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# ON THE OBSERVATIONS OF MULTIPLE MHD OSCILLATIONS IN THE SOLAR LOOPS

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Observations of multiple oscillations of various magnetohydrodynamic (MHD) modes may play crucial role in the diagnostics of the local plasma conditions of solar loops. Magnetically structured coronal loops anchored into the photosphere exhibit various kinds of MHD oscillations such as fast sausage, kink, slow acoustic oscillations etc. Exploiting various harmonics of such observed MHD oscillations may be a tracer of important local plasma conditions and structuring, e.g. scale heights and signature of stratification, equilibrium condition, characteristic speed, density contrast, loop expansion factor/magnetic field divergence etc, which can shed new light on the dynamics of the solar loops. In this review, I briefly summarize the first observational signatures of multiple MHD oscillations in various types of solar loops and discuss their significance in diagnosing the solar atmosphere.

## 1. Introduction

The combination of complex magnetic field and plasma generates MHD waves and oscillations in the solar atmosphere, which may be the major candidates for the heating and dynamics of the solar atmosphere. The idea of exploiting such observed MHD modes as a diagnostic tool for determining the local plasma properties of the solar atmosphere was firstly suggested by Roberts *et al.*[1] However, the application of MHD seismology has suffered by the lack of high-resolution observations of MHD oscillations till last decade. This scenario has changed drastically due to recent space-based observations by the Solar and Heliospheric Observatory (SOHO), the Transition Region and Coronal Explorer (TRACE), and high resolution spectra/images from the Hinode and STEREO spacecrafts. The new techniques for the back end instruments of ground-based solar telescopes (e.g. adaptive optics of Swedish Solar Telescope; Fast Spectrometers of ROSA etc) are also now providing the ubiquitous presence of such MHD waves and oscillations in the lower solar atmosphere. The newly adapted instruments from ground and space are now showing well the ubiquitous presence of various MHD modes in different solar structures, and thus providing more accurate inputs in form of the observed various wave parameters for the theory of MHD seismology to study the local plasma conditions and dynamics of the solar atmosphere.

Magnetically structured coronal loops anchored into the photosphere exhibit various kinds of MHD oscillations such as fast sausage, kink, torsional, slow acoustic oscillations etc. Exploiting such observed oscillations as a diagnostic tool for deducing physical conditions of solar plasma, is known as a potential tool of MHD seismology. The fast kink wave is most frequently observed mode as it can be directly detected by periodic spatial displacement of coronal loop axis (e.g. Nakariakov *et al.*[2]; Aschwanden *et al.*[3]; Wang & Solanki[4]; Verwichte *et al.*[5]; O'Shea *et al.*[6]; De Moortel & Brady[7]; Van Doorsselaere *et al.*[8]; Erdélyi & Taroyan[9]; Ruderman *et al.*,[10] and references cited there). Pandey & Srivastava[11] have also reported the first observational signature of kink oscillations in the stellar loops. On the other hand, the fast MHD sausage wave causes the variation of pressure and magnetic field in a coronal loop and therefore can be observed as intensity oscillations,[12] intensity and Doppler shift oscillations[9] or periodic modulation of coronal radio emission[13, 14] from various types of solar loops. The fundamental mode of slow acoustic oscillations are also now well observed in flaring and non-flaring loops both (e.g. Wang *et al.*[15, 16]; Srivastava & Dwivedi[17] and references cited therein) which causes the significant modulation of plasma emissions near the loop apex. These observations provide a basis for the estimation of coronal plasma properties (e.g. Nakariakov & Ofman[18]; Van Doorsselaere *et al.*[19] The most fascinating trend is now developing in terms of the oscillations of higher harmonics of these MHD modes in the solar loops along with the first harmonics, which may provide the crucial informations about the local plasma dynamics of the solar loops (e.g. O'Shea *et al.*[6]; Srivastava *et al.*[12]; Srivastava & Dwivedi[17] and references cited there).

