A Research on the Physical Features of Coronal Loop Oscillations† *

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Abstract  Observations of the solar full-disk were carried out by the Atmospheric Imaging Assembly (AIA) onboard the Solar Dynamics Observatory (SDO) with the Fe IX 171 Å line on 16th October 2010. The obtained high-quality data permit us to elaborate on the coronal loop oscillations. It is found that a major flare of GOES (Geostationary Operational Environmental Satellite) class M2.9 occurred in the active region NOAA 1112 during this period, which triggered a number of coronal loops on the solar surface to oscillate. Among them, there are two coronal loops exhibiting oscillations with different physical features. The oscillation of the coronal loop located at W492/S170 is a simple harmonic oscillation with a period of 385s, which abides by the oscillating equation of $x = 2.2 \sin\left[\frac{2\pi}{385}(t - 768)\right]$, while the other located at W559/S142 is a damping oscillation with a period of 449s, and the oscillating equation is expressed by $x = 24.8 e^{-\frac{2\pi}{149}t} \sin\left[\frac{2\pi}{449}(t - 1128)\right]$, where $t$ is the observational time in units of second.

Key words: sun: oscillations—sun: flares—sun: corona

1. INTRODUCTION

Solar flares are a kind of active phenomena with sudden enhancement of the local radiation happened in the solar chromosphere–transition layer, and they generally appear in the vicinity of sunspots[1]. As the most violent activity on the solar surface, a solar flare
generally releases a great deal of energy as high as $10^{34}$ erg in a short duration of several ten minutes, and forms some bright structures observable at multiple wavebands. The long-term research indicated that the great deal of energy released by a flare in a short time will cause violent changes of the material and magnetic field structures in the active region\cite{1}, and therefore a series of active phenomena associated with the flare, such as the coronal mass ejection (CME), coronal loop oscillation, filament eruption, and filament oscillation, etc., in which the coronal loop oscillation is a kind of common-seen active phenomena associated with flares\cite{2}, especially for the transverse oscillations of coronal loops\cite{3−5}. On the other hand, coronal loop oscillation technique\cite{6} provides us with a method to measure the coronal magnetic field and coronal loop structure\cite{7−9}. It is well known that for the materials of equal mass, the material at the place with a stronger magnetic field will suffer a larger recovery force, and therefore the shorter oscillation period of the coronal loop there. And after being impacted by the same external force, the magnetic loop with a greater magnetic tension will deviate from its balanced position by a relatively small amplitude, correspondingly the oscillation amplitude of the magnetic loop is also smaller. Hence, we can derive the strength of magnetic field in the solar corona according to the period and amplitude of coronal loop oscillation measured there. Besides, we can recover the magnetic field structure in the coronal loop according to the coronal loop structure when the coronal loop oscillation occurs. However the early researches were mainly based on the observational data obtained by ground-based telescopes, so it was very difficult to understand comprehensively the properties of the relevant physical processes caused by flare explosions. This is caused by the selective absorption of the terrestrial atmosphere to the various spectral lines from the sun. Those spectral lines coming from the solar photosphere and lower chromosphere can penetrate through the earth atmosphere to be observed by the ground-based telescopes, however due to the very high temperatures in the solar high chromosphere, transition layer, and corona, the ultraviolet and far-ultraviolet lines originated from there will be strongly absorbed by the earth atmosphere, the ground-based telescopes can hardly obtain the information about these regions. In recent years, along with the rapid development of space science, the successively-launched space solar telescopes have opened up a new research prospect for the solar astrophysicists, the high-quality observational data obtained from the space telescopes have provided much more details for the observation and study of solar oscillations. For example, using the observational data obtained in 1998~1999 by the Extreme ultraviolet Imaging Telescope (EIT) on the observational platform of space solar telescope launched in 1995, namely the SOlar and Heliospheric Observatory (SOHO), Thompson et al.\cite{10} discovered the spherical waves propagated in the coronal layer.

