geometry-dependent frequency crossings, have non-zero frequencies even in the absence of confinement, demonstrating that they are intrinsic domain wall excitations. Interestingly, the breathing mode is characterized by a low sensitivity to the notch geometry which could be exploited to enable reliable excitations of multiple pinned domain walls within a device, even for non-identical notches or in the presence of small lithographically-generated edge defects.

Domain walls (DWs) separate oppositely oriented magnetic domains in ferromagnetic strips and are of interest for applications ranging from data storage and (neuromorphic) computing to biomedicine and high frequency electronic oscillators. Depending on the application, a domain wall may be driven through a nanostrip (e.g., to perform a write operation in a domain wall memory device) and/or resonantly excited. These excitations correspond to resonant precessional dynamics of the device’s magnetization that are localized on the DW and which generate periodic deformations of its structure.

DW resonances can be exploited in DW oscillators, in magnonic devices for signal processing and computation and for resonant depinning or spin-wave assisted DW motion in DW shift registers. However, the use of resonant phenomena will rely on successful control of a DWs’ resonant modes. Geometrical constrictions such as notches have been widely used to provide positional stability of DWs and may also be used to control a DW’s resonant properties. Indeed, when large, the geometry of a notch can be well controlled and successfully used to tune the frequency of a DW’s translational mode within the resulting confining potential. However, for smaller geometries it becomes more difficult to fabricate notches uniformly and their size can become comparable to lithographically induced defects.

Understanding the influence of small variations in notch geometry on the resonant modes of a DW is thus important for device applications and can also be useful in predicting the effects of uncontrolled small defects.

This work is focussed on geometry-dependent resonant properties of pinned head-to-head transverse domain walls (TDWs, Fig. 1(a)). TDWs arise in thin, narrow, in-plane magnetized strips and represent an important system for high density DW devices. We use a numerical eigenmode method to study three TDW resonances: the well known translational mode, a higher frequency twisting mode and the breathing mode (recently considered for oscillator applications). We demonstrate clear, unique and, in some cases strong, dependencies of each mode’s frequency on the strip width and the depth of the notch and its position (i.e., whether it is located at the narrow or wide end of the TDW). Interestingly, we find a comparatively weak sensitivity of the breathing mode to the notch geometry which is of potential interest for device applications where reliable DW excitation is required, irrespective of the geometry of a notch.

Many numerical studies of resonant modes use time domain ‘ringdown’ methods in which Fourier analysis is employed to extract mode frequencies. These methods require the system to be subjected to an external excitation (typically a pulsed field). In contrast, the eigenmode method used in this work, as for the dynamical matrix method, enables a direct calculation of resonant magnetic modes from a system’s equilibrium magnetic configuration. This offers the ability to observe the full mode spectrum without requiring careful choice of the symmetry of the ringdown excitation. It also enables the study of modes at fields which are arbitrarily close to the static depinning field where resonant motion would normally lead to a DW moving away from the notch.

The simulated system is a 5 nm thick Permalloy strip (saturation magnetization: 860 kA/m and exchange stiffness: 13 pJ/m) with tapered ends and two central notches for TDW pinning at x = 0 [Fig. 1(a)]. Finite element micromagnetic simulations were run using Finmag (successor to Nmag). This paper focuses on excitations localized on the DW. In order to reduce computational time and memory use, we used a characteristic internode length l_{mesh} = 3 nm at x = 0 (< 5.7 nm, the NiFe exchange length) with a smooth transition to a larger l_{mesh} = 8 nm at the ends of the strip. The system was initialized with a trial head-to-head TDW configuration centered on x = 0 and allowed to relax with damping parameter α = 1, typically until dμ/dt < 10^7/μs at all points in the strip. The relaxed configuration was a TDW for all studied geometries. The system’s eigenmodes were calculated using a previ-
uously described method\textsuperscript{22} which is valid for small oscillations $\textbf{dm}(\mathbf{r})$ around the TDW’s ground state, $\mathbf{m}_0(\mathbf{r})$ [Fig. 1(a)].

