Transverse oscillation of a coronal loop induced by a flare-related jet

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Received; accepted

ABSTRACT

Context. Kink oscillations in coronal loops are ubiquitous, and the observed parameters of oscillations are applied to estimate the magnetic field strength of the loops.

Aims. In this work, we report our multiwavelength observations of the transverse oscillation of a large-scale coronal loop with a length of ≥350 Mm. The oscillation was induced by a blowout coronal jet, which was related to a C4.2 circular-ribbon flare (CRF) in AR 12434 on 2015 October 16. We aim to determine the physical parameters in the coronal loop, including the Alfvén speed and magnetic field strength.

Methods. The jet-induced kink oscillation was observed in extreme-ultraviolet (EUV) wavelengths by the Atmospheric Imaging Assembly (AIA) on board the Solar Dynamics Observatory (SDO). Line of sight magnetograms were observed by the Helioseismic and Magnetic Imager (HMI) on board SDO. We took several slices along the loop to assemble time-distance diagrams, and used an exponentially decaying sine function to fit the decaying oscillation. The initial amplitude, period, and damping time of kink oscillation were obtained. Coronal seismology of the kink mode was applied to estimate the Alfvén speed and magnetic field strength in the oscillating loop. In addition, we measured the magnetic field of the loop through non-linear force-free field (NLFFF) modeling using the flux rope insertion method.

Results. The oscillation is most pronounced in AIA 171 and 131 Å. The oscillation is almost in phase along the loop with a peak initial amplitude of ~13.6 Mm, meaning that the oscillation belong to the fast standing kink mode. The oscillation lasts for ~3.5 cycles with an average period of ~462 s and average damping time of ~976 s. The values of $\tau/P$ lie in the range of 1.5–2.5. Based on coronal seismology, the Alfvén speed in the oscillating loop is estimated to be ~1210 km s$^{-1}$. Two independent methods are applied to calculate the magnetic field strength of the loop, resulting in 30–43 G using the coronal seismology and 21–23 G using the NLFFF modeling, respectively.

Conclusions. The magnetic field strength estimated using two different approaches are in the same order of magnitude, which confirms the reliability of coronal seismology by comparing with the NLFFF modeling.

Key words. Sun: magnetic fields – Sun: flare – Sun: corona – Sun: oscillations

1. Introduction

Waves and oscillations are prevalent in the fully ionized solar corona with temperatures of several million Kelvin (MK) (see Nakariakov & Verwichte 2005, and reference therein). The periodic transverse displacements of coronal loops are usually considered as kink oscillations detected in the extreme ultraviolet (EUV) wavelengths (Andries et al. 2009, Ruderman & Erdélyi 2009). Standing fast kink-mode oscillations were initially discovered by the Transition Region and Coronal Explorer (TRACE; Handy et al. 1999) mission in 171 Å (Aschwanden et al. 1999, Nakariakov et al. 1999, Schrijver et al. 2002). Since the launch of the Solar Dynamics Observatory (SDO; Pesnell et al. 2012), kink oscillations of coronal loops observed by the Atmospheric Imaging Assembly (AIA; Lemen et al. 2012) on board SDO have been extensively investigated (e.g., Aschwanden & Schrijver 2011, White & Verwichte 2012, Verwichte et al. 2013a,b, Pascoe et al. 2016, Nisticò et al. 2017, Duckenfield et al. 2018, 2019, Nechaeva et al. 2019).

The commencement of the loop oscillation usually coincides with a nearby eruption (flare, jet, or filament eruption) in the lower corona, which is considered as the predominant mechanism for exciting kink oscillations (Zimovets & Nakariakov 2015). After the excitation, kink oscillations experience attenuation and last for several cycles in most cases (Goddard et al. 2016, Goddard & Nakariakov 2016). Resonant absorption, as a result of resonance within a finite thin layer, is believed to play a key role in the rapid damping of fast-mode kink oscillations (Goossens et al. 2002, Ruderman & Roberts 2002). Phase mixing with anomalously high viscosity is also important in the dissipation of energy during loop oscillations (Ofman & Aschwanden 2002). Small-amplitude, transverse oscillations of coronal loops without significant damping have been noticed (Anfinogentov et al. 2013, Nisticò et al. 2013, Li et al. 2018a, Zhang 2020). The observed loop oscillations in combination with magnetohydrodynamics (MHD)
Circular-ribbon flares (CRFs) are a special type of flares, whose short, inner ribbons are surrounded by circular or elliptical ribbons (Masson et al. 2009; Chen et al. 2019; Zhang et al. 2016b, 2019; Lee et al. 2024; Liu et al. 2020). Transverse loop oscillations excited by CRFs with periods of ≤ 4 min have been observed by AIA (Zhang et al. 2013; Li et al. 2018b). Recently, Zhang et al. (2020) investigated the transverse oscillations of an EUV loop excited by two successive CRFs on 2014 March 5. The oscillations are divided into two stages in their development: the first-stage oscillation triggered by the C2.8 flare is decayless with lower amplitudes, and the second-stage oscillation triggered by the M1.0 flare is decaying with larger amplitudes. The authors also estimated the magnetic field and thickness of the inhomogeneous layer of the oscillating loop with a length of ~ 130 Mm.

