SEISMOLOGY OF CORONAL LOOPS USING THE PERIOD AND DAMPING OF QUASI-MODE KINK OSCILLATIONS

I. Arregui\textsuperscript{1}, J. Andries\textsuperscript{2}, T. Van Doorsselaere\textsuperscript{3}, M. Goossens\textsuperscript{3}, and S. Poedts\textsuperscript{3}

\textsuperscript{1}Departament de Física, Universitat de les Illes Balears, E-07122 Palma de Mallorca, Spain
\textsuperscript{2}Postdoctoral Fellow of the National Fund for Scientific Research- Flanders (Belgium) (FWO-Vlaanderen)
\textsuperscript{3}Centrum voor Plasma-Astrofysica, K.U.Leuven, Celestijnenlaan 200B, B-3001 Heverlee, Belgium

ABSTRACT

We use the theory of resonantly damped quasi-mode kink oscillations together with observational estimates of periods and damping times of transversal coronal loop oscillations to extract information on physical parameters in oscillating loops.

A parametric numerical study of the quasi-mode period and damping as a function of several equilibrium parameters is used to perform and inversion to obtain those equilibrium models that reproduce the observed period and damping rates, for a set of 11 loop oscillation events. Both the period and the damping rate are used and the equilibrium Alfvén speed comes into play. An upper limit to the Alfvén speed has been derived for 9 of the 11 analysed events.

1. INTRODUCTION

The idea of coronal seismology, the determination of unknown physical parameters of the solar corona by a comparison of observed with theoretical properties of waves and oscillations in magnetic plasma configurations, goes back to Uchida (1970) and Roberts et al. (1984). The recent clear observational evidence of waves and oscillations in several coronal magnetic structures, provided by instruments on board SOHO and TRACE and the refinement of theoretical models, have given a strong impetus to coronal seismology.

For example, the interpretation of transversal coronal loop oscillations in terms of global MHD fast kink eigenmodes of a uniform flux tube, in its fundamental harmonic, has been used to estimate the coronal magnetic field strength (Nakariakov et al., 1999). More recently, the detection of double mode kink oscillations in several loops in a coronal arcade by Verwichte et al. (2004) has been used by Andries et al. (2005a) to determine the density stratification in those loops.

An important property of the observed transverse loop oscillations is their rapid damping, with an exponential decay time of only a few periods. The physical nature of the damping mechanism(s) is unknown and still under intensive discussion. Resonant absorption of quasi-mode kink oscillations (Hollweg and Yang, 1988) might provide a good explanation.

This article studies the damping of coronal loop oscillations by resonant absorption of quasi-mode kink oscillations and the combination of theory and observations to extract information on the physical conditions inside the coronal loops.

In this article, we explore the possibility of using both the period and the damping rate of transverse loop oscillations, to obtain information about the physical conditions in oscillating coronal loops. We use observed period and damping rates together with previous results of parametric studies of the period and damping of loop oscillations as a function of equilibrium parameters (Van Doorsselaere et al., 2004; Arregui et al., 2005), such as the density contrast, the radial inhomogeneity length-scale and the internal Alfvén speed. We do not make any a priori assumptions on any of these parameters of interest.

The valid equilibrium models that are able to reproduce the observed period and damping are computed. The equilibrium models obtained in that way can then be compared with observational estimates of equilibrium parameters.

2. PHYSICAL MODEL, LINEAR MHD WAVES AND NUMERICAL SOLUTIONS

A coronal loop is modelled as a gravity-free, straight, cylindrically symmetric flux tube. The magnetic field is straight and pointing in the z-direction of a cylindrical coordinate system \((r, \phi, z)\).

We neglect the plasma pressure. This classical \(\beta = 0\) approximation implies that the magnetic field is uniform, \(\vec{B} = B \hat{e}_z\), and also that the density profile, \(\rho(r, z)\), can be chosen arbitrarily.

