FORCED FIELD EXTRAPOLATION OF THE MAGNETIC STRUCTURE OF THE Hα FIBRILS IN THE SOLAR CHROMOSPHERE

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Received 2016 March 21; revised 2016 April 19; accepted 2016 May 2; published 2016 July 20

ABSTRACT

We present a careful assessment of forced field extrapolation using the Solar Dynamics Observatory/Helioseismic and Magnetic Imager magnetogram. We use several metrics to check the convergence property. The extrapolated field lines below 3600 km appear to be aligned with most of the Hα fibrils observed by the New Vacuum Solar Telescope. In the region where magnetic energy is far larger than potential energy, the field lines computed by forced field extrapolation are still consistent with the patterns of Hα fibrils while the nonlinear force-free field results show a large misalignment. The horizontal average of the lorentz force ratio shows that the forced region where the force-free assumption fails can reach heights of 1400–1800 km. The non-force-free state of the chromosphere is also confirmed based on recent radiation magnetohydrodynamics simulations.

Key words: magnetic fields – magnetohydrodynamics (MHD) – methods: numerical – Sun: chromosphere

1. INTRODUCTION

It is generally believed that Hα fibrils align with the magnetic field in the chromosphere because the “frozen in field” effect only allows for the motion of fibril plasma along the magnetic field lines. de la Cruz Rodríguez & Socas-Navarro (2011) compared the orientation of the fibrils and magnetic field obtained via high-resolution spectropolarimetric observations of Ca II lines. They found that most fibrils are aligned with the field lines, while a few cases showed significant misalignment. They speculated that the time and height difference between the Ca II line core and the Stokes Q and U peak might explain the misalignment. Schad et al. (2013) also analyzed the observation of the He i triplet, the projected angle of the fibrils, and the field lines which align within an error of ±10°.

Based on the alignment, Wiegelmann et al. (2008) extend the classical preprocessing routine of the magnetogram by also considering minimizing the angle between the horizontal projection of the field lines and fibrils. Jing et al. (2011) quantitatively assessed the non-potentiality of fibrils using the shearing angle between the orientation of the fibrils and potential field lines extrapolated from the longitudinal component of the magnetogram.

As the main tool to compute the magnetic field above the photosphere, the extrapolation of the magnetogram can be used for a direct comparison with the fibrils. Although nonlinear force-free field (NLFFF) models have successfully reconstructed many magnetic structures of filaments, EUV bright points, and active regions (AR) in the corona (Yan et al. 2001; van Ballegooijen 2004; He et al. 2011; Fan et al. 2012; Sun et al. 2012), Metcalf et al. (2008) found that small structures and field connectivity in a Sun-like reference model cannot be well reproduced using a forced boundary of the photosphere as input. Furthermore, extrapolation models are much less tested in the chromosphere. Wang et al. (2000, 2001) calculated the magnetic field of AR 7321 using a boundary integral equation (Yan & Sakurai 1997, 2000). They found, under a modest spatial resolution of 2°, that the field lines are mostly in agreement with fibrils, exhibiting some misalignments. Zhu et al. (2013) presented a new implementation of the magnetohydrodynamics (MHD) relaxation method to extrapolate the magnetic field on the Sun. In this method, a high β region like the photosphere near the bottom boundary is introduced by setting a Sun-like atmosphere model as the initial condition. By using the “stress and relax” technique, the MHD system finally reaches an equilibrium state in which the forced magnetic field is balanced by gravity and the pressure gradient. No preprocessing is required since a forced boundary is consistent with the extrapolation. This method has been tested with a Sun-like reference field. The reference field is the final state of the flux rope emergence model designed by Manchester et al. (2004). Detailed diagnostics have shown that compared with the optimization method (Wiegelmann 2004), the forced field extrapolation can reconstruct the magnetic field closer to the reference field.

