PIC simulations of stable surface waves on a subcritical fast magnetosonic shock front

Mark Eric Dieckmann[1], Cesar Huete[2], Francisco Cobos Campos[3], Antoine Bret[3], Doris Folini[4], Bengt Eliasson[5], Rolf Walder[4]

1. Dept. of Science and Technology (ITN), Linkoping University, Campus Norrkoping, SE-60174 Norrkoping, Sweden
2. Univ Carlos III Madrid, Grp Mecan Fluidos, Leganes 28911, Spain
3. Univ Castilla La Mancha, ETSI Ind, Ciudad Real 13071, Spain
4. Instituto de Investigaciones Energéticas y Aplicaciones Industriales, Campus Universitario de Ciudad Real, 13071 Ciudad Real, Spain
5. Univ Lyon, ENS de Lyon, Univ Lyon 1, CNRS, Centre de Recherche Astrophysique de Lyon UMR5574 F-69230, Saint-Genis-Laval, France
6. Univ Strathclyde, SUPA, Glasgow G4 0NG, Scotland, United Kingdom

Observations by the MMS multi-spacecraft mission [1] have revealed oscillations of the quasi-perpendicular Earth's bow shock that propagate along its front. Their propagation speed matches the Alfvén speed in the overshoot region, in line with what has been found in hybrid simulations of perpendicular high-Mach number shocks that used a kinetic model for ions and represented electrons as an inertialess fluid [2]. We present results from the fully kinetic particle-in-cell simulations in Ref. [3], which addressed boundary oscillations of a low-Mach-number fast magnetosonic shock. Our aim was to determine if stable shock boundary oscillations can be studied in a fully kinetic treatment and by isolating a monochromatic wave mode. Our initial plasma density distribution is illustrated in Fig.1 (a). It is uniform along y outside the perturbation zone, where a varying density of mobile ions deforms the shock. The magnetic field with amplitude B_0 and the plasma $\beta = 0.5$ (β: thermal to magnetic pressure ratio) is aligned with y. The shock is driven by the thermal expansion of the dense cloud. The simulation reveals free oscillations of

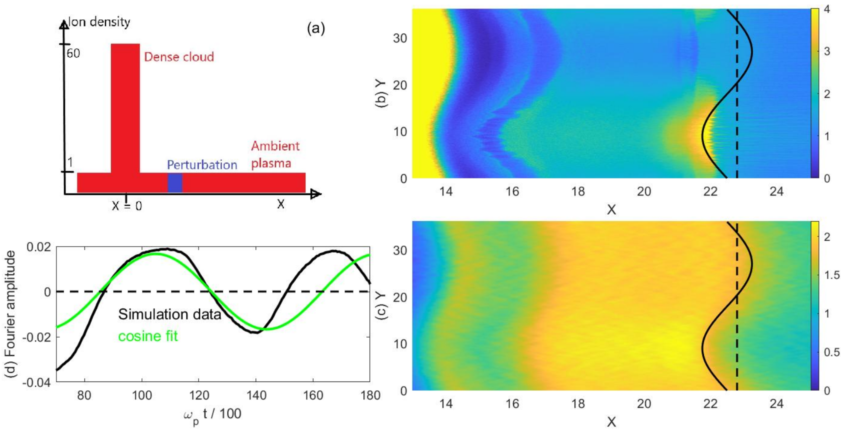

Fig. 1 Panel (a) shows the initial density distribution in units of that of the ambient plasma. The thermal expansion of the dense cloud drives a fast magnetosonic shock with a low Mach number into the ambient plasma. A sine modulation of the ion density along y deforms the shock in the perturbation zone. Panels (b, c) show the distributions of the ion density and magnetic amplitude $(B_x^2 + B_z^2)^{1/2}/B_0$ at the time $7000/\omega_p$ (ω_p: electron plasma frequency) when the shock left the perturbation zone $8.9 \leq x \leq 20.8$. Space is expressed in units of c/ω_p. The curve shows the position where the upstream magnetic field is compressed to 1.67 times its initial value and the dashed line the position of the shock in the absence of a perturbation. Panel (d) shows the evolution of the amplitude of the complex part of the Fourier mode $2\pi/L_y$ ($L_y = 36$: box length along y) normalized to L_y for times $> 7000/\omega_p$. The cosine fit has the frequency $0.7\omega_{lh}$ (ω_{lh}: lower-hybrid frequency).

the shock after it left the perturbation zone and entered the unperturbed plasma. Their frequency is just below the lower-hybrid frequency ω_{lh}. The oscillations are undamped for the shown wavelength of the seed perturbation but become increasingly damped for decreasing wavelengths. Two counter-propagating fast magnetosonic modes near their resonance at ω_{lh}, which also mediate the shock, form a standing wave. The wavelength of the shock oscillation equals 6 mm in a reference plasma with electron density 10^{15}cm^{-3}, fully ionized nitrogen, and B_0=0.85 T. Their phase velocity in this plasma exceeds the Alfvén speed 4-fold which we attribute to the high-frequency shock mode in the PIC simulation that differs from that in the hybrid simulation in Ref. [2].

References

[1] A. Johlander, *et al.*, "Rippled Quasiperpendicular Shock Observed by the Magnetospheric Multiscale Spacecraft," Phys. Rev. Lett. **117**, 165101 (2016).

[2] R. E. Lowe, and D. Burgess, "The properties and causes of rippling in quasi-perpendicular collisionless shock fronts," Ann. Geophys. **21**, 671 (2003).

[3] M. E. Dieckmann, C. Huete, F. Cobos, A. Bret, D. Folini, B. Eliasson, and R. Walder, "PIC simulations of stable surface waves on a subcritical fast magnetosonic shock front," Phys. Scr. **98**, 095603 (2023).