In this paper, I briefly summarize the first observations of multiple oscillations of various MHD modes in the solar atmosphere in light of my recent observational findings, and discuss their role in diagnosing the local plasma conditions and dynamics.

## 2. Observations of Multiple MHD Oscillations

### 2.1. *The multiple kink oscillations in cool flaring loops*

O'Shea *et al.*[6] have observed the first and second harmonics of fast kink mode of magnetoacoustic waves in the cool postflare loop system. Inspite of its incompressibility, the kink mode causes the weak perturbations in the density near the loop boundary.[20] Therefore, it leads an intensity oscillation in the EUV light curve of O V 629 Å emitted from the cool flaring TR loop system as observed by SOHO/CDS. The details of the observations and data reduction is given in O'Shea *et al.*.[6] The observations of various harmonics of fast kink oscillations as obtained by O'Shea *et al.*[6] are summarized in the Table 1 for the two cases : (i) Stationary flare in AR 10820 as observed in the dataset 33813 of SOHO/CDS on 10th Nov. 2005, (ii) Propagating disturbances (PDs) in AR 10820 as observed in the dataset 33821 of SOHO/CDS on 11th Nov 2005, O'Shea *et al.*[6] have firstly found the signature of first and second harmonics of kink oscillations in the cool, flaring TR loops associated with AR 10820. By using the observed oscillation periods of kink modes, valuable seismological informations of this flaring region associated with AR 10820 can be obtained. For the stationary flare, the period ratio is $\mathrm{P}_1/P_2 \sim 2.4$, which probably indicates the presence of an expanding TR loop system associated with the observed flare. Using Eq. (96) of Verth & Erdélyi,[21] we estimate the loop expansion factor $\Gamma = 1.52$, which is the proxy of loop expansion and magnetic field divergence. The higher value of loop expansion factor indicates the significant divergence/expansion of magnetic field lines in these cool TR loops in AR 10820. In the present case, magnetic field expansion also dominates over the density stratification in these loops as the period ratio becomes greater than 2.0,[22] which indicates that probably the magnetic field is governing the kink mode oscillation periods in the observed loops

Table 1. Observations of Kink Harmonics in AR 10820 [adapted from O'Shea *et al.*[6]].

| Observations of AR 10820 on 10th-11th Nov 2005 CDS/SOHO | First kink harmonics $\omega_1$ | Second kink harmonics $\omega_2$ by |
|---|---|---|
| (i) Stationary flare of data set 33813 (10th Nov 2005) | Frequency = 2.10 mHz<br>Probability = 99.2%<br>Amplitude = 43.8% | Frequency = 5.04 mHz<br>Probability = 98%<br>Amplitude = 26.2% |
| (ii) PD of the data set 33821 (11th Nov 2005) | Frequency = 2.54 mHz<br>Probability = 100%<br>Amplitude = 11.5% | Frequency = 6.10 mHz<br>Probability = 99%<br>Amplitude = 6.1% |

as expected. The period ratio shift >2.0 is also noticed in the case of propagating disturbances (PDs) of the data set 33821 as observed on 11th Nov 2005 in AR 10820, which is consistent with the results of stationary flare. Using Eq. (37) of Andries *et al.*[22] and the observed loop length ($2L$) of $2.02 \times 10^8$ m,[6] the antinode shift of the second harmonics (or first overtone) of 5.04 mHz observed in the stationary flaring loop is estimated as ∼15.44 Mm towards its loop apex. It should be noted that the average loop length has been estimated by O'Shea *et al.*[6] during the evolution of propagating disturbances (PDs) on 10th Nov 2005 between 21:30 UT and 21:52 UT. It seems that the loop system is also presented during the evolution of flare between 19:50 UT and 21:52 UT of the same day, although brightening could not allow to measure it. We assume that approximately same shift may occur but towards the loop footpoint when effect of density stratification will be considered dominant in the loop.[22] Therefore, by considering the approximately same shift of antinode of second harmonics as 15.44 Mm and assuming also the effect of density stratification, the approximate density scale height of such loop can be measured by using Eq. (36) of Andries *et al.*,[22] which will be ∼18.50 Mm. The density stratification does not seem dominant effect compared to magnetic field stratification in this case as period ratio is >2.0, although the consideration of same magnitude of antinode shift in both the cases allows us to measure the expected magnitude of scale height. Hence, $2L \sim 2.02 \times 10^8$ m, $H \sim 18.50$ Mm may cause a shift of ∼15.44 Mm in the antinode of second harmonics or first overtone towards loop footpoint. The similar but opposite shift may be caused by expansion ($\Gamma = 1.52$) in the observed loop. This scale height (∼18.5 Mm) may be super-hydrostatic compared to the hydrostatic scale height of ∼13 Mm for the temperature 0.25 MK at which these loops are maintained in AR 10820 and visible in TR O V 629 Å line. The exact theoretical explanation of this super-hydrostatic scale height is still open. However, to conduct more accurate and realistic magneto-seismology of solar loops, the magnetic field divergence should be taken into account.[21] The theory of kink harmonics and related MHD seismology of solar loops have been reported by Verth and Erdélyi[21] and also discussed indetail by Andries *et al.*[22]