The Solar Dynamics Observatory (SDO)\cite{11−12} launched in 2010 has operated smoothly for 2 years, and collected a large number of data of solar high-resolution full-disk observations. These high-resolution observational data have provided the extremely convenient conditions for the studies of the structures and oscillations of coronal loops. This paper has analyzed in detail the high-resolution data observed on 16th October 2010 by the Atmospheric Imaging Assembly (AIA) onboard the SDO, and obtained the evolutionary features of two coronal loop oscillations in the period of flare explosion, especially, measured accurately the oscillation periods of these two coronal loops.
2. OBSERVATION AND DATA PREPROCESSING

On 16th October 2010 the SDO/AIA made a continuous observation on the NOAA 1112 region at the Fe IX 171 Å line, and the collected data demonstrated that in the period from 19:00 UT to 19:10 UT an M2.9-class flare happened\(^{[13]}\). In the explosion process of this flare, the coronal loops at different positions on the solar disk successively exhibited periodical oscillations. In order to study precisely the characteristics of motion of these coronal loops, we have selected the interval (19:05 ∼ 19:35 UT), which is representative of the coronal loop oscillation, to make a study in detail for the whole evolutionary process of the flare. In this duration of 30 minutes, the SDO/AIA has collected totally 150 frames of high-resolution solar full-disk images with the temporal resolution 12 s/frame and the spatial resolution 0.6″/pixel. Fig.1 shows the sectional monochromatic image of the solar disk observed at 19:17:48 UT of 2010-10-16 by the SDO/AIA with the Fe IX 171 Å line, which contains the regions where the studying flare and coronal loops are situated. In order to express accurately the position of every active object on the solar disk, we take the solar disk center as the coordinate origin, and adopt Mm as the unit of length to build up the coordinate system. From Fig.1 we can find that the position of the flare explosion in the active region NOAA 1112 is in the southwestern direction far apart from the solar disk center, its accurate position is shown by a black cross in the figure, and its coordinates are W298/S290. By consulting the continuously observed images, it is found that in the period of flare explosion, many loop-shaped structures in the corona exhibit significant oscillations, in which two coronal loops in the northwest of the flare exhibit the oscillations of significant periodicity, in the following we will analyze in depth the oscillation features of this two loops. For the convenience of description, we denote these two coronal loops as loop-A and loop-B, and their positions are marked by the white rectangles. In which the accurate central position of loop-A is W492/S170, and the accurate central position of loop-B is W559/S142. Although from the monochromatic image of Fig.1 we can find the basic structures of these coronal loops, but the details of coronal loops on the solar disk have no distinct features. In order to demonstrate the features of the time evolution of the coronal loop caused by the flare, we have calculated the difference image of the selected region, as shown in Fig.2. From the difference image we can find that because of the oscillations, significant changes appear in the positions of the bright structures of loop-A and loop-B. It is seen that the two coronal loops differ obviously in structure, in which loop-A has an arc shape with two fixed foot points, and loop-B exhibits a clear three-pronged structure. By the following analysis, we will find that the oscillation features of the two coronal loops are quite different.

3. STUDY OF OSCILLATION CHARACTERISTICS OF CORONAL LOOPS

Coronal loop oscillation is a kind of common phenomenon associated with the flare explosion, and it has a positive meaning to accurately determine the physical properties of coronal loop oscillations for understanding the spatial structure and magnetic field distribution of the corona. The high-resolution data of the SDO/AIA on 16th October 2010 indicate that in the process of an M2.9-class flare in the active region NOAA 1112, many coronal loops on the solar disk exhibit successively apparent oscillations. By investigating carefully the
Fig. 1 The 171 Å intensity image of the flare observed by the AIA on 2010-10-16 (UT19:17:48). The black cross denotes the location of the flare center. The two white rectangles indicate the locations of the two coronal loops A and B, respectively.