In this paper, we report modifications of the forced field extrapolation with respect to the version of Zhu et al. (2013) and its application to reconstructing the magnetic field in the chromosphere of AR 11967 using Solar Dynamics Observatory/Helioseismic and Magnetic Imager (SDO/HMI; Schou et al. 2012) magnetograms as input. Only the magnetic field in the chromosphere is considered as the chromosphere is a more forced region than the corona and the spatial resolution of the Hα images can reach 0.″16 (Liu et al. 2014). We will assess the extrapolation based on the convergence, different forces, and resemblance to Hα fibrils observed by New Vacuum Solar Telescope (NVST; Liu et al. 2014). We are also interested in the difference between the results of the forced field and NLFFF extrapolations.

The paper is organized as follows. The modifications to the forced field extrapolation method are described in Section 2. The extrapolation results of AR 11967 are detailed in Section 3. The data used here are briefly described in Section 4. We present our discussion in Section 5 and finally conclude in Section 6.

2. METHOD

We extrapolate the magnetic field by solving MHD equations for a Sun-like atmosphere model (Fan 2001) using a relaxation method (Roumeliotis 1996). Compared with the work of Zhu et al. (2013), the viscous velocity term is replaced...
by a velocity damping term as the velocity cannot be effectively dissipated by the former. The large velocity produced by the strong forced magnetic field of the AR leads to a failed extrapolation. Using the source terms for gravity and velocity damping, the new MHD equations take the following forms:

\[
\begin{align*}
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) &= 0, \\
\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot \left[ \rho \mathbf{v} \mathbf{v} + \left( p + \frac{\mathbf{B} \cdot \mathbf{B}}{2} \right) I - \mathbf{B} \mathbf{B} \right] &= \rho \mathbf{g} - \mu \rho \mathbf{v}, \\
\frac{\partial E}{\partial t} + \nabla \cdot \left[ (E + p + \frac{\mathbf{B} \cdot \mathbf{B}}{2}) \mathbf{v} - \mathbf{B} (\mathbf{B} \cdot \mathbf{v}) \right] &= -\mu \rho \mathbf{v}^2, \\
\frac{\partial \mathbf{B}}{\partial t} - \nabla \times (\mathbf{v} \times \mathbf{B}) &= 0,
\end{align*}
\]

where \( \rho, \mathbf{v}, E, \mathbf{B}, \) and \( p \) are the mass density, velocity, total energy density, magnetic field, and gas pressure, respectively. \( g = 274 \text{ m s}^{-2} \) is the surface gravitational acceleration. The frictional coefficient \( \frac{1}{\mathbf{v}} \) represents the timescale of artificial velocity damping. The damping term is very important. Different forms of damping are applied to control the relaxation speed of the system (Roumeliotis 1996; van Ballegooijen et al. 2000; Valori et al. 2007; Jiang & Feng 2012). In this calculation, \( \mu = 0.1. \)

Another modification is the elimination of \( \nabla \cdot \mathbf{B} \). In Zhu et al. (2013), Powell’s source terms (Powell et al. 1999) are applied to prevent the accumulation of \( \nabla \cdot \mathbf{B} \) from propagating the “magnetic monopoles” with the flow. In this paper, the project scheme originally proposed by Brackbill & Barnes (1980) is further used to eliminate the \( \nabla \cdot \mathbf{B} \) error. The Conjugate Gradient iterative method (Hestenes & Stiefel 1952) is used to solve the poisson equation in the project scheme.

As noted by Zhu et al. (2013), it is important to choose a reasonable starting height for the atmosphere model as the initial condition to adapt the magnetogram. If the starting height is too low, then it is difficult to drive the heavy plasma, which results in a too long relaxation time. If too high, then it is difficult to balance the forced magnetic field with the light plasma, which results in a failed extrapolation with severely distorted field lines. In this calculation, we choose an optimized starting height \( z_0 \) at which the ratio of gas pressure and average magnetic pressure (only include \( B > 200 \text{ G} \) area) on the magnetogram is equal to 1.

