

Visions of fluid dynamics

Vortices vs. magnetic fields: Competing orders in flux tubes

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ABSTRACT

Solar atmosphere hosts intricate interactions between vortex tubes and magnetic flux, which channel convective energy into the upper atmosphere and shape large-scale magnetic activity. To probe these dynamics in a controlled setting, we perform direct numerical simulations of antiparallel vortex tubes embedded with magnetic flux tubes, varying the interaction parameter N_i that measures the Lorentz–inertial balance. High-resolution visualizations uncover distinct regimes of coupled evolution, including vortex-dominated reconnection, Lorentz-suppressed reconnection, instability-triggered cascades, and Lorentz-induced vortex disruption. The rendered structures highlight not only the physical transitions but also the striking morphologies, ranging from braided filaments to spiralized cores, that emerge as magnetic intensity strengthens. These findings show how Lorentz–inertial balance regulates reconnection, instability, and energy transfer in magnetohydrodynamic flows. Refers to: <https://www.sciencedirect.com/journal/european-journal-of-mechanics-b-fluids/about/news/visions-of-fluid-dynamics-video-competition>.

Solar turbulence provides a natural laboratory for investigating the interplay between vortical motions and magnetic fields in magnetohydrodynamic (MHD) flows. Ground- and space-based observations [1], together with magnetoconvection simulations [2], have revealed the ubiquitous presence of vortex tubes in the solar atmosphere. These vortical structures, comparable in scale to convective granules, link the solar surface to the corona, as illustrated in Fig. 1(a). Acting as channels for the transport of energy, mass, and momentum, they convey near-surface turbulence into large-scale magnetic activity [3]. By entraining plasma and twisting magnetic field lines, they tap convective energy and drive phenomena ranging from sunspot evolution to coronal mass ejections [4].

In idealized conditions, vortex and magnetic tubes are topologically frozen into the fluid, whereas in real systems, viscosity and resistivity permit reconnection [5], splitting [6], and instabilities that trigger breakdown [7] and bursting [8], collectively driving cascades that redistribute energy across scales. The efficiency of these processes is governed by the balance between magnetic and inertial forces, characterized by the interaction parameter $N_i = \Gamma_m^2 / \Gamma \eta \sigma_c^2$, where Γ is the circulation of the vortex tube, Γ_m the magnetic flux strength, η the magnetic diffusivity, and σ_c the core size. N_i thus measures the relative strength of the Lorentz force to inertial forces [9,10]. Observations suggest strong couplings between vortex and magnetic tubes in solar turbulence, yet their detailed dynamics remain elusive in plasmas. Systematic exploration across a broad range of N_i is therefore

essential to reveal how Lorentz–inertial balance drives instabilities, mediates energy transfer, and shapes the large-scale morphology of MHD turbulence.

We perform direct numerical simulations of antiparallel vortex tubes embedded with magnetic flux tubes of varying strengths by solving the three-dimensional incompressible MHD equations. The computational domain is a triply periodic cube of size $(2\pi)^3$, discretized on a uniform grid of 512^3 to 1024^3 points. Time integration is performed with a second-order Runge–Kutta scheme. A pseudo-spectral method is employed in the symmetric Elsässer formulation, with aliasing errors removed by the two-thirds truncation rule. Grid convergence has been verified, and the time step is chosen such that CFL numbers remain below 0.5 for both velocity and magnetic fields, ensuring numerical stability and full resolution of the flow evolution. Further details of the numerical implementation and validation are provided in our recent work, which is currently in press [11].

The initial condition, illustrated in Fig. 1(b), consists of a pair of antiparallel Lamb–Oseen vortex tubes with circulation $\Gamma = 1$, centered at $(y_0, z_0) = (\pm 0.81, 0)$ with core size $\sigma_c = 0.25$, embedded with co-located magnetic flux tubes of strength $\Gamma_m = 0.02, 0.06, 0.08$, and 1 , corresponding to interaction parameters $N_i = 19.2, 172.8, 307.2$, and $48,000$. The vorticity follows a Gaussian profile, while the magnetic flux distribution adopts the same form for consistency. The magnetic Prandtl number is set to unity, with vortex and magnetic Reynolds

