

Numerical MHD Simulations of Solar Magnetoconvection and Oscillations in Inclined Magnetic Field Regions

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Abstract The sunspot penumbra is a transition zone between the strong vertical magnetic field area (sunspot umbra) and the quiet Sun. The penumbra has a fine filamentary structure that is characterized by magnetic field lines inclined toward the surface. Numerical simulations of solar convection in inclined magnetic field regions have provided an explanation of the filamentary structure and the Evershed outflow in the penumbra. In this article, we use radiative MHD simulations to investigate the influence of the magnetic field inclination on the power spectrum of vertical velocity oscillations. The results reveal a strong shift of the resonance mode peaks to higher frequencies in the case of a highly inclined magnetic field. The frequency shift for the inclined field is significantly greater than that in vertical-field regions of similar strength. This is consistent with the behavior of fast MHD waves.

Keywords Sunspots: penumbra, magnetic fields · Granulation · Oscillations: solar

1. Introduction

Excitation and properties of solar oscillations have been investigated using three-dimensional (3D) numerical simulations by many authors (Nordlund and Stein, 2001; Stein and Nordlund, 2001; Georgobiani, Stein, and Nordlund, 2003; Stein *et al.*, 2004; Jacoutot *et al.*,

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2008a). The results have provided important insights into the excitation mechanism (Stein and Nordlund, 2001) and the meaning of the line asymmetry (Georgobiani, Stein, and Nordlund, 2003), and have been used for testing the local correlation tracking technique (Georgobiani *et al.*, 2007) and in time–distance helioseismology (Zhao *et al.*, 2007). However, properties of oscillations in magnetic regions using realistic simulations of solar magnetohydroconvection have been much less investigated. Analyzing the magnetohydrodynamic (MHD) simulations with initially vertical magnetic field, Jacoutot *et al.* (2008b, 2009) found a shift of the oscillation power toward higher frequencies with increasing magnetic field strength. They also found enhanced excitation of high-frequency “pseudo-modes,” which reached a maximum amplitude for a moderate field strength of ≈ 600 G. It was suggested that this may qualitatively explain the phenomenon of an “acoustic halo” observed around sunspots and active regions in the frequency range 5.5–7.5 mHz (see, *e.g.*, Jain and Haber, 2002).

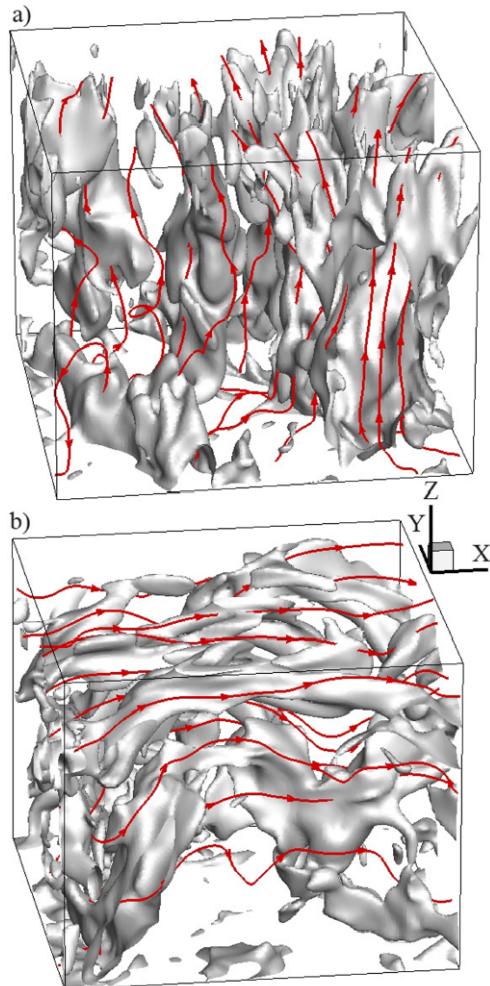
There is no doubt that the inclination of the magnetic field also has a significant influence on the oscillation properties of the resonant modes. This may be particularly important in the sunspot penumbra, where the magnetic field is strong and highly inclined. The sunspot penumbra represents a complicated mixture of almost horizontal magnetic fields, and also has a circular structure with a radial dependence of the field properties. Therefore, the interpretation of observations of penumbra oscillations in terms of the field properties is not straightforward.

