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

I.N. Kitiashvili\textsuperscript{1,2} · A.G. Kosovichev\textsuperscript{2} · N.N. Mansour\textsuperscript{3} · A.A. Wray\textsuperscript{3}

Received: 1 April 2009 / Accepted: 2 April 2009 / Published online: 3 April 2009

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 paper, 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 et al., 2003; Stein et al., 2004; Jacoutot et al., 2008a). The results have provided important insights into the excitation mechanism (Stein and Nordlund, 2001) and the meaning of the line asymmetry (Georgobiani et al., 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

\textsuperscript{1} Center for Turbulence Research, Stanford University, Stanford, CA 94305, USA email: irinasun@stanford.edu
\textsuperscript{2} Hansen Experimental Physics Laboratory, Stanford University, Stanford, CA 94305, USA email: sasha@sun.stanford.edu
\textsuperscript{3} NASA Ames Research Center, Moffett Field, CA 94035, USA
oscillations in magnetic regions using realistic simulations of solar magnetoconvection 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 the 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 \( \approx 600 \) G. It was suggested that this may qualitatively explain the phenomenon of "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 simulations 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 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 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 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 strong vertical magnetic field, such as the sunspot umbra, convection is largely suppressed. The umbra 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., 2010a). Such convective structures are observed as umbral dots (see, e.g., Ortiz, Bellot Rubio, and Rouppe van der Voort, 2001). 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 highly depends on the field inclination (see Figures 1 and 2). It 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).
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.
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.

The influence of the vertical field on convection strongly depends on the field strength. The weak field (about 1, 10 G) almost does not affect the plasma dynamics. The field is concentrated in the intergranular lanes. 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...
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). 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).

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...
Numerical Simulations of Solar Magnetoconvection and Oscillations

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, $\alpha = 85^\circ$.

(right column) initial magnetic field strengths, and $85^\circ$ 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).

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 angular 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
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 vertical velocity with a cadence of 30 seconds, after the magnetoconvection reached a stationary state.

Figures 5 b-c illustrate the power spectrum changes with increasing vertical magnetic field strength. Figures 5 d, 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 magnetic field, for comparison. In the frequency range of $0 - 6$ mHz, the power spectra 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 paper, 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 peak maxima 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
Numerical Simulations of Solar Magnetoconvection and Oscillations

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-scale) oscillations.

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 analysis 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.

Acknowledgement. We thank the International Space Science Institute (Bern) for the opportunity to discuss these results at the international team meeting on solar magnetism.

References

Bharti, L., Beeck, B., Schüssler, M.: 2010, Astron. Astrophys. 510, A12.
Cheung, M.C.M., Schüssler, M., Tarbell, T.D., Title, A.M.: 2008, Astrophys. J. 687, 1373-1387.
Georgobiani, D., Stein, R.F., Nordlund, Å.: 2003, Astrophys. J. 596, 698 – 701.
Georgobiani, D., Zhao, J., Kosovichev, A.G., Benson, D., Stein, R.F., Nordlund, Å.: 2007, Astrophys. J. 657, 1157 – 1161.
Jacoutot, L., Kosovichev, A.G., Wray, A.A., Mansour, N.N.: 2008a, Astrophys. J. 682, 1386 – 1391.
Jacoutot, L., Kosovichev, A.G., Wray, A.A., Mansour, N.N.: 2008b, Astrophys. J. 684, L51 – L54.
Jacoutot, L., Kosovichev, A.G., Wray, A.A., Mansour, N.N.: 2009, CS 383, Astron. Soc. Pac., San Francisco CS 416, 67 – 74.
Jain, R., Haber, D.: 2002, Astron. Astrophys. 387, 1092 – 1099.
Kitiashvili, I.N., Kosovichev, A.G., Wray, A.A., Mansour, N.N.: 2009, Astrophys. J. Lett. 700, L178 – L181.
Kitiashvili, I.N., Bellot Rubio, I.R., Kosovichev, A.G., Mansour, N.N., Sainz Dalda, A., Wray, A.A.: 2010a, Astrophys. J. Lett. 716, L181-L184.
Kitiashvili, I.N., Kosovichev, A.G., Wray, A.A., Mansour, N.N.: 2010b, In: Sekii, T. (Ed.) 3rd Hinode Science Meeting, ASP Conf Series, in press.
Kitiashvili, I.N., Kosovichev, A.G., Wray, A.A., Mansour, N.N.: 2010c, Astrophys. J. 719, 307-312.
Nordlund, Å., Stein, R.F.: 2001, Astrophys. J. 546, 576 – 584.
Ortiz, A., Bellot Rubio, I.R., Rouppe van der Voort L.: 2010, Astrophys. J. 713, 1282 – 1291.
Parchevsky, K.V., Kosovichev, A.G.: 2009, Astrophys. J. 694, 573 – 581.
Schüssler, M., Vögler, A.: 2006, Astrophys. J. Lett. 641, L73 – L76.
Stein, R.F., Nordlund, Å.: 2001, Astrophys. J. 546, 585 – 603.
Stein, R., Georgobiani, D., Trampedach, R., Ludwig, H.-G., Nordlund, Å.: 2004, Solar Phys. 220, 229 – 242.
Stein, R.F., Lagerfjärd, A., Nordlund, Å., Georgobiani, D.: 2010, Solar Phys. DOI 10.1007/s11207-010-9510-y.
Zhao, J., Georgobiani, D., Kosovichev, A.G., Benson, D., Stein, R.F., Nordlund, Å.: 2007, Astrophys. J. 659, 848 – 857.