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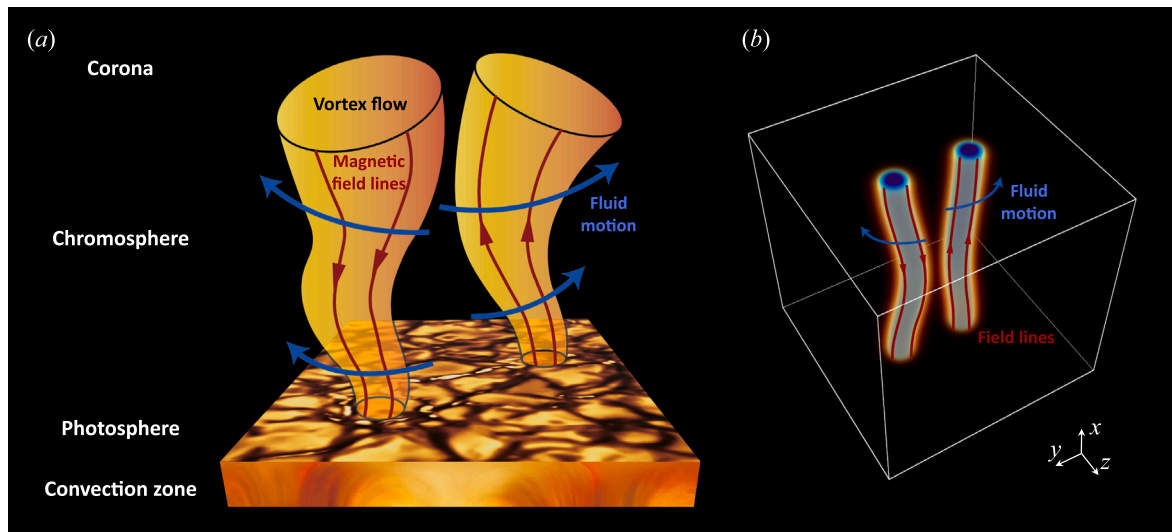


Fig. 1. (a) Conceptual illustration of vortex flows in the solar atmosphere. Vortices rise from the convection zone through the photosphere and chromosphere into the corona, where they couple with magnetic fields. Red lines denote magnetic field lines entrained within vortex tubes, and blue arrows indicate the sense of fluid rotation. (b) Initial configuration of the numerical setup: antiparallel vortex tubes carrying co-located magnetic flux tubes, visualized by the volume rendering of vorticity magnitude. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1

Simulation parameters for the four cases with different interaction parameters.

Parameter	Case I	Case II	Case III	Case IV
Domain size L^3			$2\pi \times 2\pi \times 2\pi$	
Grid resolution N^3	1024^3	512^3	512^3	512^3
Core size σ_c			0.25	
Separation l_s			1.62	
Perturbation amplitude p			0.2	
Vortex flux Γ			1	
Magnetic flux Γ_m	0.02	0.06	0.08	1
Interaction parameter N_i	19.2	172.8	307.2	48 000
Magnetic Prandtl number Pr_m			1	
Reynolds number Re			3000	
Magnetic Reynolds number Rm			3000	

numbers fixed at $Re = Rm = 3000$. To trigger coupled vortex and magnetic instabilities, the flux tubes are perturbed sinusoidally with amplitude $p = 0.2$, tilted by $\pi/3$. The parameters of all four simulation cases are summarized in Table 1. This canonical setup provides a controlled framework for examining the competition between vortex dynamics and Lorentz forces under dual frozen-in conditions at high Reynolds number.

Our visualizations reveal how the coevolution of vorticity and magnetic fields transitions across regimes, ranging from hydrodynamic-like behavior to strongly magnetically constrained dynamics. At low interaction parameters ($N_i \ll \mathcal{O}(10^2)$), where the magnetic tubes are weak, vortex dynamics dominate, with both vorticity and magnetic fields frozen into the flow. Vortex-induced motions drive joint vortex–magnetic reconnection (Fig. 2(a)), stretching flux tubes and amplifying magnetic energy, and leaving remnants of the original tubes in the form of threads. As the magnetic field strengthens, reconnection is progressively suppressed (Fig. 2(b)). At moderate interaction parameters ($N_i \sim \mathcal{O}(10^2-10^3)$), the interplay of vorticity-driven attraction and magnetic damping excites oscillatory instabilities that pluck the tubes in a string-like fashion, spawning numerous transverse secondary filaments and driving an energy cascade (Fig. 2(c)). At high interaction parameters ($N_i \gg \mathcal{O}(10^3)$), strong Lorentz forces dominate the flow, disrupting vortex cores, suppressing reconnection, and forcing tubes into axial alignment. The vortex cores are torn apart and reshaped into tightly wound spirals, forming striking patterns of twisted topology (Fig. 2(d)).

Overall, we delineate the pathways of vortex–magnetic structure evolution across N_i , with implications for plasma turbulence in both astrophysical and industrial contexts. Our recent work [11] quantified regime transitions and energy transfer at $Re = Rm = 2000$ and modeled the antagonism between vortical and magnetic dynamics. The present visualizations complement that study by extending to higher Re and N_i , thereby bridging toward solar-like regimes.