### **2.2.** *The multiple slow acoustic oscillations in non-flaring coronal loop*

Srivastava & Dwivedi[17] have studied the intensity oscillations near the apex of a non-flaring coronal loop to find the signature of MHD oscillations.

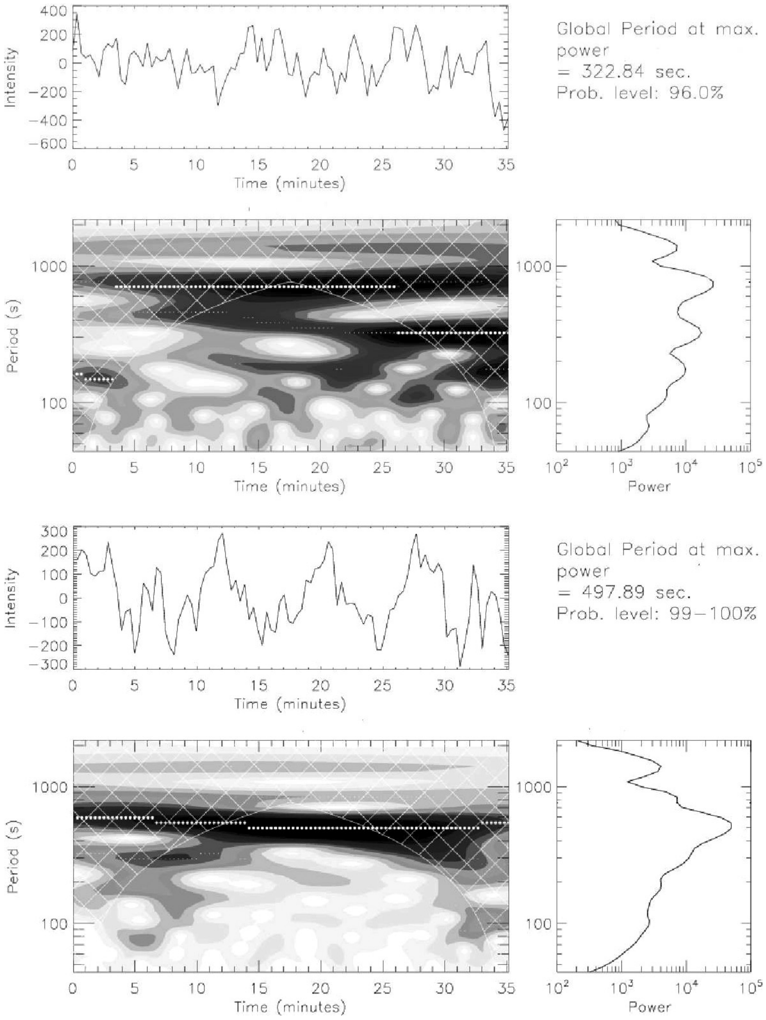

Fig. 1. The wavelet spectra for time series of Fe XII 195.12 Å for the second harmonics near the apex of non-flaring loop(left panel), and the first harmonics near its footpoint (right panel): In each wavelet, the top panel shows the variation of intensity, the wavelet power spectrum is given in the bottom-left panel, and global wavelet power in the bottom-right panel. [Figures are adapted from Srivastava & Dwivedi.[17]] Using 40" slot, the observations of this non-flaring loop system were acquired on 8 May 2008 between 09:35 UT and 10:10 UT by Hinode/EIS.The details of the observations, data reduction, power spectral analyses using wavelet technique are described in Srivastava & Dwivedi.[17]