Fig. 2 The locations of the flare center and the two coronal loops shown by the difference image.
evolutionary processes of these active objects, it is found that these coronal loop oscillations are extremely regular in time sequence, namely more close to the flare center the loop is, more early the oscillation initiates; and more distant from the flare center the coronal loop is, more late the oscillation initiates. Such a correlation for coronal loops between the initiating times of oscillations and their distances from the flare center indicates that the production of coronal loop oscillation has a close relation with the flare explosion. A reasonable explanation is: the flare explosion causes a strong impact on the high layer of the solar atmosphere, and produces disturbances propagating in the solar atmosphere. This kind of disturbances propagate on the solar surface with limited velocities, when they encounter the coronal loops, the coronal loops will be shocked and be driven to produce periodical oscillations. These phenomena of coronal loop oscillations appeared during flare explosion have attracted the attentions of many solar astrophysicists. In 2011, Aschwanden et al.\[^{13}\] made a systematic analysis on the coronal loop A in this region. They found that the pulsing phase of the flare started at about 19:10:00 UT, and a few minutes later the coronal loop A produced a periodical oscillation, with the period of 375.6 s (6.3 min). After analyzing in detail the high-resolution SDO/AIA data, we find that this flare was brightened rapidly during 19:05:00~19:07:00 UT, the brightness at the flare center attained the maximum around 19:10:00 UT, and that after the flare was brightened, periodical oscillations were produced in the two coronal loops with completely different structures on the solar disk. Hence, we determine to continue the study of the phenomena of oscillation produced in the coronal loops during this flare explosion, on the basis of the work of Aschwanden et al.\[^{13}\], and to explore the physical features of coronal loop oscillations in the explosion process of the flare. In our work, the IDL visualized programming software has been adopted to make the analysis in detail on the original data observed by the SDO/AIA, and to study in depth the physical features of the coronal loop oscillations caused by the flare explosion.

3.1 Oscillation Characteristics of the Coronal Loop-A

The time evolution of the coronal loop-A marked by a white rectangle in Fig.1 is shown as Fig.3. In Fig.3, the observing times of the coronal loop-A observed by the SDO/AIA are given on the bottom of each panel, with a time separation of 48 s. In order to see clearly the position variation of the coronal loop in the evolutionary process, we take the balanced position on the top of the coronal loop-A as a reference line, and it is marked by a series of white dashed lines in Fig.3. From Fig.3 we can find that before 19:12:36 UT the position of the coronal loop has no obvious variation, but at 19:13:24 UT, the loop top has crossed over the white dashed lines for the reference, and shifted upwards a distance. At 19:14:12 UT the coronal loop moves upwards to the position with the maximum displacement, at this moment the loop top has moved for about 5 pixel (namely 2.2 Mm), then as time elapses the coronal loop gradually moves downward, and at 19:15:48 UT it moves to the position with the negative maximum displacement, at this moment the loop top is at the position 5 pixel below the dashed line, afterwards the coronal loop moves back and forth for several periods. In the continuously-played images we can find the obvious back and forth oscillation process, but on a motionless image we can hardly find any variations of coronal loops, in order to show the characteristics of motion of the coronal loop-A, we have made the difference calculation on the images. As the temporal resolution is 12 s/frame, hence between two neighboring images in the time series the position difference is very small, and it is very difficult to show
the variations caused by the motion of the coronal loop. In order to show better the motion of the coronal loop, we calculate the difference images for every 3-frame images, and obtain the evolutionary process of difference images as shown in Fig.4.