In this paper, we report our multiwavelength observations of the transverse oscillation of a large-scale coronal loop excited by a blowout jet associated with the C4.2 CRF in active region (AR) 12434 on 2015 October 16. Zhang et al. (2016c) studied the explosive chromospheric evaporation at the inner and outer flare ribbons using spectroscopic observations. This work is building on the work of Zhang et al. (2016c) (hereafter Paper I), and the main purpose is to estimate the magnetic field of the oscillating loop using two independent approaches, coronal seismology and magnetic field extrapolation. This paper is organized as follows. Observations and data analysis are presented in Sect. 2. The results are presented in Sect. 3. A brief summary and discussion are presented in Sect. 4.

2. Observations and Data Analysis

2.1. Instruments

The transverse oscillation of the coronal loop was observed by SDO/AIA, which has a spatial resolution of 1/2 arcsec and time cadence of 12 s in EUV wavelengths. The photospheric line-of-sight (LOS) magnetograms were observed by the Helioseismic and Magnetic Imager (HMI; Schou et al. 2012) on board SDO with a spatial resolution of 1/2 arcsec and cadence of 45 s. The level_1 data from AIA and HMI were calibrated using the standard Solar SoftWare (SSW) programs aia_prep.pro and hmi_prep.pro, respectively. Soft X-ray (SXR) light curves of the flare were recorded by the GOES spacecraft with a cadence of ~ 2.05 s.

2.2. DEM analysis

The differential emission measure (DEM) analysis is a useful tool to perform temperature diagnostics. Several algorithms have been proposed and validated (e.g., Weber et al. 2004; Hannah & Kontar 2012; Aschwanden et al. 2013; Plowman et al. 2013; Cheung et al. 2015; Su et al. 2018; Morgan & Pickering 2019). The observed flux $F_i$ of each optically thin passband $i$ is determined by:

$$ F_i = \int_{T_1}^{T_2} R_i(T) \, \text{DEM}(T) \, dT, $$

(1)

where $R_i(T)$ is the temperature response function of passband $i$, and $\text{DEM}(T)$ represents the DEM of multithermal plasma as a function of temperature. $\log T_1 = 5.5$ and $\log T_2 = 7.5$ stand for the lower and upper limits for the integral. To carry out the inversion of DEM profile, we use the standard SSW program xrt_dem_iterative2.pro and six EUV passbands (94, 131, 171, 193, 211, and 335 Å). The method has been strictly justified and successfully applied to the temperature estimation of EUV hot channel as well as coronal jets (Cheng et al. 2012; Zhang & Ji 2014; Zhang et al. 2016a). Note that the background emissions should be removed before inversion.

The DEM-weighted average temperature $\bar{T}$ is defined as (Cheng et al. 2012):

$$ \bar{T} = \int_{T_1}^{T_2} \text{DEM}(T) \, T \, dT / \int_{T_1}^{T_2} \text{DEM}(T) \, dT. $$

(2)

Then, the total column emission measure (EM) along the LOS is expressed as:

$$ \text{EM} = \int_{T_1}^{T_2} \text{DEM}(T) \, dT. $$

(3)

2.3. Flux rope insertion method

We use the flux rope insertion method developed by van Ballegooijen (2004) to reconstruct the non-linear force-free field (NLFFF) of AR 12434. The advantage of this method is that it can be applied to many different situations including both ARs (Su et al. 2009, 2011, 2018a) and quiet Sun (Su et al. 2015) since no vector field observations are required and the magnetic field lines of the best-fit model match well the observed coronal non-potential structures. Su (2019) gives a detailed review on the application of the method. Reconstructing the coronal magnetic fields in the target AR requires four steps:

1. Extrapolating the potential field based on the corresponding photospheric LOS magnetogram.
2. According to observations, creating a cavity in the potential field model, and then inserting a magnetic flux rope along the selected paths.
3. Creating a grid of models by adjusting axial flux and poloidal flux of the inserted magnetic flux rope.
4. Starting magneto-frictional relaxation (Yang et al. 1986) to drive the magnetic field towards a force free state, and then comparing with observations to find the best-fit model.

