Resonant absorption as a damping mechanism for the transverse oscillations of the coronal loops observed by SDO/AIA

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Abstract

Solar coronal loops represent the variety of fast, intermediate, and slow normal mode oscillations. In this study, the transverse oscillations of the loops with a few-minutes period and also with damping caused by the resonant absorption were analyzed using extreme ultraviolet (EUV) images of the Sun. We employed the 171 data recorded by Solar Dynamic Observatory (SDO)/Atmospheric Imaging Assembly (AIA) to analyze the parameters of coronal loop oscillations such as period, damping time, loop length, and loop width. For the loop observed on 11 October 2013, the period and the damping of this loop are obtained to be 19 and 70 minutes, respectively. The damping quality, the ratio of the damping time to the period, is computed about 3.6. The period and damping time for the extracted loop recorded on 22 January 2013 are about 81 and 6.79 minutes, respectively. The damping quality is also computed as 12. It can be concluded that the damping of the transverse oscillations of the loops is in the strong damping regime, so resonant absorption would be the main reason for the damping.

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

1 Introduction

The field of coronal seismology has been developing during last decades. It seems to be heading toward revolution in the physics of the Sun. It means a very efficient instrument is achieved to explore the basic intrinsic physical parameters of the solar corona including magnetic field, temperature, and density of plasma. The slow, intermediate, and fast oscillations of the solar coronal loops were detected by various types of space telescopes (Abedini et al. 2016, 2018; Aschwanden et al. 1999; Aschwanden, Schrijver 2011; Dadashi et al. 2009; Erdélyi, Taroyan 2008; Moortel, Brady 2007; Nakariakov 1999; Ofman, Wang 2002; Safari et al. 2007; Taran et al. 2014; Verth et al. 2007; Verwichte et al. 2009; Wang, Solanki 2004; Wang et al. 2005).

From the theoretical point of view, the coronal seismology was proposed by Uchida (1970) and Roberts et al. (1984) for the flux tube standing waves. The coronal seismology is based on the dispersion relation defined for a plasma cylinder; a cylinder with non-uniform plasma structure formed by a magnetic field (Abedini et al. 2012; Andries et al. 2005; Edwin, Roberts 1983; Erdélyi, Fedun 2007; Esmaeili et al. 2015, 2017; Esmaeili et al. 2018; Farahani et al. 2019).

arXiv:1902.09649v1 [astro-ph.SR] 25 Feb 2019
With the advancement of technology, due to high-resolution spatial imaging, the new coronal seismological field entered the golden age of explorations. The first evidence for fast MHD kink mode was achieved from TRACE observation, which was based on detecting the transverse loop movement oscillations with the theoretically expected periods of kink mode Schrijver et al. (2002). Some kink modes seem to be majorly in the transverse direction Aschwanden et al. (1999); while other modes clearly oscillate in perpendicular direction Wang, Solanki (2004).

The second-order geometrical and physical effects of coronal oscillation have been theoretically studied; nevertheless, the effect of curvature of loops on the oscillation period van Doorsselaere et al. (2004b), the impact of the elliptic transverse cross sections on damping of oscillation Ruderman (2003), and also the effect of density stratification on the loop oscillation have been carefully specified Andries et al. (2005); Dymova, Ruderman (2005); Farahani et al. (2014); Fathalian, Safari 2010; Grant et al. (2015); Mendoza-Briceno et al. (2004); Pascoe et al. (2018, 2017); Safari et al. 2007; Shukhobodskiy et al. (2018); Soler et al. (2011); Verth et al. (2007, 2010).

The observation of the first two harmonics of the horizontally polarized kink waves excited in the coronal loop system was reported by Guo et al. (2015). Zhang et al. (2016) also investigated the evolution of two prominences ($P_1, P_2$) and two bundles of coronal loops ($L_1, L_2$). Another development concerning the non-damping oscillations at flaring loops was recently published by Li et al. (2018). As a seismological application, periods and damping rates of the fast sausage oscillations in multishelled coronal loops were investigated by Chen et al. (2015). Also, Jin et al. (2018) recently studied the damping of two-fluid MHD Waves in stratified solar atmosphere.

Analysis of the transverse oscillations of loops (kink mode) in an active flaring region indicates that the initiation of these oscillations is caused by a disturbance, movements from the center of a flare towards the outside at the velocity of 700 km/s, which can produce a shock wave Aschwanden (2006). The understanding of coronal loop oscillations and the mechanism underlying their damping has been subjected to a vast studies. Various damping mechanisms for oscillations of the coronal loops have been discussed by Roberts (2000).

Hollweg, Yang (1988) were the first ones who investigated and discussed the damping of kink oscillations caused by resonant absorption. A method to analyze the dissipative processes in the regimes with the vicinity of the singularity has been developed by Sakurai et al. (1991a); Sakurai et al. (1991b); Goossens et al. (1992), and Goossens et al. (1995). Ruderman, Roberts (2002) rebuilt this idea. They considered this problem for a straight magnetic flux tube disturbed in cold plasma. The tube had a homogeneous core and a thin layer of thickness $l$ whose density uniformly reduced from center to the tube boundary.