In our simulations, we model a small area of a penumbra, where the mean magnetic field strength is almost uniform. This simplifies the simulations and allows us to obtain dependencies on the strength of the inclined field. For this initial investigation, we used our simulation data (Kitiashvili *et al.*, 2009) previously obtained by using a radiative MHD code SolarBox (Jacoutot *et al.* 2008a, 2009), for the top 5-Mm-deep layer of the convective zone and a 0.5 Mm layer of the low atmosphere with spatial resolution 50 km \times 50 km \times 42 km. Radiative transfer was calculated with a local thermodynamic equilibrium (LTE) approximation using a four-bin opacity distribution function. The ray-tracing transport calculations implemented the Feautrier method for a 14-ray (two vertical, four horizontal, eight slanted) angular quadrature. The code was tested (Jacoutot *et al.*, 2008a) by comparing with the results of a similar code (Nordlund and Stein, 2001; Stein and Nordlund, 2001), and also with some cases of higher-resolution simulations (12.5 km \times 12.5 km \times 10.5 km). In the simulations, the mean magnetic field strength and inclination are maintained by the boundary conditions (Kitiashvili *et al.*, 2009). The simulation results have been used for studying the basic features of the Evershed flow and the filamentary structures, including the “sea-serpent” behavior of magnetic field lines in the penumbra (Kitiashvili *et al.*, 2010a).

2. Magnetoconvection in Vertical and Highly Inclined Magnetic Field Regions

Magnetic fields have a strong influence on convective motions. For instance, in regions with a strong vertical magnetic field, such as the sunspot umbra, convection is largely suppressed. The umbral convection is characterized by horizontally small and vertically long convective cells, and slow flows (Schüssler and Vögler, 2006; Bharti, Beeck, and Schüssler, 2010; Kitiashvili *et al.*, 2010b). Such convective structures are observed as umbral dots (see, *e.g.*, Ortiz, Bellot Rubio, and Rouppe van der Voort, 2010). The horizontal magnetic fields tend to stretch convective granules along the field lines as shown in the simulations of the horizontal flux emergence (Cheung *et al.*, 2008; Stein *et al.*, 2010). The interaction of convective motions and magnetic field depends strongly on the field inclination (see Figures 1 and 2). It

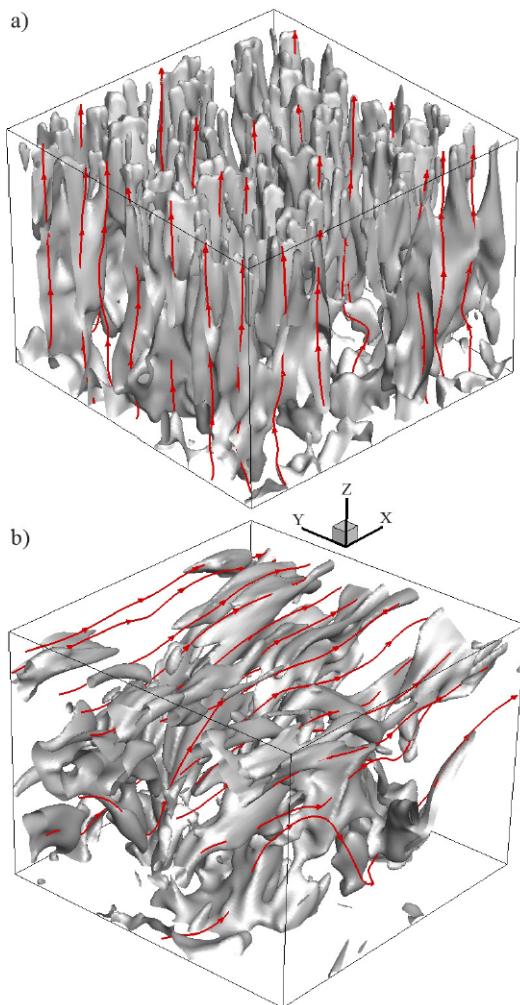
Figure 1 Structure of the magnetic field magnitude ($B_0 = 600$ G) for different mean inclinations: (a) vertical field ($\alpha = 0^\circ$) and (b) highly inclined field ($\alpha = 85^\circ$). Isosurfaces correspond to 1100 G (a) and 1200 G (b) magnetic field strength. Red curves are magnetic field lines.



is natural that the vertical magnetic field structure represents vertical flux tubes for a strong field (Figure 2a). However, in the inclined field ($\alpha = 85^\circ$) of the same strength, the magnetic field structure is very different and forms arch-like structures below the surface and almost horizontal elongated tubes at the surface (Figures 1b, 2b).

