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Resonant Absorption of a Solar Coronal Loop Observed by SDO/AIA

Javad Ganjali[1] · Nastaran Farhang[1] · Shahriar Esmaeili[2] · Mohsen Javaherian[3] · Hossein Safari[1]

[1] Department of Physics, Faculty of Science, University of Zanjan, P.O. Box: 45195-313, Zanjan, Iran [2]
Department of Physics and Astronomy, Texas A&M University, 4242 TAMU, University Dr., College Station, TX 77840, US [3]
Research Institute for Astronomy and Astrophysics of Maragha (RIAAM), University of Maragheh, P.O. Box: 55136-553, Maragheh, Iran

Abstract. Solar coronal loops represent variety of fast, intermediate, and slow normal mode oscillations. In this study, the transverse oscillations of a coronal loop observed on 11 October, 2013 are analyzed using the extreme ultra-violet (EUV) images of the Sun. Employing the 171 Å solar images recorded by the Solar Dynamic Observatory (SDO)/Atmospheric Imaging Assembly (AIA), we extracted the oscillation parameters such as period, damping time, loop length, and the loop width. The period and the damping of this loop are obtained to be 19 ± 1 and 70 ± 1 minutes, respectively. Also, the damping quality, the ratio of the damping time to the period, is obtained to be 3.6. Therefore, we conclude that the damping of the transverse oscillation of this loop is in the strong damping regime. It is suggested that the resonant absorption would be a well suitable candidate for the damping mechanism of the studied loop.

Keywords: Sun: corona Sun: loop Sun: oscillations

1 Introduction

The solar coronal structures based on the seismological techniques have been widely explored during the past decades. From the theoretical point of view, coronal seismology was firstly proposed by Uchida (1970) and Roberts et al. (1984), and has been applied ever since. In coronal seismology, the wide variety of non-uniform plasma structures (formed by the solar magnetic field e.g., coronal loops) are considered as cylindrical elements and their spatial and temporal evolutions are investigated by solving the magnetohydrodynamic (MHD) equations for their particular boundary conditions. This way, the dispersion relation of the oscillatory flux tube is obtained, which describes the plasma oscillation modes and its properties such as period of oscillations, amplitude, and the damping time. Therefore, a comparison between the predicted characteristics of the oscillatory modes (based on seismology and the observed properties) gives insight about the intrinsic parameters of the solar corona such as magnetic field, temperature, and the density of plasma (Edwin & Roberts, 1983; Nakariakov, 1999; Goossens et al., 2002; Ofman & Aschwanden, 2002; Ruderman & Roberts, 2002; Karami et al., 2002; Van Doorsselaere et al., 2004a,b; Andries et al., 2005; Safari et al., 2006; Erdelyi & Fedun, 2007; Dadashi et al., 2009; Abedini et al., 2012; Esmaeili et al., 2015; Esmaeili et al., 2016; Esmaeili et al., 2017; Farahani et al., 2017; Abedini & Mousavi Monfared, 2017).

With the advancement of technology and development of high-resolution instruments, the coronal seismology has headed toward a revolution in the detection of wave-like perturbations

(Mendoza-Briceno et al., 2004; Andries et al., 2005; Dymova & Ruderman, 2005; Safari et al., 2007; Verth et al., 2007; Fathalian & Safari, 2010; Verth et al., 2010; Soler et al., 2011; Farahani et al., 2014; Grant et al., 2015; Pascoe et al., 2017; Shukhobodskiy et al., 2018; Pascoe et al., 2018). The first evidence for the fast MHD kink mode was discovered from TRACE observations based on the detection of the transverse movements of a coronal loop with the theoretically expected periods of kink modes (Schrijver et al., 2002). 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). Analysis of the transverse oscillations of the loops in an active flaring region indicated that the initiation of these oscillations is due to a disturbance propagating from the center of a flare towards the outside with velocity of 700 km/s which could produce shock waves (Aschwanden, 2006). Also, periods and the damping times of the fast sausage oscillations in multi-shelled coronal loops were investigated by Chen et al. (2015). Another development concerning the non-damping oscillations of flaring loops was published by Li et al. (2018). Recently, Jin et al. (2018) studied the damping of two-fluid MHD waves in the stratified solar atmosphere. Moreover, the second-order geometrical and physical effects of coronal oscillations have been studied; Nevertheless, the effect of the curvature of the loops on the period of oscillations (Van Doorsselaere et al., 2004b), the impact of the elliptic transverse cross sections on the damping of oscillations (Ruderman, 2003) and also, the effect of the density stratification on the loop oscillations have been carried out (Safari et al., 2007).