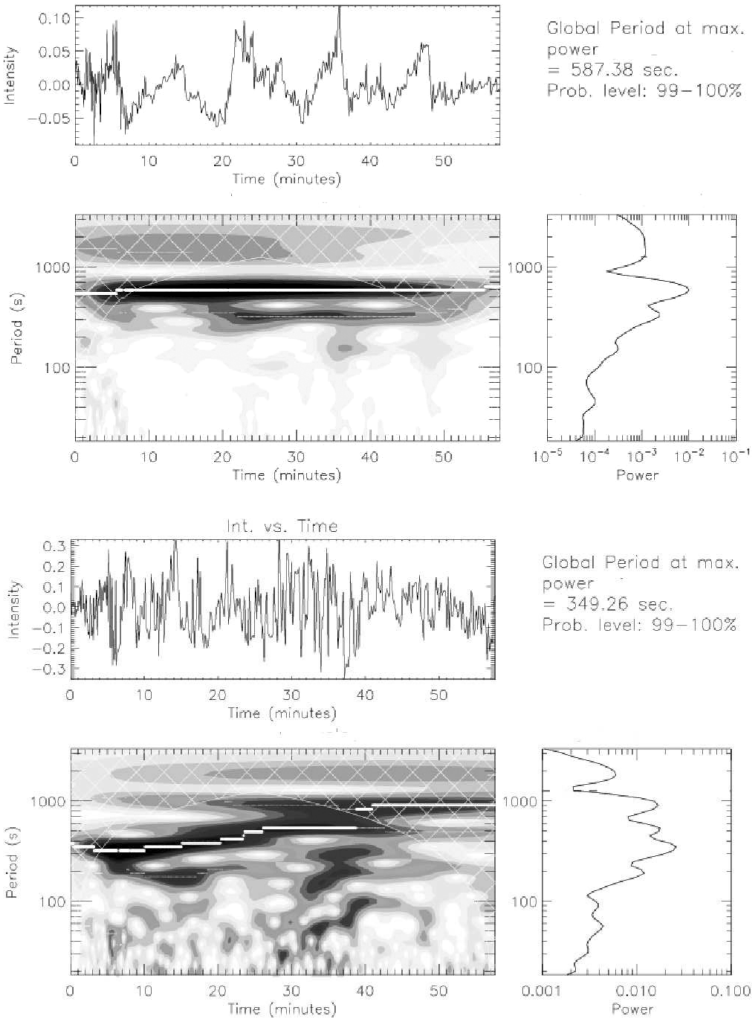

Fig. 2. The wavelet spectra of the time series of H-alpha for the first harmonics near the apex of cool post flare loop(top−left panel), and the second harmonics near its footpoint (top−right panel): In each wavelet, the top panel shows the variation of intensity, the wavelet power spectrum is given in the bottom-left panel, and global wavelet power in the bottom-right panel [Figures are adapted from Srivastava *et al.*.[12]] The cool post flare loop system is shown in the bottom most panel, which is observed from 15-cm Solar Tower Telescope at ARIES on 02 May 2001.The details of the observations, data reduction, power spectral analyses using wavelet technique are described in Srivastava *et al.*[12]