The algorithm computes a number of modes of increasing frequency, $f$. Each $f$ has a real and an imaginary part with the latter typically 3-4 orders of magnitude smaller than the former. We quote the real part\textsuperscript{22} of $f$. Eigenmodes localized at the TDW can be identified by visual inspection of the spatially resolved eigenvectors. Either the dynamic component, $\textbf{dm}(\mathbf{r})$, may be inspected alone or it can be scaled and added to $\mathbf{m}_0(\mathbf{r})$, enabling a visualization of the actual TDW dynamics for each mode (see supplementary animations\textsuperscript{22}).

The three lowest frequency TDW modes correspond to translational, breathing or twisting deformations. In Figs. 1(b-d) these three calculated modes are shown (dynamic component, $\textbf{dm}(\mathbf{r})$, only) for a 75 nm strip with symmetric, triangular notches both having a width, $w_{\text{notch}} = 20$ nm and a depth of intrusion into the strip, $d_{\text{notch}} = 10$ nm. The translational mode ($2.61$ GHz) corresponds to an oscillatory, side-to-side motion of the standing waves with a zero-displacement node (crossing the nanostrip, this mode has similarities with two ends (near the top/bottom of the nanowire) moving standing waves with a zero-displacement node ($H < H_{\text{depin}}$)). The different $H$-dependencies of the twisting and breathing mode, coupled with their intrinsically close frequencies results in a mode crossing which, for this 5 nm thick strip, occurs at $w = w_c \approx 88.4$ nm. For $w \approx w_c$ [Fig. 3(b)], we obtain a translational mode as well as two other distinct TDW modes which are output as mixed twisting-breathing modes [Fig. 3(c)]. Analogous mixed modes were also calculated using another mode solver\textsuperscript{22} from the SpinFlow3D package. This apparent mixing effect arises due to the arbitrary basis chosen by the eigensolver, and each mixed mode can be shown to be a linear combination of the orthogonal twisting and breathing eigenmodes\textsuperscript{22}. This mode mixing can be noticed when visually inspecting the modes for $|w - w_c| \lesssim 1.5$ nm with the computed modes becoming more ‘pure’ (i.e. a dominant breathing or twisting characteristic) as $|w - w_c|$ increases. In Fig. 3(b), all modes at $w \neq 88.4$ nm are la-

\begin{figure}[h]
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\includegraphics[width=\textwidth]{fig1.png}
\caption{FIG. 1. (a) Zero-field equilibrium magnetization configuration, $\mathbf{m}_0(\mathbf{r})$, in a 75 nm wide NiFe strip with symmetric notches ($w_{\text{notch}} = 20$ nm, $d_{\text{notch}} = 10$ nm) containing a head-to-head TDW with $m_y$ color scaling. The black arrows indicate the local magnetization direction. The $x$ and $y$ axis origins are also shown. (b-d) Snapshots of the (b) translational ($m_y$ color scaling), (c) breathing ($m_y$ color scaling) and (d) twisting ($m_x$ color scaling) modes showing the dynamic component only ($\textbf{dm}(\mathbf{r})$).}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig2.png}
\caption{FIG. 2. (a) Deformed domain wall in a 75 nm strip for $H_x = 5530$ A/m. Translational mode frequencies as a function of $H_x$ for a strip width of 75 nm and 60 nm with symmetric notches: $d_{\text{notch}} = 10$ nm and $w_{\text{notch}} = 20$ nm. The different $f$ versus $w$ dependencies of the twisting and breathing mode, coupled with their intrinsically close frequencies results in a mode crossing which, for this 5 nm thick strip, occurs at $w = w_c \approx 88.4$ nm. For $w \approx w_c$ [Fig. 3(b)], we obtain a translational mode as well as two other distinct TDW modes which are output as mixed twisting-breathing modes [Fig. 3(c)]. Analogous mixed modes were also calculated using another mode solver\textsuperscript{22} from the SpinFlow3D package. This apparent mixing effect arises due to the arbitrary basis chosen by the eigensolver, and each mixed mode can be shown to be a linear combination of the orthogonal twisting and breathing eigenmodes\textsuperscript{22}. This mode mixing can be noticed when visually inspecting the modes for $|w - w_c| \lesssim 1.5$ nm with the computed modes becoming more ‘pure’ (i.e. a dominant breathing or twisting characteristic) as $|w - w_c|$ increases. In Fig. 3(b), all modes at $w \neq 88.4$ nm are la-
\end{figure}
beled either as twisting or breathing with the label corresponding to the mode which is dominant. Note that we expect no mode coupling in this eigenmode approach since this requires damping which is not included\(^2\). It was possible to observe the translational and breathing modes via the ringdown method with an excitation field applied respectively in the \(x\) and \(y\) direction (however, we were not able to efficiently excite the twisting mode\(^3\)). Fourier analysis of the ringdown dynamics at a strip width of 80 nm demonstrated excitation of the transaltional and breathing modes at frequencies of \(f_{\text{trans}} = 2.6 \pm 0.1\) GHz and \(f_{\text{breathe}} = 6.4 \pm 0.1\) GHz, in good agreement with the eigenmode results (\(f_{\text{trans}} = 2.61\) GHz and \(f_{\text{breathe}} = 6.38\) GHz for \(w = 80\) nm as per Fig. 3). Experimentally, microwave frequency \(x\) or \(y\) oriented (effective) magnetic fields can be generated by striplines\(^4\), Oersted fields due to in-plane current injection\(^5\), or tailorable spin torques in magnetoresistive devices\(^6,7\).