The influence of the vertical field on convection strongly depends on the field strength. The weak field (about 1, 10 G) barely affects the plasma dynamics. The field is concentrated in the intergranular lines. When a moderate, 100 G, vertical magnetic field is imposed in an initially nonmagnetic convection layer, it may lead to spontaneous formation of a stable, pore-like, magnetic structure (Kitiashvili *et al.*, 2010c). However, in strong magnetic field regions the behavior of convection is different. Figure 3 shows such changes (from left to right) of the temperature, vertical velocity, and vertical magnetic field for $B_0 = 600$ G (left column) and $B_0 = 1200$ G (right column). The simulations show the decreasing size of the convective granules, slower evolution, suppression of convective flows, and magnetic field concentrations in the intergranular lines. This is in agreement with previous results (Schüssler and Vögler, 2006; Jacoutot *et al.*, 2008b).

Figure 2 Structure of the magnetic field magnitude ($B_0 = 1200$ G) for different mean inclinations: (a) vertical field ($\alpha = 0^\circ$) and (b) highly inclined field ($\alpha = 85^\circ$). Isosurfaces correspond to 1450 G (a) and 1700 G (b) magnetic field strength. Red curves are magnetic field lines.



The magnetic field inclination breaks the horizontal homogeneity of convection and leads to the formation of a mean shear flow (Evershed flow) (Kitiashvili *et al.*, 2009). The effect becomes stronger with increasing field inclination and strength. Figure 4 shows an example of such changes for the 600 G (left column) and 1200 G (right column) initial magnetic field strengths, and 85° inclination. In this case, the convective cells are stretched in the direction of the magnetic field inclination. The degree of the shape deformation depends on both the field strength and the inclination angle. A weak inclination ($\approx 30^\circ$) of a strong magnetic field (such as 1200 G) results in only a small stretching of granules along the magnetic field lines (Kitiashvili *et al.*, 2010b). When the magnetic field inclination increases, the magnetic effects on the granulation dynamics are much stronger. In particular, the high inclination leads to strong, horizontal mean flows resembling the Evershed effect (Kitiashvili *et al.*, 2009) and to formation of a filamentary structure in the form of strongly stretched convective cells, which become more narrow for the stronger field (see two bottom rows in Figure 4).