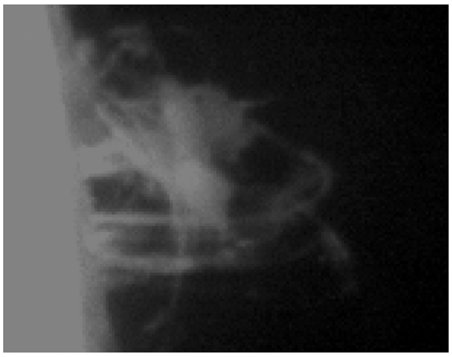

Fig. 2. (*Continued*)

They analyse the time series of the strongest Fe XII 195.12 Å image data, observed by 40" SLOT of the EUV Imaging Spectrometer (EIS) onboard the Hinode spacecraft. Using a standard wavelet tool, they produce power spectra of intensity oscillations near the apex of a non-flaring coronal loop system, and detect intensity oscillations of a period of $\sim$322 s with a probability of 96%. This oscillation period of $\sim$322 s is found to be in good agreement with theory of the second harmonics (or first overtones) of standing slow acoustic oscillations.[23] They detect, for the first time, the observational signature of multiple (first and second) harmonics of slow acoustic oscillations in such non-flaring coronal loop. Such oscillations have been observed in the past in hot and flaring coronal loops only, but have been predicted recently to exist in comparatively cooler and non-flaring coronal loops as well.[24] They find the periodicity $497s$ with the probability 99$-$100% near the clearly visible western footpoint of the loop, and interpret these oscillations to be likely associated with the first harmonics (or fundamental mode) of slow acoustic oscillations. The details of this unique observational result are given in Srivastava & Dwivedi.[17]

In this observation, the period ratio $P_1/P_2 = 1.54$ is significantly smaller than 2.0 which may be associated with the density stratification in such loops.[25] Using the period ratio shift and seismology theory of McEwan *et al.*[25] [Eq. 24], the estimated scale height $\sim$10 Mm is found to be very low compared to the hydrostatic scale height at the inner coronal temperature. This may be the signature of the departure of such loops from the hydrostatic equilibrium. The period ratio shift may also be due to the magnetic field divergence in the coronal loop system. However, it is ruled out due to the fact that the slow wave is longitudinal compressive wave and weakly depends on the magnetic field in a plasma of low-beta. Hence, the magnetic stratification may not have a strong effect on the period of slow waves which is mainly affected by the temperature structure along the loop. Finally, we confirmed the fact that the density stratification dominates over the magnetic field divergence in the studied EUV loop system as the period ratio is less than 2.0.

### 2.3. *The multiple sausage oscillations in cool post flare loop*

Recently, Srivastava *et al.*[12] have firstly observed the multiple sausage oscillations of the period $P_1 = 597$ s (first harmonics or fundamental mode) and $P_2 = 349\,\mathrm{s}$ (second harmonics or first overtones) in the cool post-flare loop of length $L = 97\,\mathrm{Mm}$ and width $2a = 6.0\,\mathrm{Mm}$ with their H-alpha observations, and studied the seismological properties of the selected loop. They have found that the density contrast is very high ∼600 in that loop, and therefore, they concluded that the observed global sausage modes can exist only in the overdense cool post flare loops only. This prediction supports the previous findings of Nakariakov *et al.*[14] and Aschwanden *et al.*,[26] while this is the first case applied to the cool H-alpha post flare loop system. The postflare loops usually have a very high density contrast of the order of 100–1000. The studied loops are cool post flare ones which are overdense and the estimated density ratio (600) falls in the expected limit. Therefore, the trapped sausage mode may occur in such loops, although wave leakage can not be ruled out as a prominent dissipative mechanism. Using the period ratio and theory of both Andries *et al.*[27] and McEwan *et al.*,[25] the scale height is estimated as ∼17 Mm which is much greater than the scale height at the formation temperature of H-alpha line in the lower solar atmosphere.The super-hydrostatic scale heights are well observed in the coronal loops, however, it is unique and the first observational signature of super-hydrostatic scale height (17 Mm) in the overdense and cool post flare loop system. This may be due to its departure from hydrostatic equilibrium condition, although the exact theoretical explanations are still open for this super-hydrostatic scale height estimated for cool post flare loop system from the period ratio observation. Srivastava *et al.*[12] have also estimated Alfvénic speed ∼300 km/s outside the loop, and also the damping time of such wave modes as 20 min for the selected loop. The estimation of such crucial seismological parameters indicates the potential capabilities to diagnose the observed multiple sausage oscillations in determining loop dynamics and plasma conditions.