Resonant absorption occurs when the waves entered the flux tube from the footpoints area are frequently reflected and the kink oscillation frequency of the tube becomes equal to the local Alfvén frequency in a place within the resonant layer of the tube. Thus, resonant will occur for the standing waves, and the energy of these waves will be converted to the thermal energy of the environment through the ohmic resistivity and viscous dissipation.

Considering the fact that the damping time caused by resonant absorption is about the order of $(a/l)P$, where $l$, $a$, and $P$ are length, radius, and period of the loop respectively, Ruderman, Roberts (2002) employed a new proposed mechanism for the data observed by Nakariakov (1999), and concluded that $l/a = 0.23$. Goossens et al. (2006) used the mechanism proposed by Hollweg, Yang (1988), and Ruderman, Roberts (2002) in order to estimate the amount of $(l/a)$ for 11 damped loops. They obtained this value in the range 0.16 to 0.491. These answers were obtained by assuming $l \ll a$. These results were inspired by van Doorsselaere et al. (2004a) for elimination of the limitation of $l \ll a$ as well as numerically solving the damping of the loop. They came to the conclusion that the difference between numerical and analytical values for $l/a \leq 1/3$ is very small. Even for $l \approx a$, the difference was not more than 0.25. Recently, Su et al. (2018) investigated the strength of the magnetic...
field using the densities obtained by the differential emission measure (DEM) method and they concluded that the magnetic field decays during the oscillation. Goossens et al. (1992) studied the resonant absorption and obtained the ratio of the damping rate to the oscillation frequency for the long wavelengths in case the magnetic field is constant and parallel to the axis of the tube everywhere. The ratio of the damping time to the oscillation period is obtained 4.97, which has a value of about 3 to 5 based on observations. Eventually, we conclude that the resonant absorption is an acceptable mechanism for explaining the damping observed in the transverse kink oscillations of coronal loops.

This paper is organized as follows, the method applied for extracting the oscillation is introduced in Section 2. In Section 3, we present the extracted results for frequencies and damping times of the loops recorded on 22 January 2013 and 11 October 2013. The main conclusions are also presented in Section 4.

2 Method

The coronal loops of the Sun are curved and bright structures. The hot plasma trapped around the magnetic field lines inside the loop leads to seem brighter than their surrounding environment. Due to factors such as fast oscillating waves caused by flares, coupling with oscillating modes enforced by pressure, and pulses of driven hot plasma, these magnetic loops represent the normal oscillation modes. The coronal loops have lengths from a few mega meters to several hundred mega meters. The limitation of the spatial resolution capability of solar observatories in the EUV and X-ray pass bands has made it almost impossible to observe and analyze the internal structure of the thin loops Esmaeili et al. (2017); Esmaeili et al. (2016). Coronal seismology provides an alternative method for understanding the physical and geometrical structure of the loops.

Pursuing higher spatial resolution, the Solar Dynamic Observatory (SDO) spacecraft was launched in February 2010 to study the Sun interior, solar magnetic field, solar coronal hot plasma, and effects of photospheric phenomena on space weather. In this study, we used the solar data provided by the Atmospheric Imaging Assembly (AIA) instrument on-board the SDO which provides full-disk images of the Sun’s atmosphere with a time cadence of 12 seconds in various EUV pass bands. Therefore, the damping of loops are investigated using successive EUV images at 171 Å.

To this end, we will address the creation of space-time images from consecutive EUV images of the coronal loops at a specified time interval. By means of the Gaussian function fitting to each time element of these images, parameters such as the spatial oscillation amplitudes and the width of the loops are extracted. Then, through analyzing the spatial oscillation amplitudes of the loop, the periods and the damping time are obtained. In this study, consecutive images of loops on 11 October 2013 at 07:11:59 to 08:21:59 UT (Figure 1a) and 22 January 2013 at 02:20:00 to 03:41:00 UT (Figure 1b) provided by http://jsoc.stanford.edu are investigated. To extract the oscillations for each data set, we applied the displacements correction due to the differential rotation of the Sun. To co-align the consecutive images to one reference, all data were derotated (see Alipour, Safari (2015)).

In order to create the space time image, arbitrary number of points (based on length and width of the loop) are selected using the spline interpolation in two directions to form a rectangular region perpendicular to the loop axis (as shown with green lines in Fig. 1). Averaging over intensities of distinct pixels on different rows within the appointed box creates an element of the space time image for the desirable locations at a specific time. Performing the same procedure for each successive image results in the space time image (Fig. 2), in which the transverse oscillating mode is extracted by averaging over the intensities perpendicular to the loop axis.
Figure 1. Partial image of the Sun at 171 Å provided by SDO/AIA. Left panel: the observed loop on 11 October 2013. Right panel: the observed loop on 22 January 2013.

