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Nonlocal compensation of magnetic damping by spin injection has been theoretically shown to establish dynamic, noncollinear magnetization states that carry spin currents over micrometer distances. Such states can be generically referred to as dissipative exchange flows (DEFs) because spatially diffusing spin currents are established by the mutual exchange torque exerted by neighboring spins. Analytical studies to date have been limited to the weak spin injection assumption whereby the equation of motion for the magnetization is mapped to hydrodynamic equations describing spin flow and then linearized. Here, we analytically and numerically study easy-plane ferromagnetic channels subject to spin injection of arbitrary strength at one extremum under a unified hydrodynamic framework. We find that DEFs generally exhibit a nonlinear profile along the channel accompanied by a nonlinear frequency tunability. At large injection strengths, we fully characterize a magnetization state we call a contact-soliton DEF (CS-DEF) composed of a stationary soliton at the injection site, which smoothly transitions into a DEF and exhibits a negative frequency tunability. The transition between a DEF and a CS-DEF occurs at the maximum precessional frequency and coincides with the Landau criterion: a subsonic to supersonic flow transition. Leveraging the hydraulic-electrical analogy, the current-voltage characteristics of a nonlinear DEF circuit are presented. Micromagnetic simulations of nanowires that include magnetocrystalline anisotropy and nonlocal dipole fields are in qualitative agreement with the analytical results. The magnetization states found here along with their characteristic profile and spectral features provide quantitative guidelines to pursue an experimental demonstration of DEFs in ferromagnetic materials and establish a unified description for long-distance spin transport.

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-0.4
-0.45
$n = m$

into account in Eqs. (5a) and (5b). An analytical methodology
for this task is boundary-layer theory [33

Fig. 2(c) that the full numerical solution (solid black curve) approaches the DEF and CS-DEF frequency tunabilities in the small and large injection limits, respectively. Whereas a first-order transition is not observed, it is insightful to find an analytical expression for a practical observable, such as the maximum precessional frequency, $\tilde{\Omega}_{\max}$. For this, we can utilize the implicit equation for a DEF fluid velocity profile, Eq. (15), to take the derivative with respect to $\bar{u}$ and equate $\partial/\partial\bar{u}\,(\tilde{\Omega}_{\mathrm{DEF}}) = 0$. Because Eq. (15) is implicit, the maximum frequency will be an implicit equation as well. Utilizing Eq. (16), we can eliminate $\tilde{\Omega}_{\mathrm{DEF}}$ and, after some algebra, we obtain the injection at maximum frequency, $\bar{u}_{\max}$, that depends on the input density at maximum frequency, $\bar{n}_{\max}$, according to

$$\bar{u}_{\max} = \pm\sqrt{\frac{1-\bar{n}^2_{\max}}{1+3\bar{n}^2_{\max}}}. \tag{24}$$

Interestingly, this is precisely the sonic curve, Eq. (3). This relation is a central result of this work. There are three physical implications of Eq. (24). First, the relation bounds the phase space for DEFs to the UHS subsonic regime, below the solid curve in Fig. 1

density and injection at the frequency maximum for 100, $(\bar{}_{max}, \bar{}_{max})$, is shown by a black circle in Fig. 3(a). These results have a clear physical interpretation. For short channels, the problem limits to a local balance between injection and damping. Therefore, the energy introduced into the system is primarily invested in spin precession. In the opposite limit of long channels, the energy is mainly invested in establishing a DEF to compensate damping nonlocally, and $\bar{}_{max}$ is large.

Analytical expressions for both $\bar{}_{max}$ and $\tilde{\Omega}_{max}$ can be

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