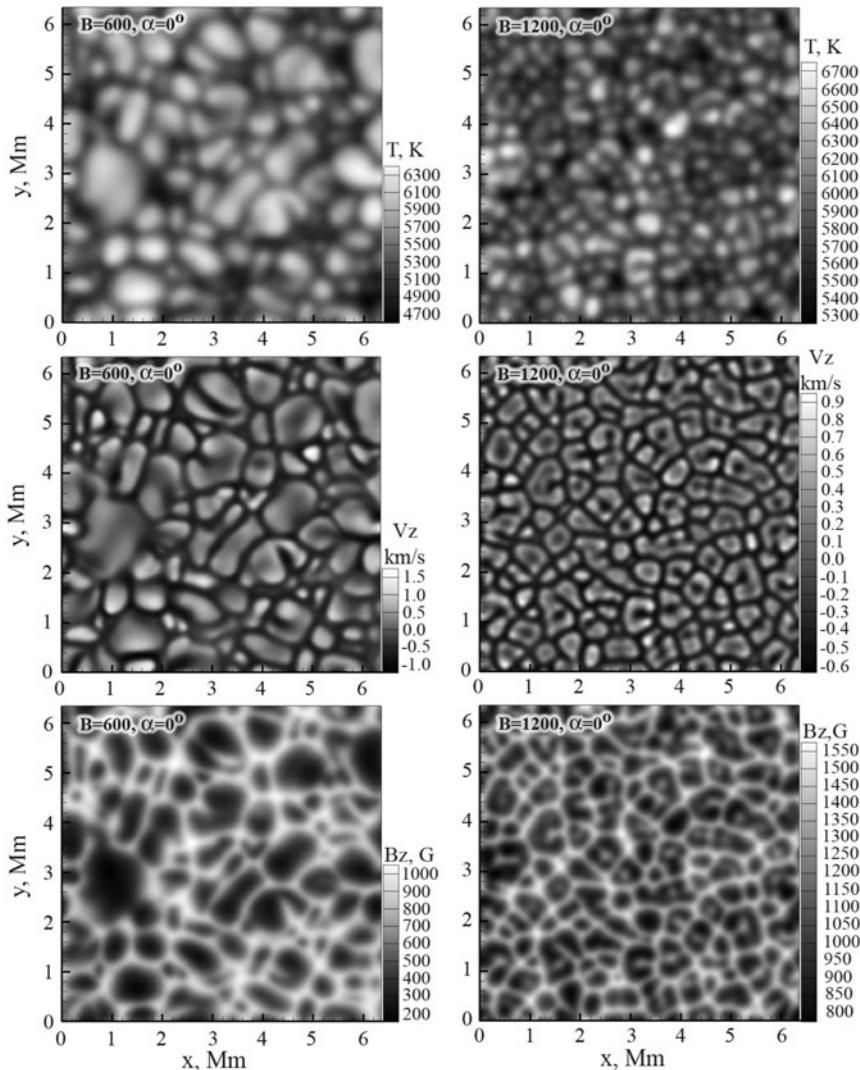


Figure 3 Snapshots (from top to bottom) of temperature [T], vertical velocity [V_z] and vertical magnetic field [B_z], for initial vertical field $B_{z0} = 600$ G ($\alpha = 0^\circ$, left column) and $B_{z0} = 1200$ G (right column), at a constant depth corresponding to the photospheric level, approximately defined at the optical depth of unity.

Such changes of the solar magnetoconvection, depending on the inclination and strength of the magnetic field, can also be reflected in the oscillatory behavior.

3. Frequency Shift of the Radial Oscillations

We investigate effects of the magnetic field on the oscillations by calculating the power-spectral density for the vertical-velocity fluctuations, averaged over the whole horizontal domain. This corresponds to considering the radial oscillations or oscillations of a low an-