From Fig.4 we can find that before 19:11:48 UT there is no any structure existed on the difference images, indicating that basically the coronal loop-A has no significant motion before this moment. Up to 19:12:36 UT and 19:13:24 UT, above the coronal loop appears an apparent bright belt, indicating that the coronal loop begins to move upwards; at 19:14:12 UT, the difference image exhibits the very weak structure of the coronal loop, this is because that when the coronal loop moves to the position with the maximum displacement, the kinetic energy is totally converted into potential energy, at this moment the velocity of the coronal loop...
loop approaches to zero, and on the difference image it appears as a weakly varied feature; after moving to the place with the maximum displacement, under the action of recovery force the coronal loop makes the accelerated motion downward, at 19:15:00 UT the coronal loop A begins to move downward, as the time goes by, from the difference images we can see clearly the back and forth alternations of the loop-A position. Combining the images of Figs.3~4, which demonstrate the position variation of the coronal loop with the time, we can find that before 19:29:24 UT the position of loop-A has oscillated for 3 periods, the point with the strongest oscillation is at the top of the coronal loop, hence we make a time-slice diagram by truncating a series of observed data on the loop-top position of loop-A and along the north-south direction, as shown in Fig.5. In Fig.5, the abscissa indicates the observing time in units of min with 19:00:00 UT as the zero point, the duration of the observations is 19:10:00~19:40:00 UT (in this figure the corresponding range of abscissas is 10~40 min), and the ordinate expresses the spatial position of the observing point. From Fig.5 we can find that on the time-slice diagram there is a white/bright belt in periodical variation, this white belt indicates straightforwardly that the motion on the top of loop-A exhibits apparently the feature of simple harmonic oscillation. Fig.5 shows that loop-A begins to oscillate at about 19:12:00 UT, lasts for about 4 total periods, and that in the whole process the oscillation amplitude basically remain s to be 2.2 Mm, without markable attenuation. In order to describe quantitatively the oscillation characteristics of this coronal loop, we adopt the sine curve \( x = A \sin[\omega_0(t - t_0)] \) to fit the white belt of Fig.5, the result indicates that for the amplitude \( A = 2.2 \text{ Mm} \), the angular frequency \( \omega_0 = \frac{2\pi}{385} \text{ rad/s} \), and the initial time \( t_0 = 768 \text{ s} \), the fitting curve and the white/bright belt on the time-slice diagram are coincident very well, and the fitted result is shown by the black dotted line in Fig.5. Hence we suggest that the equation of oscillation on the loop top of loop-A is \( x = 2.2 \sin\left[\frac{2\pi}{385}(t - 768)\right] \), from this equation we can find that the oscillation period of loop-A is \( P_A^0 = 385 \text{ s} \) (namely 6.42 min), this measured period is basically consistent with the result given by Aschwanden et al.\cite{13} in 2011.

Fig. 5 Time-slice image showing the oscillation on the top of loop-A
3.2 Oscillation Characteristics of the Coronal Loop B