3. Results

3.1. Transverse coronal loop oscillation

Figure 1 shows the EUV images observed by AIA in 171, 131, 193, and 211 Å before flare. The northeast footpoint of the large-scale coronal loop (yellow dashed line) is rooted in AR 12434 and is very close to the C4.2 CRF pointed by the red arrow. As is described in Paper I, the flare brightened up from 13:36:30 UT. The accompanying blowout jet started to rise at ~ 13:39 UT and propagated in the southeast direction at a speed of ~ 300 km s$^{-1}$. Transverse oscillation of the long loop was excited by the jet and lasted for a few cycles (see the online movie oscillation.mov).

Figure 2 shows the SXR light curves of the flare in 1–8 Å (red line) and 0.5–4 Å (blue line). The SXR emissions started to increase at ~ 13:36:30 UT and reached the peak values at
To investigate the transverse loop oscillation, we choose three points along the loop: the first one is near the loop top, the third one is close to the southwest footpoint, and the second one in between. We place three artificial slices (S1, S2, and S3) across the points and just perpendicular to the loop, which are drawn with white solid lines in Fig. 1. The corresponding time-distance diagrams in 171 Å are plotted in the top three panels of Fig. 3. It is seen that excited by the jet, the loop deviated from the equilibrium state and began to move southward at ~13:39 UT coherently. Then the loop moved backward and oscillated with decaying amplitude for more than three cycles. The almost identical phases of the transverse loop oscillation at different positions along the loop indicate that the oscillation belong to the standing fast kink mode.

To determine the parameters of kink oscillation along different slices, we mark the positions of the loop manually, which are connected with magenta dashed lines in Fig. 3. The kink oscillation is fitted with an exponentially decaying sine function ~13:42:30 UT, before declining gradually until ~13:51 UT (see also Fig. 5 in Paper I). The time of loop oscillation during 13:39–14:05 UT is labeled with yellow area. It is found that the start time of transverse loop oscillation coincides with the fast ejection of jet (see also Fig. 4 in Paper I), and the oscillation covers part of the impulsive and whole decay phase of the flare, lasting for ~26 min. The excitation of loop oscillation in our study can be interpreted by the schematic cartoon (Zimovets & Nakariakov 2015, see their Fig. 2).
As mentioned in Sect. 1, estimation of the magnetic field strength of oscillating loops is an important application of coronal seismology. To estimate the magnetic field of the large-scale coronal loop in Fig. 1 we consider the loop as a straight cylinder with the magnetic field lines frozen. The period of standing kink-mode oscillation depends on the loop length \((L)\) and phase speed \((C_A)\) (Nakariakov et al. 1999):

\[
P = \frac{2L}{C_A}, \quad C_A = \sqrt{\frac{2}{1 + \rho_e/\rho_i}} C_k,
\]

where \(C_A\) is the Alfven speed in the loop, and \(\rho_e\) and \(\rho_i\) stand for the external and internal plasma densities.

In Fig. 1 the apparent distance between the footpoints of loop is \(\sim 256''\), while the real distance becomes \(\sim 268''\) after correcting the projection effect. Since there were no stereoscopic observations from the STEREO (Kaiser 2005) spacecrafts, the true geometry of the loop could not be inferred by stereoscopy. We assume a semi-elliptical shape of the loop initially in the \(xz\)-plane, which is determined by the major axis \((2a)\) and minor axis \((2b)\). The minor axis is taken to be the length of the loop baseline.
Fig. 5. Three-dimensional (3D) geometry of the semi-elliptical loop, with major and minor axes being 350′′ and 264′′. The rotation angles of the initial loop around x, y, and z axes are -60°, -9°, and 40°, respectively. The colors along the loop represents the heights, and the thin light blue lines represent the projections of the loop onto the three planes.

Fig. 6. The observed loop (red dashed line) in Fig. 1 and projected semi-elliptical loop in the xy-plane (blue solid line).

The observed loop (red dashed line) in Fig. 1 and projected semi-elliptical loop, with major and minor axes being 350′′ and 264′′. The rotation angles of the initial loop around x, y, and z axes are -60°, -9°, and 40°, respectively. The colors along the loop represents the heights, and the thin light blue lines represent the projections of the loop onto the three planes.