Understanding the coronal loop oscillations and the mechanism underlying their damping has been subjected to a wide range of studies (Sakurai et al., 1991; Goossens et al., 1992, 1995; Roberts, 2000; Ruderman & Roberts, 2002). Several damping mechanisms (e.g., non-ideal MHD effects, lateral wave leakage, footpoints wave leakage) are proposed for the damping of coronal loop oscillations (e.g., Aschwanden, 2005). Hollweg & Yang (1988) discussed whether the damping of kink oscillations is due to the resonant absorption. Resonant absorption occurs as waves entering a flux tube at its footpoints 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, resonance occurs for the standing waves and the energy converts into heat through the ohmic and viscous dissipations.

Considering the fact that the damping time caused by resonant absorption is of the order $(l/a)P$, where a is the radius of the loop, P is the period of oscillations, and l is the thickness of a layer near the lateral boundary in which the plasma density varies, Ruderman & Roberts (2002) employed a new approach to analyse the data observed by Nakariakov (1999), and concluded that $l/a = 0.23$. Goossens et al. (2006) assumed that $l \ll a$, and applied the mechanism proposed by Hollweg & Yang (1988), and Ruderman & Roberts (2002) in order to estimate the value of (l/a) for eleven loops. They obtained this value to be lied in the range 0.160 to 0.491. Inspired by these results, Van Doorsselaere et al. (2004a) eliminated the assumption of $l \ll a$, and numerically solved MHD equations to investigate the damping mechanism of the coronal loops. They concluded that the difference between the numerical and analytical values for $l/a \leq 1/3$ is very small. Even for $l \simeq a$, the difference was not more than 0.25.

In this research, we study the oscillation parameters of a coronal loop observed on 11 October, 2013 and investigate whether this oscillation evanishes due to resonant absorption. The applied method for extracting oscillations from the consecutive EUV images is introduced in Section 2. In Section 3, we present the obtained results for frequencies and damping times of the loop. The conclusion is discussed in Section 4.

2 Method

Coronal loops are the curved bright magnetized structures on the Sun's surface. The hot plasma trapped along the magnetic field lines inside the loop cause them to seem brighter than their surrounding environment. Due to the factors like fast oscillating waves, 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 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 solar loops (Esmaeili et al., 2016; Esmaeili et al., 2017). Coronal seismology provides an alternative method for understanding the physical and geometrical structures of the solar loops.

Pursuing higher spatial resolution, the SDO spacecraft was launched in February 2010 to study the Sun's atmosphere, solar magnetic field, solar coronal hot plasma, and effects of photospheric phenomena on the space weather by providing full-disk images of the Sun's atmosphere with a time cadence of 12 seconds in various pass-bands. In this study, we use the EUV images of the Sun recorded on 11 October, 2013 (between 07:11:59 and 08:21:59 UT) provided by AIA instrument onboard SDO in 171 Å. Then, the oscillation parameters and the damping mechanism of the observed loop are investigated.

To this end, we need to construct the space-time diagram from the consecutive EUV images of the coronal loop. Figure 1 represents the studied loop structure. The data was recorded on 11 October, 2013 between 07:11:59 and 08:21:59 UT. In order to apply the corrections regarding the differential rotation of the Sun, all images are co-aligned and derotated with respect to the first image (see Alipour & Safari (2015) for more details). Then, arbitrary number of points (based on the 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). Each temporal element of the space-time diagram is constructed by taking the average of distinct pixels' intensities located on different rows within the appointed box. The space-time diagram is resulted from applying the same procedure on each successive image (Fig. 2). In other words, the transverse oscillating mode of the loop is detected by taking the average of the pixels intensities perpendicular to the loop axis. Fitting a Gaussian function to each time element of the space-time diagram, parameters such as spatial oscillation amplitudes, and the width of the loops are extracted. Afterward, the period of the oscillation and the damping time are obtained through analyzing the amplitudes, which is discussed in more details in Section 3.

3 Results

As manifested in the space-time diagram of Fig. 2, the transverse oscillation of the coronal loop is clearly visible. Considering the complexity of the simultaneous analysis of all these oscillations, we just study the oscillation properties of the most noticeable loop detected in the space-time diagram (Fig. 3). The spatial oscillation parameters are driven employing a Gaussian function as follows:

$$F(x,t) = f(t)\exp\left(-\left(\frac{x-a(t)}{\sqrt{2}\sigma(t)}\right)^2\right) + b(t). \tag{1}$$

where f, a, and σ are the intensity amplitude, center of the brightness (which we consider as the center of the loop), and the standard deviation of the loop (a criterion of the loop width), respectively. Also, x is the length along the green selected slit represented in Fig.