As in Andries et al. (2005b), we consider a two-dimensional variation of plasma density of the form

\[
\rho(r, z) = \rho(r) \left[1 - \alpha \sin \left(\frac{\pi z}{L}\right)\right],
\]

with a separable dependence on the radial direction and the axial direction.
As for the radial dependence of the density, we follow Van Doorsselaere et al. (2004), and adopt a sinusoidal non-uniform profile which continuously connects the constant internal density, \(\rho_i\), and the constant external density, \(\rho_o\), in a transitional layer of thickness \(l/R\).

A parametric numerical study of the fast MHD kink eigenmode period and damping rate was performed for a wide range of values for several loop parameters, such as the inverse aspect ratio of the loop (\(\varepsilon = \pi R/L\)), the thickness of the inhomogeneous layer (\(l/R\)), the density contrast (\(\zeta = \rho_i/\rho_o\)) and the longitudinal stratification parameter (\(\alpha\)).

The results of those parametric studies give the dependence of the period, damping time and damping rate of the fundamental fast kink eigenmode in the following form

\[
\frac{P}{\tau_{AI}} = f_1(\varepsilon, \alpha, \zeta, l/R), \quad (1a)
\]

\[
\frac{\tau_d}{\tau_{AI}} = f_2(\varepsilon, \alpha, \zeta, l/R), \quad (1b)
\]

\[
\frac{P}{\tau_d} = f_3(\zeta, l/R). \quad (1c)
\]

Here \(\tau_{AI} = R/V_{AI}\) is the internal Alfvén travel time that enters in our analysis through the normalisation in space and velocity employed in the numerical codes and determines the time unit. Note that in Eqs. (1) only two of three mentioned functions are independent, hence we will restrict our analysis to the period and the damping rate.

We use observational estimates for \(L\), \(R\) (Aschwanden et al., 2002). The \(\alpha\) dependency can be taken into account by considering the weighted mean density. The functions \(f_i\) thus only depend on \(l/R\) and \(\zeta\).

We are left with three free parameters that are difficult to obtain from observations; the Alfvén speed (\(V_{AI}\)), the density ratio (\(\zeta\)) and the inhomogeneity length-scale (\(l/R\)). On the other hand, we have two observables: the period of the oscillation (\(P\)) and the damping rate \(P/\tau_d\). This means that, with the current model and the available observations, any method for obtaining a seismic determination of the unknown parameters using the observed period and damping of loop oscillations can only yield a 1D solution space containing the valid equilibrium models that reproduce the observations, unless some additional assumption is made.

3. ANALYSIS

The oscillatory properties of transverse loop oscillations, such as the period and the damping rate correspond to the same physical system with the same equilibrium parameters. Both the period and the damping rate provide us with important and largely independent sources of information about the physical conditions in oscillating coronal loops.

A selection of 11 oscillating coronal loop events was used by Ofman and Aschwanden (2002) and Goossens et al. (2002) in their analysis of phase mixing and resonant absorption as damping mechanisms. Here, the same selection of loop oscillation events is considered. The physical and geometrical properties of interest for these loops are collected in the left-hand side of Table 1.

From the computational side, we use the output from the parametric study by Van Doorsselaere et al. (2004) expressed by Eqs. (1) with \(\alpha = 0\). As mentioned before, because the time normalisation is the same for the period and the damping time, only two of the three functions given by Eqs. (1) are independent. The functions describing the period (Eq. 1a) and damping rate (Eq. 1c) turn out to be the most suitable for our analysis.

In order to incorporate the time unit, and, hence, the internal Alfvén speed in our analysis, a three-dimensional data-cube is constructed by considering a range of internal Alfvén speeds. To determine the valid equilibrium models for all loop oscillation events in Table 1, a range of \(V_{AI}\) from 0 to 3000 km s\(^{-1}\) has been sufficient. A sampling of \(\Delta V_{AI} = 10\) km s\(^{-1}\) has been considered. Finally, we thus end up with two three-dimensional data cubes of the form, \(P = P(\zeta, l/R, V_{AI})\) and \(P/\tau_d = P/\tau_d(\zeta, l/R)\) for each loop oscillation event. These data cubes can now be combined with the observed periods and damping rates by requiring that

\[
P(\zeta, l/R, V_{AI}) = P_{obs}, \quad (2a)
\]

\[
\frac{P}{\tau_d}(\zeta, l/R) = \left(\frac{P}{\tau_d}\right)_{obs}. \quad (2b)
\]

As such, we obtain the equilibrium models, \(\{\zeta, l/R, V_{AI}\}\) that reproduce the observed periods and damping rates \(P_{obs}\) and \(P/\tau_d\) for each oscillation event.