Finally, we consider mode frequencies for varying notch geometries (depinning fields as a function of notch geometry have been studied previously\(^8\)). In Figs. 4(a,b), each TDW eigenfrequency is plotted as a function of notch intrusion depth with symmetric, 20 nm wide notches on each side of the strip. \(f_{\text{trans}}\) decreases smoothly with \(d_{\text{notch}}\), with \(f_{\text{trans}}\) equal to 0 at \(d_{\text{notch}} = 0\), consistent with the wall being free to translate laterally in the absence of pinning. \(f_{\text{breathe}}\) and \(f_{\text{twist}}\) remain finite even with \(d_{\text{notch}} = 0\), suggesting that these modes are intrinsic excitations of the TDW structure (i.e. TDW confinement is not required to yield a finite eigenfrequency). In Figs. 4(c,d), we show mode frequencies observed when changing the notch intrusion depth on only one side of the strip (either at the wide end or at the narrow end of the TDW) while keeping the geometry of the other notch constant. Consistent with the results above, \(f_{\text{trans}}\) is most sensitive to changes in the notch geometry at the more strongly pinned, narrow end of the wall. Indeed, the changes in \(f_{\text{trans}}\) and \(f_{\text{twist}}\) are weakest when \(d_{\text{notch}}\) is modified at the wide part of the wall, further indication that it is less dominant in determining the mode frequency (crossed, open circles and diamonds in Fig. 4(c,d)). Reducing \(d_{\text{n}}\) from 10 nm to 2 nm at the narrow end of the wall however generates a 40% reduction in \(f_{\text{trans}}\). This is accompanied by a transition to a more pure translation of the TDW structure rather than having the highest amplitude dynamics at the wide end of the TDW [Fig. 4(a)].

The breathing mode exhibits a very low sensitivity to changes in the notch geometry: it changes by only 3% over the simulated range of \(d_{\text{notch}}\) values in Figs. 4(b,d). In contrast to the twisting and translational modes, breathing mode dynamics do not result in a local (twisting) or net (translational) movement of the DW away from the notches. Rather, the dynamics are concentrated at the TDW’s edges. Simulations run with the notch at the wide end of the wall displaced away from \(x = 0\) did lead to small changes in \(f_{\text{breathe}}\) (\(d_{\text{notch}} = 10\) nm, \(w_{\text{notch}} = 20\) nm) with some distortion of the breathing mode observed when the notch was right at the TDW’s edge. However the maximum frequency change still remained within 3% of the \(f_{\text{breathe}}\) observed for both notches located at \(x = 0\).

