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The Effect of Steady Flow on the Physical Quantities of Slow Magneto Acoustic Waves in Solar Coronal Plasma

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Abstract. Damping of slow magnetohydrodynamic(MHD) waves and oscillations are believed to contribute to the heating of the solar corona. Since the launch of solar space telescopes, many observational evidences for the occurrence of slow MHD waves have been detected in various structures of the solar corona. In this paper, we studied the effect of steady flow of coronal plasma on the damping time and other physical quantities of slow magneto-acoustic waves in the presence of thermal conduction and compressive viscosity. The perturbed and linearized MHD Equations of a flowing coronal plasma are solved both analytically and numerically by Mac Cormack method to investigate the effect of steady flows on physical quantities of slow magneto-acoustic waves. The results of this study show that with increasing magnitude values of the Mach number from 0 to 0.6 and increasing the compressive viscosity and thermal conduction coefficient with increasing the temperature from 2 to 6 MK, the oscillation periods, the damping times and the damping qualities change significantly. Also, the results of this study show that the values and limits of the physical quantities calculated for magneto-acoustic waves in a flowing viscous plasma in the presence of thermal conduction at high temperatures (more than 4 MK) correspond to observational values. Moreover, the results indicate that background velocity of the coronal plasma is an effective factor in the damping of slow magneto-acoustic waves. Damping of slow magneto-acoustic waves in a flowing solar coronal plasma is stronger than the damping of slow magneto-acoustic waves in a stationary coronal plasma. So, steady flow along with the other damping mechanisms of slow magneto-acoustic waves must be considered in theoretical models.

Keywords: Sun: corona, Mach number, magneto-acoustic waves

1 Introduction

MHD waves (or oscillations) in coronal structures are a popular tool for probing the structures and physical parameters of the solar coronal plasma. Magnetized coronal plasma structures can support three types of MHD waves, Alfvén, slow and fast magneto-acoustic waves. In recent years, slow magneto-acoustic waves have been observed frequently in various structures of the solar corona with solar space telescopes. Analysis of imaging data from solar space telescopes shows that slow magneto-acoustic waves are usually produced and propagated in areas such as the polar plume, inter plume regions and the fan loop structures of active regions of the solar corona (see,*e.g.*,[1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11]). For example, propagating slow magneto-acoustic waves were firstly detected in polar plumes with *Extreme-Ultraviolet Imaging Telescope* (EIT) on board the *Solar and Heliospheric Observatory* (SOHO) and *Ultraviolet Coronagraph Spectrometer* (UVCS) [2, 12]. Also, propagating slow waves were detected in coronal loops with SOHO/EIT [13]. Slow-mode loop oscillations were detected in the polar plume structures using *Solar Ultraviolet Measurements of Emitted Radiation* (SUMER) instrument on board the SOHO [4, 5] The slow modes were initially observed in hot EUV coronal loop with *EUV Imaging Spectrometer* (EIS) on board Hinode spacecraft [14]. First, direct observations of slow magneto-acoustic waves in microwave emission were reported by Kim *et al.* (2012)[6]. Flare-induced fast magneto-acoustic waves along funnel-like structures were discovered using *Atmospheric Imaging Assembly* (AIA) on board the *Solar Dynamics Observatory* (SDO) space telescope [15, 16]. The observed phase speed of slow waves fluctuates from a few kilometers per second to several hundred kilometers per second, and their damping lengths are about a few mega meters to several ten mega meters(see, *e.g.*, [17, 18, 19]. The oscillation periods and damping times of the magnetic-acoustic waves are observed in the range of a few minutes to a few hours (see, *e.g.*, [11, 12, 17, 18, 20, 21, 22, 23]). The damping mechanisms of magneto-acoustic waves in the sun's atmosphere have been theoretically studied by several researchers. They found that factors such as thermal conductivity, compressive viscosity, radiation, gravitational stratification, convergence and divergence of magnetic field lines may be responsible for the damping of slow waves (see, *e.g.*, [24, 25, 26]). For example, Ofman and Wang (2002)[27] numerically solved the linearized magneto-hydro-dynamic equations. They found that thermal conduction was the most important damping mechanism for standing slow waves in the isothermal coronal loops. De Moortel *et al.* (2002) [28] studied the effects of both thermal conductivity and compressive viscosity on the propagating and standing magneto-acoustic waves in the corona loops. They indicated that thermal conduction alone could not justify the strong damping of slow waves and the compressive viscosity factor must also be added to the theoretical model. Carbonell *et al.* (2004) [29] investigated the effect of radiation on damping time and the oscillation period of slow magneto-acoustic waves. They showed that radiation partially reduced the damping time of the oscillations. And it does not significantly change the period of oscillations. Roberts (2006)[30] theoretically investigated the effect of gravitational stratification on slow magneto-acoustic waves. He concluded that the effect of gravitational stratification on periodicity and damping time of slow waves was negligible. Abedini *et al.* (2012) [22] studied the oscillations of hot corona loops with gravitational stratifications in the presence of heat conduction, compressive viscosity, and radiation. They verified that optically thin radiation is not a main cooling mechanism in hot coronal loops. Also, thermal conduction and compressive viscosity are main energy dissipation mechanisms in the damping of slow magneto-acoustic waves of the hot long coronal loops. In short coronal loops, the viscosity at high temperatures alone can justify the strong damping fluctuations of the corona loops. In most of the proposed theoretical models, it is assumed that the solar corona plasma that emits magneto hydro dynamic waves is without background velocity. However, observations show that the coronal plasma has a background velocity [31, 32]. In recent years, limited work has been done on the effect of plasma background velocity on the physical quantities of slow magneto-acoustic waves [33, 34, 35]. In this paper, the effect of plasma background velocity of coronal plasma in the presence of compressive viscosity and thermal conductivity on the physical quantities of propagating and standing slow magneto-acoustic waves is carefully studied. For this purpose, linearized MHD equations are solved analytically and numerically by MacCormack numerical solution method. For different values of Mach number, the effect of steady current on the physical quantities of slow magneto-acoustic waves in the presence of viscosity and thermal conductivity is investigated. The results show that the steady follow has no effect on the damping time of forward and backward propagation slow waves. The background velocity of coronal plasma in the direction of the propagation waves(with positive Mach numbers)reduces the period of oscillations. The background velocity of coronal plasma in the opposite direction of the propagation waves(with negative Mach numbers)increases the period of oscillations. So the damping quality(damping time per period)of propagating slow waves increases and decreases with increasing the magnitude values of positive and negative Mach numbers, respectively. In other words, increasing the amount of plasma background velocity in the opposite direction of wave propagation makes the oscillation damping stronger. For standing waves (fundamental modes), by increasing the amount of positive Mach numbers (flow along to the direction of magnetic field) and negative Mach numbers (flow opposite to the direction of magnetic field) from 0 to 0.6 and changing the viscosity and thermal conductivity coefficients by increasing the temperature from 2 to 6 Mega Kelvin, the period of oscillation increases from 55% to 71% , damping time and damping quality decrease from 31% to 50% and 18.5% to 30%, respectively. The values and ranges of the physical quantities calculated for standing slow magneto-acoustic waves in the current plasma with high the Mach numbers and temperatures (greater than 4 mega kelvin) in the presence of viscosity and thermal conductivity correspond to the observed values. In addition, the results show that plasma background velocity is an effective factor in damping magneto-acoustic waves and should be considered along with other damping mechanisms such as compressive viscosity, thermal conductivity, gravitational stratification and radiation. This article is organized as follows. Section 2 describes a description of the model and equations. Section 3 presents the results of the numerical solution of slow MHD equations. Section 4 presents the summary and conclusion.