By the similar method for analyzing the physical properties of loop-A, we have made a systematic analysis for the oscillation characteristics of loop-B as well. Fig.6 shows the evolution of the coronal loop, which is marked by a white rectangle in Fig.1 and denoted as loop-B, with the time. In Fig.6, the times that loop-B being observed by the SDO/AIA are also marked on the bottom of each image, and the time separation is identically taken as 48 s. Because of the significant difference in structure between loop-A and loop-B, for the coronal loop-B we select the position with the most significant oscillation, namely the position of the node of the loop-B three-pronged structure (here it indicates the central position of the loop-B three-pronged structure) for reference, which is also marked by a series of white dashed lines in Fig.6. Because of the particular structure of loop-B, we can not see the variation of its position from the monochromatic images of Fig.6. For exhibiting clearly the features of motion of loop-B, we make likewise the difference calculation for every 3 frames of images, and obtain the evolutionary process of difference images as shown in Fig.7. From Fig.7 we can find that before 19:14:12 UT there is no obvious bright/dark-belt structures on the difference images, indicating that before this moment the coronal loop-B is basically motionless. At 19:15:00 UT, the bright/dark-belt structure of three-pronged shape appears on the difference image, the bright-belt part is positioned above, and the dark-belt part is positioned below, this indicates that at this moment loop-B has a upward (namely northward) motion, this initiating time of oscillation is later than the corresponding time of loop-A for about 144 s. At 19:17:24 UT the relative positions of the bright and dark belts are interchanged, the bright belt is positioned below and the dark belt is positioned above, indicating that at this moment the node moves downward (namely southward); at 19:19:48 UT the node moves to the position with the maximum displacement; at 19:20:36 UT, the node of the coronal loop moves again upward; and as time proceeds, the difference images demonstrate clearly the back and forth alternations of the loop-B position. At 19:27:48 UT the structure of the coronal loop on the difference image becomes very weak, and afterwards the images are basically unchanged. Combining the images of Figs.6~7, which demonstrate the position variation of the coronal loop with the time, we can find that before 19:29:24 UT the coronal loop B has performed about two periods of oscillations, and the oscillation amplitude attenuates gradually. Here, we continue to analyze the oscillation of loop-B by means of time-slice image, which is made of a series observed data truncated at the node of loop-B along the north-south direction, as shown by Fig.8. For the consistency with the time-slice image of loop-A, in Fig.8 we continue to define the abscissa as the observing time in units of min with 19:00:00 UT as the zero point; and the ordinate indicates the spatial position of the observing point in units of Mm. From Fig.8 we can find that there is a white belt of periodical variation in the time-slice image, it represents the oscillation features of loop-B, that different from the white belt of equal-amplitude oscillation in Fig.4, the oscillation amplitude of the white belt in Fig.8 decreases with time, exhibiting the characteristic of damping oscillation. Fig.8 shows that at about 19:15:00 UT loop-B begins to oscillate, and the oscillation lasts for about 3 periods, in the whole process the maximum amplitude of displacement is 20 Mm. From Fig.8 we can find that the oscillation amplitude of the first half period is far less than that of the second half period, we can not yet infer the reason for this. In order to describe quantitatively the oscillation features of this coronal loop, neglected the data points of the first half period, we make fitting on the white belt from the time of 19:17:24 UT by using
the equation of a damping sine wave \[ x = A' e^{-\delta(t-t_0)} \sin[\omega_f(t-t_0)] \], the result indicates that for the amplitude \( A' = 24.8 \text{ Mm} \), the damping coefficient \( \delta = \frac{2\pi}{343} \text{ s}^{-1} \), the angular frequency of damping oscillation \( \omega_f = \frac{2\pi}{449} \text{ rad/s} \), and the initial time \( t_0 = 1128 \text{ s} \), the fitting curve and the white/bright belt on the time-slice diagram are coincident very well, and the fitted result is shown by the black dotted line in Fig. 8. Hence we suggest that the equation of oscillation at the node of loop-B is \[ x = 24.8 e^{-\frac{2\pi}{343}t} \sin\left[\frac{2\pi}{449}(t-1128)\right] \], from this equation we can find the damping oscillation period of loop-B being \( P_f = 449 \text{ s} \), the damping coefficient being \( \delta = \frac{2\pi}{343} \text{ s}^{-1} \). Based on \( \omega_f = \frac{2\pi}{449} \text{ rad/s} \) and \( \delta = \frac{2\pi}{343} \text{ s}^{-1} \), we can calculate the inherent angular frequency \( \omega_0' = \sqrt{\omega_f^2 + \delta^2} = \frac{2\pi}{439} \text{ rad/s} \) of the coronal loop-B in the case of no damping, and the corresponding inherent oscillation period \( P_0^B = 439 \text{ s} \).