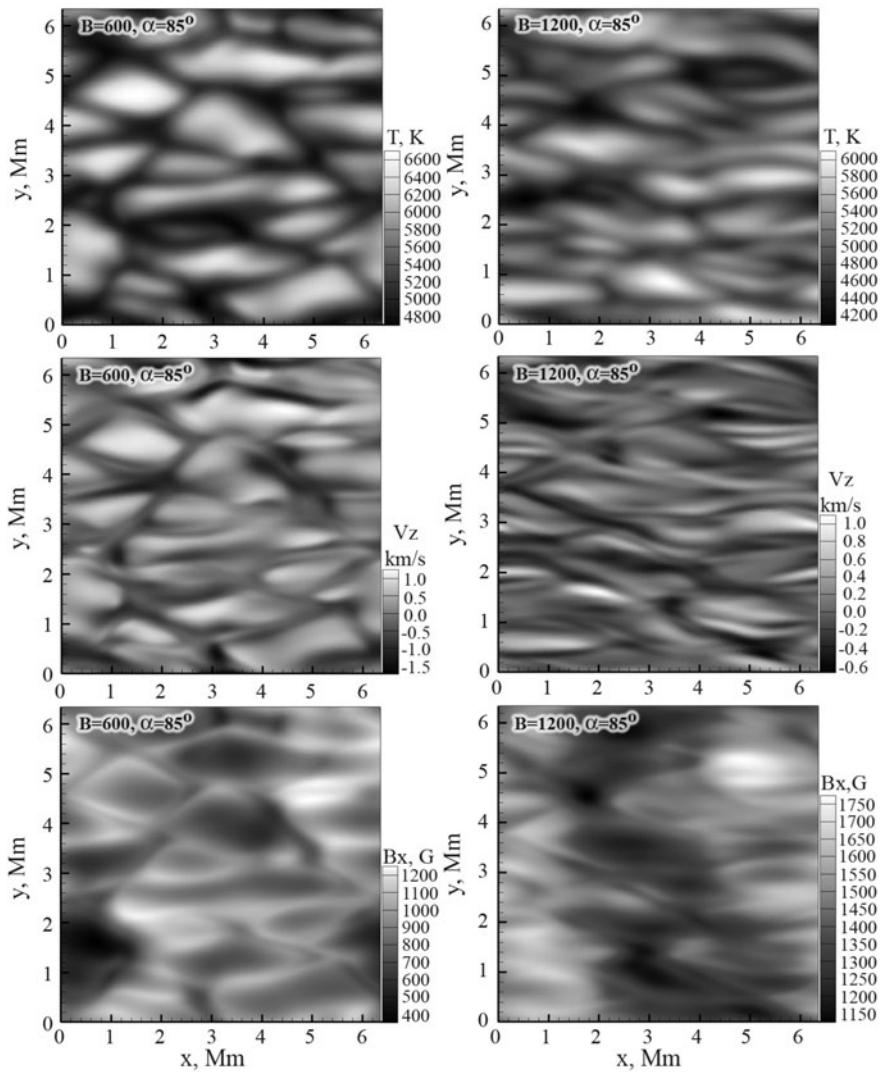


Figure 4 Snapshots of temperature [T], vertical velocity [V_z] and horizontal component of magnetic field [B_x], for highly inclined ($\alpha = 85^\circ$) initial field cases for $B_0 = 600$ G (left column) and $B_0 = 1200$ G (right column).

gular degree with the horizontal wavelength much larger than the size of the computational domain (6 Mm). Because of the small domain of the simulations, we do not attempt to extract high-degree modes. For calculating the power spectra, we used 20 hours of the simulated data sets of the vertical velocity with a cadence of 30 seconds, after the magnetoconvection reached a stationary state.

Figures 5b and c illustrate the power spectrum changes with increasing vertical magnetic field strength. Figures 5d and e show the power spectra for the highly inclined fields of the same strengths. The two identical top panels (Figure 5a) show the spectrum without the magnetic field, for comparison. In the frequency range of 0–6 mHz, the power spectra

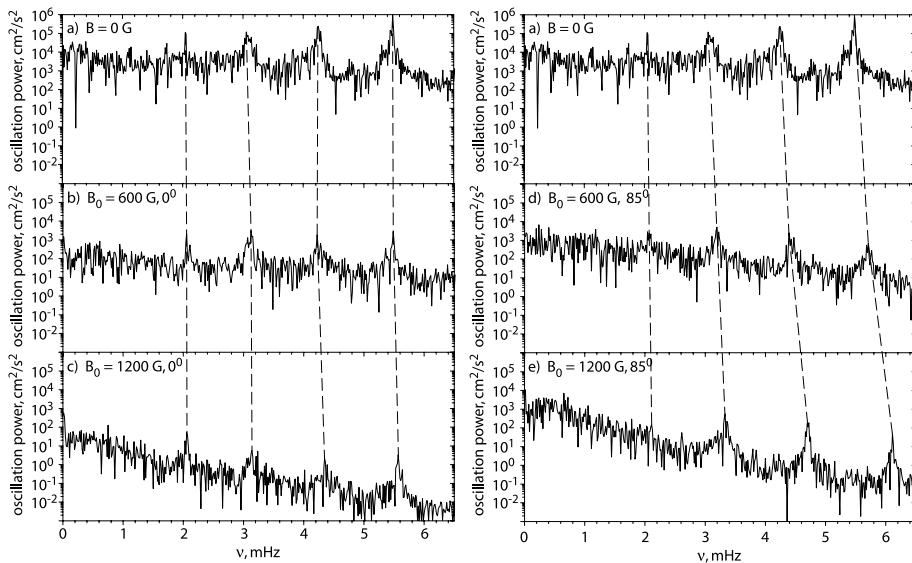


Figure 5 Oscillation power spectra of the vertical velocity for different magnetic field strengths and inclinations: (a) $B_0 = 0$ G; (b) $B_0 = 600$ G, $\alpha = 0^\circ$; (c) $B_0 = 1200$ G, $\alpha = 0^\circ$; (d) $B_0 = 600$ G, $\alpha = 85^\circ$; and (e) $B_0 = 1200$ G, $\alpha = 85^\circ$.

have four mode peaks, the frequencies of which are determined by the resonant conditions between the bottom boundary conditions of our domain and the near-surface reflective layer. In this article, we have not considered the high-frequency spectrum because the top boundary condition was reflecting.