3.3. Magnetic field determined by NLFFF modeling

To validate the magnetic field strength of the oscillating loop inferred from coronal seismology, we carry out NLFFF modeling to construct magnetic field models by using the flux rope insertion method (van Ballegooijen 2004). We have briefly introduced the method in Sect. 2.3, and more details can be found in Bobra et al. (2008) and Su et al. (2009, 2011).

The boundary condition for the high-resolution region is derived from the LOS magnetogram taken by HMI at 13:36 UT on 2015 October 16. The longitude-latitude map of the radial component of the magnetic field in the high-resolution region is presented in Fig. 8(b). Three flux ropes with the same poloidal flux (0 Mx cm⁻¹) are inserted. However, the axial fluxes are different, namely, 8×10²⁰ Mx, 1×10²⁰ Mx and 4×10²⁰ Mx, respectively. In Fig. 8(c), selected model field lines matching the observed non-potential coronal loops are overlaid on the AIA 171 Å image. The length of the pink line (~354 Mm) accounts for ~94% of the loop length assuming a semi-elliptical
shape. We obtained the magnetic field strength at several locations along the model field line, which lies in the range of 21–23 G and is in the same order of magnitude as the result of coronal seismology.

4. Summary and Discussion

In this work, we report our multiwavelength observations of the transverse oscillation of a large-scale coronal loop induced by a blowout jet related to a C4.2 CRF in AR 12434 on 2015 October 16. The oscillation is most pronounced in AIA 171 and 131 Å. The oscillation is almost in phase along the loop with a peak initial amplitude of $\sim 13.6$ Mm, meaning that the oscillation belong to the fast standing kink mode. The oscillation lasts for $\sim 3.5$ cycles with an average period of $\sim 462$ s and average damping time of $\sim 976$ s. The values of $\tau/P$ lie in the range of 1.5–2.5. Based on coronal seismology, the Alfvén speed in the oscillating loop is estimated to be $\sim 1210$ km s$^{-1}$. Two independent approaches are applied to calculate the magnetic field strength of the loop, resulting in $30–43$ G using the coronal seismology and $21–23$ G using the NLFFF modeling. The results of two methods are in the same order of magnitude, which confirms the reliability of coronal seismology in diagnosing coronal magnetic field.

As mentioned in Sect. 1, transverse loop oscillations triggered by CRFs have been observed. Zhang et al. (2015) analyzed an M6.7 flare as a result of partial filament eruption on 2011 September 8. Kink oscillation was induced in an adjacent coronal loop within the same AR (see their Fig. 7). The oscillation with a small amplitude ($\sim 1.6$ Mm) lasted for $\sim 2$ cycles without significant damping. The estimated parameters are listed and compared with this study in Table 2. It is found that the values of $C_k$ and $C_A$ are close to each other for the two events. Both the loop length and period in this study are $\geq 2$ times larger than those for the event in 2011. However, the density and magnetic field of the loop in 2011 are much larger than those in our study. Zhang et al. (2020) investigated the decayless and decaying kink oscillations of an EUV loop on 2014 March 5. For comparison, the parameters, including the shortest loop length and period among the three events, are also listed in the last row of Table 2.
Aschwanden & Schrijver (2011) compared the magnetic field of an oscillating loop determined by coronal seismology with the result of magnetic extrapolation based on the potential field source surface (PFSS) modeling using the photospheric magnetogram. It is found that the average extrapolated magnetic field strength exceeded the seismologically determined value (~4 G) by a factor of two. After improving the method of estimation of physical parameters by taking the effect of density and magnetic stratification into account, the extrapolated magnetic field is optimized (Verwichte et al. 2013a, Guo et al. 2015) reported the kink oscillation of a coronal loop with a total length of ~204 Mm, which was excited by the global fast magneto-acoustic wave as a result of flux rope eruption and the associated eruptive flare on 2013 April 11. Based on coronal seismology, they derived the spatial distribution of magnetic field (~8 G) along the loop, which matches with that derived by a potential field model (Long et al. 2017) estimated the magnetic field of a trans-equatorial loop system using two independent techniques. It is found that the magnetic field strength (~5 G) estimated by two approaches are roughly equal.

Acknowledgements. The authors are grateful to the referee for valuable suggestions. The authors also appreciate Drs. Z. F. Ding, D. Li, and F. Chen for valuable discussions. SDO is a mission of NASA’s Living With a Star Program. AIA and HMI data are courtesy of the NASA/SDO science teams. Q.M.Z. is supported by the Science and Technology Development Fund of Macau (275/2019/A1), and the Strategic Priority Research Program on Space Science, CAS (XDA15052200, XDA15320301).