Fig. 1 displays the 1D solution spaces in the three-dimensional parameter space obtained for loop oscillation events #5 (Fig. 1a) and #10 (Fig. 1b). Also shown are the projections of the solution curves onto the different two-dimensional parameter planes. As can be appreciated, the values of the Alfvén speed for valid equilibrium models in our parameter regime are constrained to a rather limited range. The lowest values correspond to equilibrium models with large density contrasts and relatively low inhomogeneity length-scales. Then, moving along the 1D solution curve, valid equilibrium models have increasingly larger Alfvén speed.

In both events, the lower limit for the Alfvén speed is obtained for the largest density contrast. As such, this is not a true lower limit, since the density contrast could be larger. However, the flattening of the 1D solution curve and the increase in the separation of equilibrium models towards larger density ratios suggest that the Alfvén speed will not vary significantly when the density contrast is allowed to increase past its current limit.

In the case of loop oscillation event #5, the highest value
Table 1. Summary of physical and geometrical properties of the 11 loop oscillation events selected by Ofman and Aschwanden (2002); Goossens et al. (2002) (left hand-side) and computed constraints for the valid equilibrium models (right hand-side). Events marked with an asterisk do not exhibit physical constraints since these constraints originate in these cases from the limitations used in the numerical solutions ($\zeta \geq 1.5$).

<table>
<thead>
<tr>
<th>Loop</th>
<th>$R$ (10$^6$ m)</th>
<th>$L$ (10$^6$ m)</th>
<th>$\varepsilon = \pi R / L$</th>
<th>$P$ (s)</th>
<th>$\tau_d$ (s)</th>
<th>$P/\tau_d$</th>
<th>$l/R$</th>
<th>$V_{Al}$ (km s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.60</td>
<td>1.68</td>
<td>0.067</td>
<td>261</td>
<td>870</td>
<td>0.30</td>
<td>0.20–0.83*</td>
<td>880–1080*</td>
</tr>
<tr>
<td>2</td>
<td>3.35</td>
<td>0.72</td>
<td>0.146</td>
<td>265</td>
<td>300</td>
<td>0.88</td>
<td>0.58–2.0</td>
<td>170–190</td>
</tr>
<tr>
<td>3</td>
<td>4.15</td>
<td>1.74</td>
<td>0.075</td>
<td>316</td>
<td>500</td>
<td>0.63</td>
<td>0.41–2.0</td>
<td>670–770</td>
</tr>
<tr>
<td>4</td>
<td>3.95</td>
<td>2.04</td>
<td>0.061</td>
<td>277</td>
<td>400</td>
<td>0.69</td>
<td>0.45–2.0</td>
<td>1110–1250</td>
</tr>
<tr>
<td>5</td>
<td>3.65</td>
<td>1.62</td>
<td>0.071</td>
<td>272</td>
<td>849</td>
<td>0.32</td>
<td>0.22–0.90*</td>
<td>770–950*</td>
</tr>
<tr>
<td>6</td>
<td>8.40</td>
<td>3.90</td>
<td>0.068</td>
<td>522</td>
<td>1200</td>
<td>0.44</td>
<td>0.30–2.0</td>
<td>1010–1190</td>
</tr>
<tr>
<td>7</td>
<td>3.50</td>
<td>2.58</td>
<td>0.043</td>
<td>435</td>
<td>600</td>
<td>0.73</td>
<td>0.47–2.0</td>
<td>1270–1420</td>
</tr>
<tr>
<td>8</td>
<td>3.15</td>
<td>1.66</td>
<td>0.059</td>
<td>143</td>
<td>200</td>
<td>0.72</td>
<td>0.46–2.0</td>
<td>1780–1950</td>
</tr>
<tr>
<td>9</td>
<td>4.60</td>
<td>4.06</td>
<td>0.036</td>
<td>423</td>
<td>800</td>
<td>0.53</td>
<td>0.35–2.0</td>
<td>2460–2900</td>
</tr>
<tr>
<td>10</td>
<td>3.45</td>
<td>1.92</td>
<td>0.056</td>
<td>185</td>
<td>200</td>
<td>0.93</td>
<td>0.57–2.0</td>
<td>1690–1840</td>
</tr>
<tr>
<td>11</td>
<td>7.90</td>
<td>1.46</td>
<td>0.169</td>
<td>390</td>
<td>400</td>
<td>0.98</td>
<td>0.62–2.0</td>
<td>200–220</td>
</tr>
</tbody>
</table>