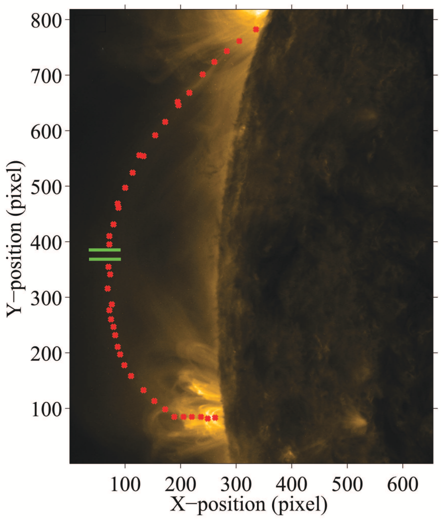

Figure 1: Image of the studied loop recorded by AIA/SDO 171 Å on 11 October, 2013 at 07:11:59 UT.

1, and b represents the background intensity. To be more specific, both the spatial and intensity oscillation amplitude at each time is obtained by fitting the Equation (1) on the corresponding column of the space-time diagram.

In order to calculate the loop width, the space-time diagram is constructed over various parts of the loop except near the footpoints. In other words, several slits (perpendicular to the loop axis) similar to the green slit shown in Fig. 1 are considered. Application of the Gaussian function of Equation (1), the loop width (at the position of each slit) is equal to $w = 2\sigma\sqrt{2ln2}$. The average and statistical uncertainty of the loops width are obtained by taking the mean and standard deviation of the measured widths for several slits. Therefore,

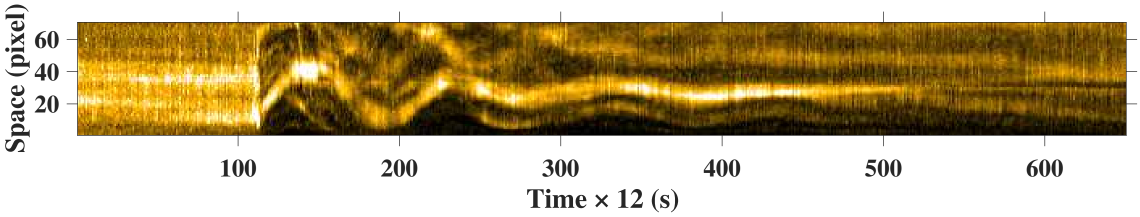

Figure 2: The space-time diagram of the studied loop observed on 11 October, 2013, obtaining from 650 consecutive EUV images provided by SDO/AIA at 171 Å.

the length and width of the studied loop obtained are 345 ± 35 Mm, and 6.85 ± 0.5 Mm, respectively. The period of the oscillation is attained by fitting the following function ($A(t)$) on the spatial oscillation amplitudes (Su et al., 2018):

$$A(t) = a_0 + a_1 \exp\left(\frac{-(t-t_0)}{\tau}\right) \cos\left(\frac{2\pi(t-t_0)}{P_0 + kt - \phi}\right) + a_2\frac{t-t_0}{p_0}, \qquad (2)$$

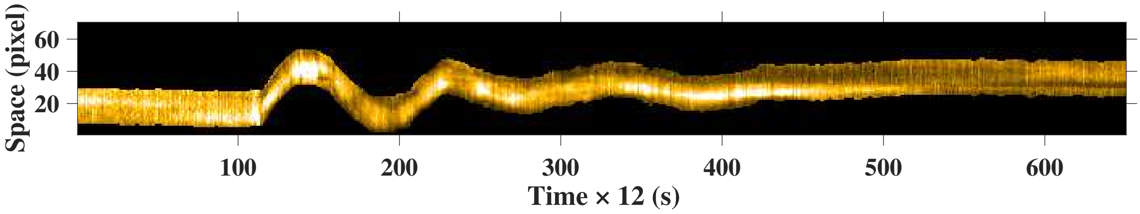

Figure 3: The most noticeable oscillating wave structure extracted from the space-time diagram of the loop shown in Fig. 1.

where a_0 is the spatial amplitude, t is time, t_0 is the start time of the oscillation, and τ represents the damping time. The parameters P_0, k, and ϕ are the period of oscillation, the evolution rate, and the oscillation phase, respectively. Equation (2) describes the equilibrium position of the spatial amplitudes. The spatial oscillation amplitudes of the loop together with the result of fitting Equation (2) on them are manifested in Fig. (4).