The ratio between the periods of the fundamental and those of the first harmonics of sausage waves is proportional to $P_1/P_2 \sim 1.68$, which is significantly smaller than 2.0. Similar phenomena were observed for fast kink oscillations,[5] slow acoustic oscillations[17] for the coronal loops. The deviation of $P_1/P_2$ from 2.0 in homogeneous loops is very small due to the wave dispersion,[25] although the longitudinal density stratification may cause this significant period ratio shift from 2.0 for longitudinal tubular modes (e.g. sausage, slow-acoustic modes).[8, 17, 27] Since the oscillations are sausage MHD modes, the resonant absorption is ruled out as a dissipation mechanism. Therefore the wave leakage in the surroundings may be the most plausible cause for the wave damping. There is again a signature of the domination of density stratification over the magnetic field divergence in this loop system.

## 3. Discussion and Conclusions

Magnetically structured coronal loops anchored into the photosphere exhibit various kinds of MHD oscillations such as fast sausage, kink, torsional, slow acoustic oscillations etc. Exploiting various harmonics of such observed oscillations may be a tracer of important local plasma conditions, e.g. scale heights and signature of stratification, equilibrium conditions, characteristic speeds, density contrasts, loop expansion factor/ magnetic field divergence etc, which may provide new informations on the plasma conditions and dynamics of the solar loops.

This short paper summarizes the recent first observational signatures of multiple MHD oscillations of different MHD modes in various types of solar loops, and their diagnostic capabilities. The observations of multiple kink oscillations in the cool, TR flaring loops are found to be a tracer of the magnetic field divergence and loop expansion which dominates over the effect of density stratification.The density scale height is found to be ~18 Mm in the cool TR loops exhibiting the kink oscillations. The estimated density scale height is found to be a super-hydrostatic scale height and hence may have important implications on the dynamics of these cool, TR, flaring loops. The observations of multiple slow acoustic oscillations in the non-flaring coronal loop system are found to be a tracer of the non-hydrostatic and density stratified plasma environment in which the plasma flow and slow standing waves are simultaneously presented,[17] and the magnetic field stratification and loop expansion are not a well dominating candidate to control the plasma dynamics related with these slow modes.

Similarly, the observations of multiple sausage oscillations in the cool post flare loops are found to be a tracer of overdense, non-hydrostatic, density stratified atmosphere. There, the magnetic field divergence/loop expansion is again not a probable candidate to control the oscillation dynamics of tubular sausage mode coupled with the magnetic field. Furthermore, the super-hydrostatic scale height is observed for the first time in these loops complementing that they are well known for the coronal loops. Although this may not be universal phenomenon, the oscillation dynamics may be governed by the domination of density stratifications in the loops which support various harmonics of longitudinal tubular modes (e.g. sausage mode which perturbs both the magnetic field and density, and slow acoustic mode which perturbs density only). The magnetic field divergence/flux tube expansion may not be well dominant in such loops even after its presence in all kinds of solar flux tubes (e.g. Srivastava *et al.*[12]; Srivastava & Dwivedi[17]). The loops which support kink harmonics, may have well dominant effect of magnetic field divergence/flux tube expansion over the density stratifications as observed by O'Shea *et al.*[6] However, this case study should be tested with the forthcoming high resolution space based observations.

In conclusion, the observations of multiple MHD oscillations provide the wide range of diagnostics capabilities of local plasma conditions in various types of solar loops. The forthcoming high resolution observations of multiple MHD oscillations from both ground and space and the sophisticated new theory of MHD seismology of solar loops will be very important to reveal the mystery of the complex plasma motions/oscillations and its physical conditions in the various solar loops.

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