2 Description of the Model and Equations

Coronal loops are modeled as a straight magnetic flux tube of length L along the z axis with a uniform magnetic field and a steady flow of plasma along the coronal loop axis. The equilibrium values of temperature, density and pressure of the coronal loop structures are assumed to be constant. In the one-dimensional MHD equations, the effects of thermal conductivity and compressive viscosity are considered as follows:

$$E_c = \frac{\partial}{\partial z}(\kappa_{||}\frac{\partial T_0}{\partial z}),\ E_\eta = \frac{4}{3}\eta_0(\frac{\partial v}{\partial z})^2, \tag{1}$$

Here, E_c and E_η, are the heating or cooling rate of thermal conduction and compressive viscosity per unit volume, respectively. Also, $\kappa_{||} = 10^{-11}{T_0}^{\frac{5}{2}}Wm^{-1}K^{-1}$ and $\eta_0 = 10^{-17}{T_0}^{\frac{5}{2}}kgm^{-1}s^{-1}$ represent the coefficient of the thermal conduction and compressive viscosity [36, 37]. The dimensionless MHD equations after perturbation and linearization in the presence of steady flow along the coronal loop reduces to 1D form as

$$(\frac{\partial}{\partial \bar{t}} + M\frac{\partial}{\partial \bar{z}})\bar{\rho_1} = -\frac{\partial \bar{v_1}}{\partial \bar{z}}, \tag{2}$$

$$(\frac{\partial}{\partial \bar{t}} + M\frac{\partial}{\partial \bar{z}})\bar{v_1} = -\frac{1}{\gamma}\frac{\partial \bar{p_1}}{\partial \bar{z}} + \frac{4}{3}\epsilon\frac{\partial^2 \bar{v_1}}{\partial \bar{z}^2}, \tag{3}$$