Further details of the forced field extrapolation method can be found in Zhu et al. (2013).

Table 1
Extrapolation Metrics for AR 11967

| Model   | CWsin | \((|f|) \times 10^4\) | \(E_B\) | \(E_{pot}\) | \(E_{by}/E_{pot}\) | lost \(E_{free}\)(%) |
|---------|-------|-----------------------|--------|-----------|-----------------|-------------------|
| Fce     | Full  | 0.42                  | 2.58   | 16.27     | 14.62           | 1.11              | ...               |
| A       | 0.65  | 2.21                  | 0.111  | 0.054     | 2.06            | ...               |
| B       | 0.23  | 1.47                  | 4.02   | 3.69      | 1.09            | ...               |
| C       | 0.65  | 4.52                  | 0.059  | 0.054     | 1.10            | ...               |
| Wie     | Full  | 0.13                  | 11.7   | 16.52     | 14.59           | 1.13              | −17.1             |
| A       | 0.11  | 10.1                  | 0.070  | 0.050     | 1.39            | 65.1              |
| B       | 0.09  | 10.2                  | 4.10   | 3.71      | 1.11            | −17.0             |
| C       | 0.10  | 8.86                  | 0.043  | 0.054     | 0.79            | 3.0               |
| Fce preprocessed | Full  | 0.34                  | 1.56   | 15.80     | 14.37           | 1.10              | 13.1              |
| A       | 0.56  | 1.22                  | 0.101  | 0.050     | 2.02            | 10.4              |
| B       | 0.21  | 0.82                  | 3.93   | 3.64      | 1.08            | 15.3              |
| C       | 0.53  | 2.40                  | 0.061  | 0.053     | 1.15            | −38.8             |

Note. Energy unit is \(10^{33} \text{ erg}\).
3. OBSERVATIONAL DATA

The NVST, located on the northeast side of Fuxian Lake in China, has three channels with which to observe the Sun. The Hα 6535 Å channel, with a bandwidth of 0.25 Å, is used for observing the chromosphere. The Hα data adopted here cover part of the central area of AR 11967 with a field of view of 15" × 15" and a pixel size of 0".163 at 06:48:00 UT on 2014 February 3. The HMI on board the SDO measures the vector magnetic field with a pixel size of 0".5 at the same time.

Figure 1 shows the observation of AR 11967 with HMI and NVST-Hα.

4. EXTRAPOLATION AND COMPARISON

We carry out our computations in a box of 768 × 640 × 80 grids with the same resolution as the HMI magnetogram using three different algorithms: the potential method (“Pot”), the optimization method using grid refinement and a preprocessed magnetogram implemented by Wiegelmann (2004; “Wie”), and the forced field extrapolation (“Fce”). Unless otherwise stated, only the results below 10 grids (3.6 Mm) are considered.

The metrics describing the quality of the results are the current weighted average of \( \sin \theta \) (CWsin, Wheatland et al. 2000), the unsigned mean of the absolute fractional flux ratio \( \langle |f| \rangle \), and the magnetic energy. These metrics are defined as follows:

\[
\text{CWsin} = \frac{\int_V J_\sigma dV}{\int_V J dV}, \quad \sigma = \sin \theta = \frac{|J \times B|}{|J B|},
\]

\[
\langle |f| \rangle = \frac{1}{V} \int_V \nabla \cdot \frac{B}{6B/\Delta x} dV,
\]

Figure 2. Comparison of the NVST-Hα image with field lines computed by the “Pot,” “Wie,” and “Fce” models. “Fce preprocessed” is the “Fce” result with a preprocessed magnetogram used as input. The field lines of each panel start from the same location.

Figure 3. Temporal evolution of the magnetic energy (left) and CWsin (right).
Figure 4. Temporal evolution of the magnetic field lines from $T = 0$ to $T = 337.6 \approx 70\tau$ against the map of $B_z$.