3 Results and Discussion

In the space-time image of Fig. 2, the kink oscillation modes of several loops observed on 22 January 2013 are shown. Considering the complexity of the simultaneous analysis of all these oscillations, we just extract the most noticeable loop from this space-time image and address its parameters (Figure 3). This oscillations started at 07:11:59 UT and ended at 08:21:59 UT. A Gaussian function was employed to derive the oscillation amplitudes as follows:

$$F(x,t) = f(t) \exp \left( -\frac{(x - a(t))^2}{2\sigma(t)} \right) + b(t).$$

This fitting is performed for each column of the space-time image. In this regard, the parameter $f(t)$ is the index of intensity oscillation amplitudes, $a(t)$ is the index of spatial oscillation amplitudes, $x$ is the length of the space-time rectangle created in pixel unit, $\sigma(t)$ is related to the the width of Gaussian function, and $b$ represents the background intensity. The loop width is also obtained by $w = 2\sigma\sqrt{2ln2}$.

Figure 2. The space-time image of the loop observed on 11 October 2013, obtaining from 650 consecutive EUV images provided by SDO/AIA.

The lengths of the two studied loops are obtained about $345 \pm 35$ Mm (Figure 1a) and $195 \pm 20$ Mm (Figure 1b), respectively. Therefore, using the values of $\sigma$, the width of loops are 6.85 Mm and 3.7 Mm, respectively.
At the next stage the period of studied loop is attainable by fitting the following function \( A(t) \) describing equilibrium position of the spatial oscillation amplitudes (e.g., [Su et al. (2018)]):

\[
A(t) = a_0 + a_1 \exp \left( \frac{-(t-t_0)}{\tau} \right) \cos \left( \frac{2\pi(t-t_0)}{P_0 + k\tau - \phi} \right) + a_2 \frac{t-t_0}{P_0},
\]

where \( a_0 \) is the amplitude, \( t \) is time, and \( \tau \) represents damping time. The parameters \( P_0, k, \) and \( \phi \) are the period of oscillation, the evolution rate, and the oscillation phase, respectively. The spatial oscillation amplitudes of the loop recorded on 11 October 2013 and the corresponding fit are represented in Fig. 4.

According to the fit results, \( \tau \) is obtained about 70 minutes and the oscillation period is obtained around 19 minutes. The damping quality, the ratio of the damping time to the period of oscillation \( Q = \frac{\tau}{P_0} \) [Ruderman, Roberts (2002); Safari et al. (2006)], is computed about 3.6. It seems that the main mechanism for the strong damping of the loop oscillation is the resonant absorption.

We have also studied the loop recorded on 22 January 2013 at 02:20:00 UT (Figure 1 b), following the same procedure described earlier. The oscillation of this loop started at 02:20:00 UT and ended at 03:41:00 UT. The space-time image corresponding to this data set is shown in Figure 5. The period and damping time are obtained about 6.79 and 81 minutes, respectively. The damping quality is computed about 12. Figure 6 represents the result of fitting Eq. (2) to the spatial oscillation amplitudes of the loop over the interval 720 to 3182 seconds.

**Figure 3.** The extracted oscillating wave from the space-time image of Figure 1, corresponding to the loop observed on 11 October 2013.

**Figure 4.** The spatial oscillation amplitudes of the loop recorded on 11 October 2013, and the result of fitting Eq. (2) to the amplitudes.
4 Conclusions

In this paper, we studied the period and the damping time of transverse kink oscillations using successive EUV images for two loops recorded on 11 October 2013 (loop 1) and 22 January 2013 (loop 2) provided by SDO/AIA. The spatial oscillation amplitudes for each data set are derived using the appropriate Gaussian function (Eq. 1). The lengths of the loop 1 and 2 are calculated $345 \pm 35$ Mm and $195 \pm 20$ Mm, respectively. We determined that the period and the damping time for the loop 1 are about 19 and 70 minute, respectively. For the loop 2, the period and damping time are also calculated about 81 and 6.79 minute, respectively. Therefore, the damping quality for the loop 1 and 2 are 12 and 3.6, respectively. According to the obtained damping qualities for each studied case, which can be classified as the strong damping, we conclude that the resonant absorption may be the main mechanism for damping of these oscillations.

Several damping mechanisms (e.g., non-ideal MHD effects, lateral wave leakage, footpoints wave leakage, phase mixing and resonant absorption) were investigated for the damping of coronal loop oscillations (e.g., Aschwanden (2005)). The results of the present study and also many other previous research show that the kink mode oscillation of coronal loops are damped due to the resonant absorption in the strong damping regime. From the theoretical point of view (e.g., Ruderman, Roberts (2002), Safari et al. (2007)), at a thin resonant layer (boundary
layer) at the lateral boundary of the coronal loops with the inhomogeneous density along the cross section, the energy of the kink mode oscillations can be transferred to the localized Alfvén waves. This energy may heat up the coronal loops to several million kelvins.

Acknowledgements

The authors thank NASA/SDO and the AIA science team for providing data publicly available.

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