The damping time is obtained as $\tau = 70 \pm 1$ minutes and the period of oscillation is obtained to be 19 ± 1 minutes. Therefore, the damping quality, the ratio of the damping time to the period of oscillation ($Q = \frac{\tau}{P}$) is 3.6. Previously, Safari et al. (2006) discussed that if the resonant absorption be the main mechanism for the strong damping of a loop oscillations, then the damping quality would have values between 1.7 to 8. Accordingly, it seems that the main damping mechanism for the studied loop is the resonant absorption.

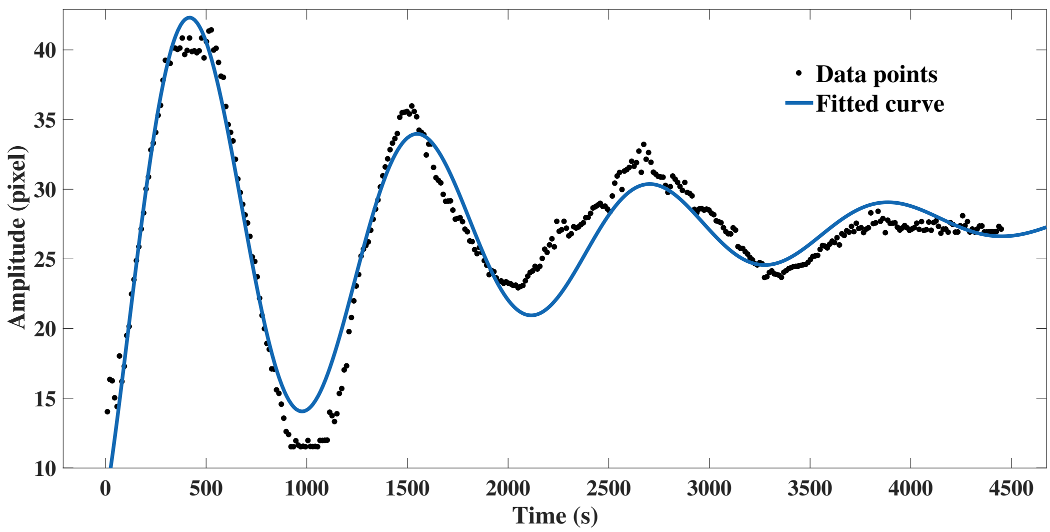

Figure 4: The spatial oscillation amplitudes of the loop recorded on 11 October, 2013 (black dots), and the result of fitting Equation (2) to the amplitudes (blue line).

4 Discussion

We studied the transverse oscillations of a coronal loop recorded by SDO/AIA on 11 October, 2013 to investigate its oscillation parameters. The length of the loop is calculated to be 345 ± 35 Mm applying spline interpolation. The spatial and intensity oscillation amplitudes were extracted using a Gaussian function (Equation (1)). Consequently, the period and the damping time are obtained to be 19 ± 1 and 70 ± 1 minutes, respectively. Therefore, the damping quality is found to be 3.6. According to the obtained damping quality, we conclude that the resonant absorption might be the main mechanism for the damping of the studied oscillation.

The results of the present study and also many other previous research (e.g., Karami et al. (2009); Goossens et al. (2011); Asensio Ramos, A. & Arregui, I. (2013)) show that the kink mode oscillations of the coronal loops are damped due to the resonant absorption in the strong damping regime. From the theoretical point of view, within a thin resonant layer at the lateral boundary of the coronal loop with 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.

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References

Abedini, A., & Mousavi Monfared, M. S. 2017, Iranian Journal of Astronomy and Astrophysics, 4, 183

Abedini, A., Safari, H., & Nasiri, S. 2012, Solar Physics, 280, 137

Alipour, N., & Safari, H. 2015, The Astrophysical Journal, 807, 175

Andries, J., Goossens, M., Hollweg, J. V., Arregui, I., & Doorsselaere, T. V. 2005, Astronomy & Astrophysics, 430, 1109

Aschwanden, Markus, J. 2006, Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 364, 417

Aschwanden, M. J. 2005, Physics of the Solar Corona (Springer Berlin Heidelberg), 320

Asensio Ramos, A., & Arregui, I. 2013, A&A, 554, A7

Chen, S.-X., Li, B., Xia, L.-D., & Yu, H. 2015, Solar Physics, 290, 2231

Dadashi, N., Safari, H., & Nasiri, S. a. 2009, Iranian Journal of Physics Research, 9

Dymova, M. V., & Ruderman, M. S. 2005, Solar Physics, 229, 79

Edwin, P. M., & Roberts, B. 1983, Solar Physics, 88, 179

Erdelyi, R., & Fedun, V. 2007, Science, 318, 1572

Esmaeili, S., Nasiri, M., Dadashi, N., & Safari, H. 2015, in AAS/AGU Triennial Earth-Sun Summit, Vol. 1, AAS/AGU Triennial Earth-Sun Summit, 403.17