Figure 5. Horizontal average of different forces, $\sum \frac{1}{N} (f_x^2 + f_y^2)^{1/2}$ (left), $\sum \frac{1}{N} \sum f_z$ (right).
where $E_B$ and $E_{pot}$ are the extrapolated magnetic field energy and potential energy, “lost $E_{free}$” is the relative free energy lost for a model compared with the “Fce” result. Table 1 contains the metrics characterizing four regions: full, A, B, and C (see the outlined squares in Figures 2 and 4). The magnetic field is strong (weak) in square B (A and C). The CWsin metric in B is smallest, since the strong field region is close to a force-free state. In “Fce,” the full region CWsin is 0.42, which is larger than “Wie” (0.13) and the previously reported result of the NLFFF model applied to the AR (Schrijver et al. 2008; De Rosa et al. 2009; Jiang & Feng 2013). Such a result is expected because the raw magnetogram is used in “Fce,” while here “Wie” uses a preprocessed magnetogram in which the net force and torque are eliminated. Table 1 also shows that “Fce” contains slightly less free energy than “Wie” in the full domain. In square A, however, “Fce” contains much more free energy than “Wie.”

In Figure 2, we compare the extrapolated field lines with NVST-Hα fibrils in the chromosphere. As expected, the non-potential extrapolations show better results than those from “Pot.” For clarity, we outline squares A and B, which are the same subregion in Figure 4.

Square B shows a typical X-shaped structure where reconnection took place. The X-shape identified by the Hα fibrils indicates the field line orientation. Both the “Fce” and “Wie” results are in good agreement with fibrils located at the lower and right side of the null point. On the left side, the “Fce” field lines show more real bend than those of “Wie.” We cannot determine which results are better on the upper side. Generally, the “Fce” results reveal a closer match to the observed X-shape structure.
In square A, we see a very different field orientation. The “Fce” field lines closely resemble the Hα fibrils, while the “Wie” lines show obvious misalignment, similar to the “Pot” results. The metrics in Table 1 demonstrate that square A is a very non-potential \( (E_B/E_{pot} = 2.06) \) region. “Fce” demonstrates the ability to recover the magnetic field in the non-potential region.

Figure 3 shows the rapid convergence of the magnetic energy and angle between \( B \) and \( J \) during relaxation. The energy and current weighted sin metrics reach their final values after times \( t = 20 \) and 30 \( \tau \) (\( \tau \) is the fast wave cross time), respectively. To further check the convergence, we plot the temporal evolution of the field lines (see Figure 4) during the relaxation process. We note that the field lines in many subregions (especially A and B) slowly change their orientation, which indicates the injection or transfer of energy. The magnetic field reaches a final stable state after about \( t = 168 \approx 35\tau \). The final state clearly shows a non-potential configuration compared with the initial state.

5. DISCUSSION

5.1. Preprocess

Preprocessing the magnetogram has been very popular (Fuhrmann et al. 2007; Schrijver et al. 2008; De Rosa et al. 2009; Tadesse et al. 2009; Guo et al. 2013; Cheng et al. 2014; Jiang et al. 2014; Wang et al. 2015), which makes it more consistent with NLFFF. Metcalf et al. (2008) showed that preprocessing improved the metrics quantifying the agreement between the NLFFF solution and reference model field. Schrijver et al. (2008) applied 14 NLFFF models with 4 different codes and a variety of boundary conditions to AR 10930 and obtained the best results for the preprocessed data.