Figure 1. Three-dimensional view of the obtained 1D solution curves representing the valid equilibrium models that reproduce observed periods and damping rates in the parameter space ($\zeta$, $l/R$, $V_{Al}$) together with their projection onto different two-dimensional planes. a: loop oscillation event #5 and b: loop oscillation event #10. Circles represent the sampling of the internal Alfvén speed, used for the computation of the curves.

for the Alfvén speed ($V_{Al} = 950$ km s$^{-1}$) is obtained at $\zeta = 1.5$, which coincides with the minimum density contrast considered in the numerical solutions. Thus, the obtained upper limit for the Alfvén speed is actually restricted by the limitations on the numerical data and does not constitute a physical upper limit. When $\zeta$ is allowed to decrease even further, higher values for the Alfvén speed will be allowed.

In case of loop oscillation event #10, we see that now the largest value of the Alfvén speed for valid equilibrium models ($V_{Al} = 1840$ km s$^{-1}$) is attained for a larger contrast than the minimum value available from numerical simulations. This allows us to obtain a physical upper limit on $V_{Al}$. This means that, although we did not make any a priori assumptions for any of the equilibrium parameters, we can obtain a physical upper limit to the internal Alfvén speed.

The above described procedure has been applied to all

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11 loop oscillation events present in Table 1, where the lower limits to the inhomogeneity length-scale and the constraints on internal Alfvén speeds are shown. In 9 of the 11 cases, an upper limit of the internal Alfvén speed has been deduced. The other 2 events correspond to the cases in which we are limited by our minimum density contrast. For the Alfvén speed, this is not a physical upper limit. When the lower boundary on $\zeta$ would be decreased, higher values for the Alfvén speed will be allowed.

The values for the internal Alfvén speed obtained for loops #2 and #11 are particularly striking (see Table 1). It is clear that these low values for the Alfvén speed closely correspond to a high value for the inverse aspect ratio $\varepsilon$. If the values for the inverse aspect ratio would be comparable to the other oscillation events, the Alfvén speeds would also be in the acceptable range.

4. SUMMARY AND CONCLUSIONS

This article reports how both the period and damping time of transversal coronal loop oscillations can be used to obtain information about the physical conditions in oscillating loops. We have adopted resonant absorption of quasi-mode kink oscillations as the mechanism responsible for the damping of loop oscillations. Observed values of the period and damping rate have been used together with the results of a parametric numerical study of the frequency of quasi-mode kink oscillations in 1D fully non-uniform equilibrium models.

The analysis described in this chapter allowed the individual study of loop oscillation events and took into account the particular physical and geometrical parameters for each case. In contrast to the analysis of Aschwanden et al. (2003), our analysis does not use any a priori information.

The combined use of the period and damping rate to do coronal loop seismology has been considered. Two observables are used to restrict three physical parameters: the density contrast, the inhomogeneity length scale and the internal Alfvén speed. In principle, only a 1D solution curve in the three-dimensional parameter space can be obtained. It turns out, however, that the projection of the solution curve onto the Alfvén speed axis turns out to be in a rather limited range. Furthermore, of 9 of the 11 analysed cases a physical upper limit to the Alfvén speed has been established. Even though no a priori information was assumed on any equilibrium parameter, a fairly restricted range for the Alfvén speed could be derived.

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