Esmaeili, S., Nasiri, M., Dadashi, N., & Safari, H. 2016, Journal of Geophysical Research: Space Physics, 121, 9340

Esmaeili, S., Nasiri, M., Dadashi, N., & Safari, H. 2017, in SOLARNET IV: The Physics of the Sun from the Interior to the Outer Atmosphere, 116

Farahani, S. V., Ghanbari, E., Ghaffari, G., & Safari, H. 2017, Astronomy & Astrophysics, 599, A19

Farahani, S. V., Hornsey, C., Doorsselaere, T. V., & Goossens, M. 2014, The Astrophysical Journal, 781, 92

Fathalian, N., & Safari, H. 2010, The Astrophysical Journal, 724, 411

Goossens, M., Andries, J., & Arregui, I. 2006, Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 364, 433

Goossens, M., Andries, J., & Aschwanden, M. J. 2002, Astronomy & Astrophysics, 394, L39

Goossens, M., Erdélyi, R., & Ruderman, M. S. 2011, Space Science Reviews, 158, 289

Goossens, M., Hollweg, J. V., & Sakurai, T. 1992, Solar Physics, 138, 233

Goossens, M., Ruderman, M. S., & Hollweg, J. V. 1995, Solar Physics, 157, 75

Grant, S. D. T., Jess, D. B., Moreels, M. G., et al. 2015, The Astrophysical Journal, 806, 132

Guo, Y., Erdélyi, R., Srivastava, A. K., et al. 2015, The Astrophysical Journal, 799, 151

Hollweg, J. V., & Yang, G. 1988, Journal of Geophysical Research, 93, 5423

Jin, Y.-J., Zheng, H.-N., & Su, Z.-P. 2018, Chinese Physics Letters, 35, 075201

Karami, K., Nasiri, S., & Amiri, S. 2009, Monthly Notices of the Royal Astronomical Society, 394, 1973

Karami, K., Nasiri, S., & Sobouti, Y. 2002, Astronomy & Astrophysics, 396, 993

Li, D., Yuan, D., Su, Y. N., et al. 2018, Astronomy & Astrophysics, 617, A86

Mendoza-Briceno, C. A., Erdelyi, R., & Sigalotti, L. D. G. 2004, The Astrophysical Journal, 605, 493

Nakariakov, V. M. 1999, Science, 285, 862

Ofman, L., & Aschwanden, M. J. 2002, The Astrophysical Journal, 576, L153

Pascoe, D. J., Anfinogentov, S. A., Goddard, C. R., & Nakariakov, V. M. 2018, The Astrophysical Journal, 860, 31

Pascoe, D. J., Russell, A. J. B., Anfinogentov, S. A., et al. 2017, Astronomy & Astrophysics, 607, A8

Roberts, B. 2000, Solar Physics, 193, 139

Roberts, B., Edwin, P. M., & Benz, A. O. 1984, The Astrophysical Journal, 279, 857

Ruderman, M. S. 2003, Astronomy & Astrophysics, 409, 287

Ruderman, M. S., & Roberts, B. 2002, The Astrophysical Journal, 577, 475

Safari, H., Nasiri, S., Karami, K., & Sobouti, Y. 2006, Astronomy & Astrophysics, 448, 375

Safari, H., Nasiri, S., & Sobouti, Y. 2007, Astronomy & Astrophysics, 470, 1111

Sakurai, T., Goossens, M., & Hollweg, J. V. 1991, Solar Physics, 133, 227

Schrijver, C. J., Aschwanden, M. J., & Title, A. M. 2002, Solar Physics, 206, 69

Shukhobodskiy, A. A., Ruderman, M. S., & Erdélyi, R. 2018, Astronomy & Astrophysics, 619, A173

Soler, R., Terradas, J., Verth, G., & Goossens, M. 2011, The Astrophysical Journal, 736, 10

Su, W., Guo, Y., Erdélyi, R., et al. 2018, Scientific Reports, 8

Uchida, Y. 1970, Publications of the Astronomical Society of Japan,, 22, 341

Van Doorsselaere, T., Andries, J., Poedts, S., & Goossens, M. 2004a, The Astrophysical Journal, 606, 1223

Van Doorsselaere, T., Debosscher, A., Andries, J., & Poedts, S. 2004b, Astronomy & Astrophysics, 424, 1065

Verth, G., Doorsselaere, T. V., Erdélyi, R., & Goossens, M. 2007, Astronomy & Astrophysics, 475, 341

Verth, G., Terradas, J., & Goossens, M. 2010, The Astrophysical Journal, 718, L102