Fig. 6 Intensity images showing the evolution of loop-B

Fig. 7 Difference images showing the evolution of loop-B
Coronal loop oscillation is a kind of common-seen phenomenon associated with a flare explosion, the oscillation period is the basic physical parameter of coronal loop oscillation, and it is of important significance to accurately measure the period of coronal loop oscillation for understanding the physical properties of an exploding solar flare and the spatial structure of the solar corona. Based on the high-quality SDO/AIA data observed on 16th October 2010, we have performed an analysis in detail. The result indicates that after an M2.9-class flare occurred in the active region NOAA 1112, apparent oscillations happen on the two coronal loops A and B in the northwest direction, which exhibit completely different features. In which, the loop-A exhibits a typical simple harmonic oscillation with the period of $P_A^0 = 385$ s; and the loop-B exhibits a damping oscillation, its oscillation amplitude attenuates gradually with the time, the period of its damping oscillation is $P_f = 449$ s and the damping coefficient is $\delta = \frac{2\pi}{343} \text{s}^{-1}$, corresponding to the inherent oscillation period $P_B^0 = 439$ s. Obviously, the inherent oscillation period $P_A^0$ of loop-A is less than the inherent period $P_B^0$ of loop-B, such a difference of oscillation period is very probably caused by the different structures of the coronal loops A and B. Fig.2 shows that the coronal loop-A has two fixed foot points rooted in the lower solar atmosphere, and that its shape exhibits the common-seen arc structure. But the coronal loop-B has a three-pronged shape, after investigating carefully its evolutionary process we find that among its three branches, the roots of the two branches have no fixed foot points, namely besides the branch in the eastern side, which has fixed foot point rooted in the lower solar atmosphere, the other two branches in the western side have no fixed foot points, but float in the atmosphere of solar corona. Hence, when the oscillation happens under the action of external disturbance, the coronal loop-A suffers a strong recovery force produced by its two fixed foot points, on the contrary loop-B suffers a small recovery force because that it has only one fixed foot point. Assuming that the plasma densities in different coronal loops are close to each other, then
the corresponding plasma mass $m$ in unit volume can be approximately considered as a constant, from the formula of oscillation period $P = \frac{2\pi}{\omega} = 2\pi\sqrt{\frac{m}{k}}$ we can find that for the identical $m$, the greater elastic coefficient corresponds to the shorter period, in other words, the oscillation period of the coronal loop A drawn by two fixed foot points will be shorter than that of the coronal loop-B drawn by only one foot point.

In addition, it is found that the initiating time of oscillation of loop-B is later than that of loop-A for about 144s, this may be related with the distance between the coronal loop and the flare. By analyzing the evolutionary process of the whole event, we can easily find that oscillations may happen to many coronal loops on the solar surface after a solar explosion, this implies that solar flare should be the direct cause leading to coronal loop oscillations. Apparently, the energy of the flare should propagate to different positions on the solar surface by means of a kind of disturbance, because of the difference of distance, the initiating time of oscillation will differ for the coronal loops at different distances. From Fig.1 we can find that loop-A and loop-B are all positioned in the northwest of the flare, but their distances to the flare center differ. By positioning accurately, we have obtained the accurate positions of the flare and two coronal loops: W298/S290 for the flare center, W492/S170 for the coronal loop-A, and W559/S140 for the coronal loop B. According to these accurate coordinates, we can very easy to calculate the distance from the coronal loop-A to the flare center being 252 Mm, and the distance from loop-B to the flare center being 346 Mm, consequently the distance of loop-B to the flare center is greater than that of loop-A by 94 Mm. Based on the time difference of oscillation initiation $\Delta t = 144$ s and the difference of distance $\Delta l = 94000$ km, we can calculate the propagation velocity of the flare-excited disturbance that causes the coronal loop oscillation to be $v = \frac{\Delta l}{\Delta t} = 653$ km/s. If such kind of disturbance propagates outwards from the flare center with the constant velocity $v = 653$ km/s, then we can deduce that such kind of disturbance at the flare center is produced at 19:06:00 UT. The previous studies indicate that flare explosion will often produce the filament eruption, when a CME is caused by such kind of filament eruption within 0.5 solar radius, its velocity is generally in the range of 100~300 km/s. Obviously, the velocity of disturbance measured by us is greater than the velocity of CME in the lower corona. Besides, the coronal matter produced during the flare explosion generally moves upwards, but the result of our analysis shows that the disturbance causing the coronal loop oscillation should propagate along the solar surface, hence we can conclude that such kind of disturbance causing the coronal loop oscillation is not resulted by the motion of CME. About the nature of such kind of disturbance, it remains to further investigate by collecting even more observational data.

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