In summary, we have used direct micromagnetic eigenmode calculations to study the breathing, twisting and translational modes of TDWs in magnetic nanostrips containing triangular notches. The frequencies of all modes increase with decreasing strip width with the translational (and twisting) modes exhibiting a strong sensitivity to the notches’ intrusion depths. The use of the eigenmode method enables the study of modes near the TDW depinning field at which point the frequency of the translational mode drops sharply to zero. A weak sensitivity of the breathing mode’s frequency to the notch geometry was found, a result which holds even when the notches are slightly displaced from one another laterally. This result may be promising for using the breathing mode in oscillators and for microwave assisted domain wall depinning since the frequency of the breathing mode will be least sensitive to a strip’s defects and non-uniformity. This is important for reliable excitation of single DWs or simultaneous excitation of multiple DWs pinned at different positions within a strip\(^5,16\).

\section*{Acknowledgments}

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FIG. 3. (a) Frequencies of the three normal modes as a function of strip width, \( w \). The notches are symmetric \((d_{\text{notch}} = 10 \text{ nm}, w_{\text{notch}} = 20 \text{ nm})\). At \( w = 88.4 \text{ nm} \) the calculated modes are mixed breathing-twisting modes (see inset, b). (c) shows snapshots of the amplitude of the dynamic component (red) of the mixed modes found for \( w = 88.2 \text{ nm} \) at 6.091 GHz (c, upper, primarily a breathing mode) and 6.099 GHz (c, lower, primarily a twisting mode).

FIG. 4. (a,b) TDW eigenfrequencies versus \( d_{\text{notch}} \) when varying \( d_{\text{notch}} \) for both notches simultaneously. (c,d) Eigenfrequencies when varying \( d_{\text{notch}} \) only at one side of the strip, either at the wide end or narrow end of the wall while keeping the other notch intrusion depth fixed at \( d_{\text{notch}} = 10 \text{ nm} \). For all data \( w_{\text{notch}} = 20 \).

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Except for those simulations in which magnetic fields close to the DW depinning field are applied, the error in the mode frequency associated with the larger $f_{\text{mesh}}$ at the device ends was found to be less than 1%.
For a strip width of 75 nm and a thickness of 5 nm, using $\frac{dm}{dt} < 0.1^\circ/\text{ns}$ resulted in changes in the mode frequency of 1.1 Mhz or less (0.04% maximum) for each of the three TDW eigenmodes. However, the stopping criterion must be smaller when close to depinning [Fig. 2(b)].
To be provided with final published version. Please contact the first author in the interim.
See supplemental material at [URL will be inserted by AIP] for animated .GIF files which show the full resonant TDW dynamics, $\mathbf{d}(\mathbf{r}) + m_0(\mathbf{r})$, for each of the three TDW modes at a strip width of 75 nm with $d_{\text{notch}} = 10$ nm and $w_{\text{notch}} = 20$ nm.
Let $\mathbf{v}_1, \mathbf{v}_2$ be the ‘mixed mode’ eigenvectors as returned by the solver (their entries $(\in C)$ encode the amplitude and relative phase of the magnetization oscillations at each mesh node). To show that these can be reduced to the ‘pure’ modes we need to find scalars $a_1, a_2 \in C$ such that the linear combination $v = a_1v_1 + a_2v_2$ represents a breathing/twisting mode. The breathing mode is characterised by being fully symmetric about the $y$-axis, i.e. the oscillations in the left and right half of the nanostrip are out of phase by $180^\circ$: $v(x, y, z) = -v(-x, y, z)$. The expression $\int [v(x, y, z) + v(-x, y, z)]$ thus measures the deviation from symmetry for an eigenmode $v$ and we can find the ‘most symmetric’ linear combination by minimizing this with respect to $a_1, a_2$. Since each eigenvector is only determined up to a scalar, we can assume that $a_1 = 1$ (or $a_2 = 1$), reducing the dimensionality of the optimization problem. The obtained linear combination is confirmed to be an eigenvector corresponding to a breathing mode. Similarly, the twisting mode can be recovered by using the condition $v_{\text{twist}}(x, y, z) = v_{\text{twist}}(-x, y, z)$.
We attempted spatially uniform excitations along the $x, y$ and diagonal axes as well as a field parallel to the $x$-axis everywhere with strength proportional to the $y$-position [i.e. pointing in positive (negative) $x$-direction at positive (negative) $y$ as per Fig. 2(a)].
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