For the forced field extrapolation used here, however, the force in the magnetogram is very important for driving the MHD system to a forced equilibrium. This is indicated in Figure 5. In the \( x-y \) plane, the average of the resulting force is smaller than the lorentz force at any height, which means that the lorentz force is partly canceled out by the pressure gradient. In the \( z \) direction, the situation is more complicated because gravity is included. Due to the heavy plasma around the bottom boundary, the pressure gradient and gravity are the dominant forces. The resultant force in the \( z \) direction remains smaller than the lorentz force at any height. Moreover, we repeat our relaxation using the same initial and boundary conditions but with a preprocessed magnetogram used as input. The smoothing of the magnetic field using a preprocessing procedure can be seen clearly in Figure 6, which leads to more force-free results as expected (see “Fce preprocessed” metrics in Table 1). However, the field lines of the “Fce preprocessed” result show an obvious misalignment with the fibrils in square A (see Figure 2). Also, the “Fce preprocessed” result lost 13% of the free energy compared to the “Fce” result in the whole region (see the lost \( E_{free} \) metric in Table 1).

5.2. The Height of the Forced Field

To derive the height under which the lorentz force cannot be ignored, we plot the average, unsigned total lorentz force divided by the average magnetic pressure gradient at each height (see Figure 7). The lorentz force ratio in the strong magnetic field volume is larger than 0.1 below 1400 km, while the height reaches 1800 km in the weak field. The forced region is much higher than the 400 km computed by Metcalf et al. (1995). Such a forced chromosphere state was also found in the recent radiation-MHD simulation by Leenaarts et al. (2015).

5.3. Why is A a Special Region?

From the above comparisons, we find that the magnetic fields computed by “Fce” and “Wie” differ most in square A. Why is this?

First, we note that A is a weak field region. However, this is not a sufficient condition because the two models show similar field lines in C where the magnetic field is also weak. Then, we note the energy ratio metric \( E_B/E_{pot} \) which describes the deviation of the extrapolation from the potential field. In square A, this metric is far larger than in other regions. Furthermore, we calculate the metric everywhere (shown in Figure 8). We can see that square A is located at the large energy ratio region of “Fce,” while the ratio is small in square C. However, we do not see a large energy ratio in square A for “Wie.” Therefore, we believe that square A contains a large percent of the free energy, and the forced field extrapolation can reconstruct the magnetic field in this region more successfully than in the NLFFF model. The snow appearing near the upper and lower boundaries of “Fce” stem from the noise in the raw magnetogram. The “Fce” with a preprocessed boundary eliminates the snow (not show here). The metric of free energy lost (see Table 1) shows that the “Wie” result contains 17% more free energy than the “Fce” result. In square A, however, “Wie” lost 69% of the free energy.

It must be pointed out that due to the highly inclined geosynchronous orbit of SDO, the relative velocity between the HMI instrument and the Sun can range \( \pm 3 \text{ km s}^{-1} \) (Hoeksema...
et al. 2014). This leads to temporal and spatial variations of the inverted magnetic field over a period of 12 hr. The systematic errors in the magnetic field data contaminate the results (Schuck et al. 2015). The unsigned fluxes in Figure 3 of Chintzoglou & Zhang (2013) show an obvious dip near midnight on February 14, 15, and 16. The energy flux profile in the bottom of Figure 2 of Vemareddy (2015) shows clear oscillation over a timescale of 12 hr. The free energy of the extrapolated magnetic field is also affected by these systematic errors.

6. CONCLUSION

We have applied a forced field extrapolation method to model the chromospheric magnetic field above AR 11967 with HMI magnetogram. We reach the following conclusion. (1) The relaxation process is converged by checking the temporal evolution of $CW_{\sin}$, the magnetic energy, and the magnetic field lines. (2) “$Fce$” can recover the field lines successfully in the chromosphere, while “Wie” may fail in the region containing a large percent of the free energy. (3) The raw magnetogram without preprocessing is required for “$Fce$”. (4) The “$Fce$” results show that the forced region can reach a height of 1400–1800 km, which is much higher than was previously estimated.

This work is jointly supported by National Natural Science Foundation of China (NSFC) through grants 11403044, 11473040, and 11273031. The data used are courtesy of the NVST and SDO science teams.

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