Comparison of the oscillation spectra in Figure 5 shows three main dependencies: *i*) suppression of the power by the magnetic field, *ii*) shift of the mode peaks to a higher frequency, which is greater for the stronger field, and *iii*) increase of the width of the resonant peaks with the magnetic field. In the vertical field, $B_{z0} = 600$ G, the shift of the mode frequencies shows a trend to higher frequencies. The frequency shift increases in the stronger field, $B_{z0} = 1200$ G. It is interesting that the power suppression is stronger for the vertical magnetic field than for the inclined field, but the frequency shift is significantly stronger for the inclined field than for the vertical field. Also, the frequency dependence of the shift is stronger for the inclined magnetic field. The frequency shifts estimated from the positions of the peaks are shown in Figure 6. The dependence on the magnetic field strength seems to be nonlinear, in particular, for the two higher modes, but, obviously, this requires further investigation.

4. Conclusions

We have used radiative MHD simulations of magnetoconvection in the upper convective boundary layer and the low atmosphere of the Sun to investigate changes in the oscillation power spectrum in the cases of vertical and highly inclined magnetic fields. The oscillations in these simulations are naturally excited by the turbulent convection. We have investigated only the behavior of the radial (or large horizontal scale) oscillations.

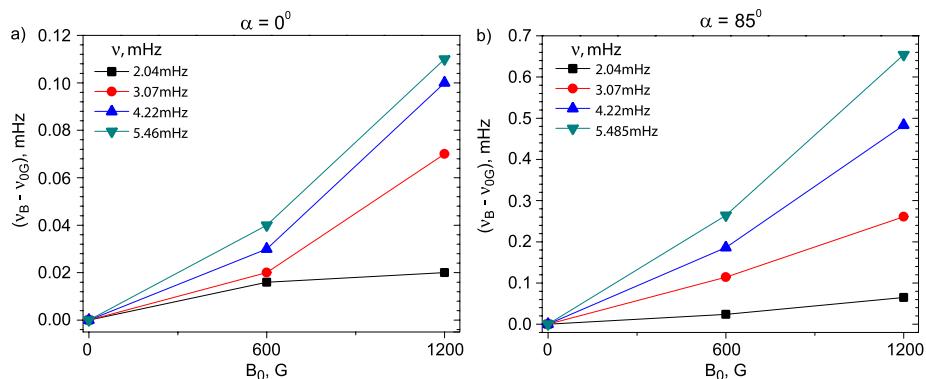


Figure 6 Frequency shifts of the oscillation modes (indicated by different colors) relative to the case of nonmagnetic convection for the vertical ($\alpha = 0^\circ$, panel a) and almost horizontal ($\alpha = 85^\circ$, panel b) magnetic fields.

The results show two basic effects of the magnetic fields: power suppression and shifts of the mode peaks to higher frequencies. The power suppression is stronger for the vertical magnetic field, but the frequency shift is stronger for the inclined magnetic field. The stronger frequency shift in the inclined magnetic field can be understood in terms of physical properties of fast MHD waves. The speed of these waves is higher when they travel across the magnetic field lines, and this leads to higher modal frequencies. These results may have important implications for local helioseismology analyses and for comparison with linear modeling of oscillations in magnetic fields (e.g., Parchevsky and Kosovichev, 2009). In particular, our results indicate that the frequency shift measured in sunspot regions using the ring-diagram technique of local helioseismology without discriminating the sunspot umbra and penumbra regions may come mostly from the penumbra because the contributions of various parts of the analyzed area are weighted by the local oscillation power of these parts.

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