CRediT authorship contribution statement

Weiyu Shen: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Rodolfo Ostilla-Mónico:** Investigation, Methodology, Writing – original draft, Writing – review & editing. **Xiaoju Zhu:** Conceptualization, Funding acquisition, Project administration, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Xiaoju Zhu reports financial support was provided by German Research Foundation. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at <https://doi.org/10.1016/j.euromechflu.2025.204393>.

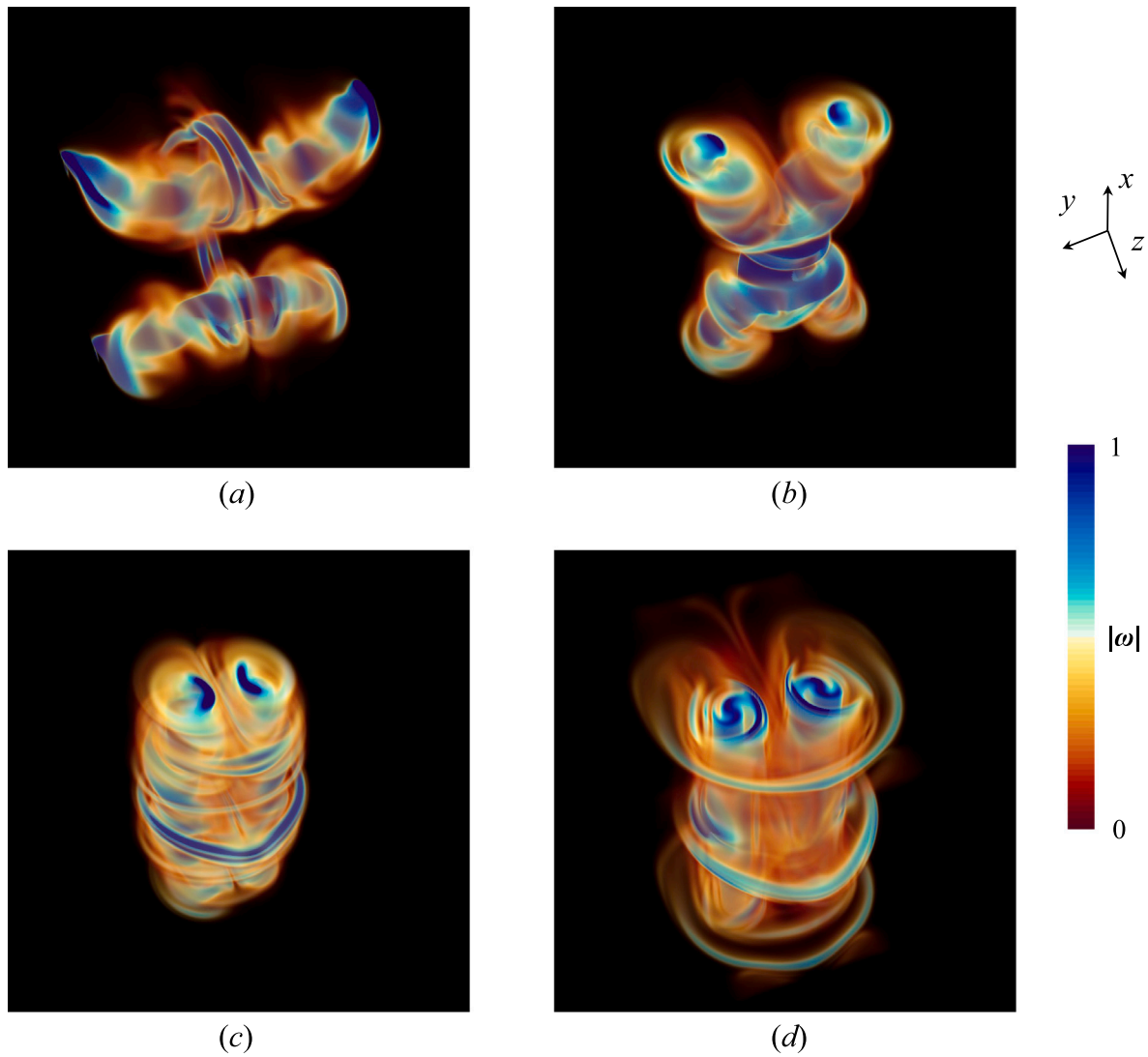


Fig. 2. Representative flow structures from independent simulations at the same non-dimensional evolution time $t^* = t / (2\pi l_s^2 / \Gamma) = 6.06$ for different interaction parameters N_i , visualized by volume rendering of vorticity magnitude: (a) vortex-dominated reconnection ($N_i = 19.2$), (b) Lorentz-suppressed reconnection ($N_i = 172.8$), (c) instability-triggered cascade ($N_i = 307.2$), (d) Lorentz-induced vortex disruption ($N_i = 48000$).

Data availability

Data will be made available on request.

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