$$(\frac{\partial}{\partial \bar{t}} + M\frac{\partial}{\partial \bar{z}})\bar{p_1} = -\gamma\frac{\partial \bar{v_1}}{\partial \bar{z}} + d\frac{\partial^2 \bar{T_1}}{\partial \bar{z}^2}, \tag{4}$$

$$\bar{p_1} = \bar{\rho_1} + \bar{T_1}, \tag{5}$$

In the equations 2 - 5, the dimensionless parameters $M = \frac{v_0}{c_s}$, $\epsilon = \frac{\eta_0}{\rho_0 L c_s}$ and $d = \frac{(\gamma-1)\kappa_{||}T_0}{p_0 \tau c_s^2}$ are the Mach number, the dimensionless coefficient of compressive viscosity and thermal conductivity, respectively. And the quantities $p_0,\ \rho_0,\ \tau, v_0,\ L$ and c_s are the equilibrium

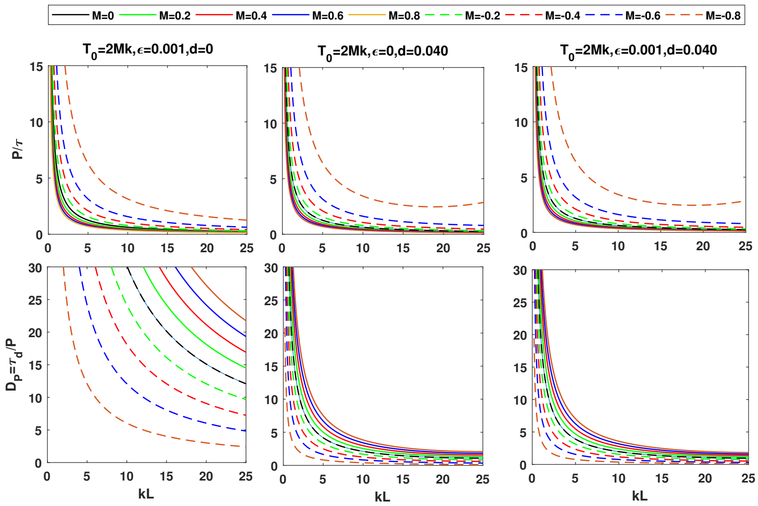

Figure 1: The dimensionless period of oscillationsP/τ and the damping qualityτ_d/P of the propagating waves in the presence of compressive viscosity (left panels), thermal conductivity (middle panels) and both compressive viscosity and thermal conductivity (right panels) are plotted as function of kL for different Mach numbers (black lines ($M = 0$), green lines ($M = \pm 0.2$), red lines ($M = \pm 0.4$), blue lines ($M = \pm 0.6$) and brown lines ($M = \pm 0.8$). Solid lines correspond to positive Mach numbers and dashed lines correspond to negative Mach numbers.

pressure, the equilibrium plasma density, the specific time ($\tau = \frac{L}{c_s}$), the background velocity of plasma, the loop length and sound speed in the plasma, respectively. Also, the other dimensionless variables are defined as

$$\bar{t} = \frac{t}{\tau}, \ \bar{z} = \frac{z}{L}, \ \bar{v_1} = \frac{v_1}{c_s}, \ \bar{\rho_1} = \frac{\rho_1}{\rho_0}, \ \bar{p_1} = \frac{p_1}{p_0}. \tag{6}$$

In order to investigate the effect of steady flow of plasma on the behavior of slow waves, all disruption terms are assumed to be $\exp(\bar{k}\bar{z} - \bar{\omega}\bar{t})$. With a few algebraic calculations, the dispersion relationship in the presence of compressive viscosity and thermal conductivity is obtained as follows

$$(\bar{\omega} - M\bar{k})^3 + i(\frac{4}{3}\epsilon\bar{k}^2 + d\bar{k}^2)(\bar{\omega} - M\bar{k})^2 - (\frac{4}{3}\epsilon d\bar{k}^4 + \bar{k}^2)(\bar{\omega} - M\bar{k}) - i\frac{1}{\gamma}d\bar{k}^4 = 0, \tag{7}$$

Here, $\bar{k} = kL$ and $\bar{\omega} = \omega\tau$ are dimensionless wave number and angular frequency, respectively. In the following, for simplicity, the bar marks have been omitted from the dimensionless quantities. The dispersion relation 7 shows that the background velocity changes only the real part of frequency of the propagating waves, but it does not change the imaginary part of the frequency. Due to the dependence of the real part of frequency on the Mach number, then the damping quality and the phase speed of the propagating waves will depend on the background velocity of plasma. In Figure 1, the dimensionless period of oscillations (P/τ) and the damping quality ($D_p = \tau_d/P$) of the propagating waves in the presence of compressive viscosity (left panels), thermal conductivity (middle panels) and combined effects of compressive viscosity and thermal conductivity (right panels) are plotted as function

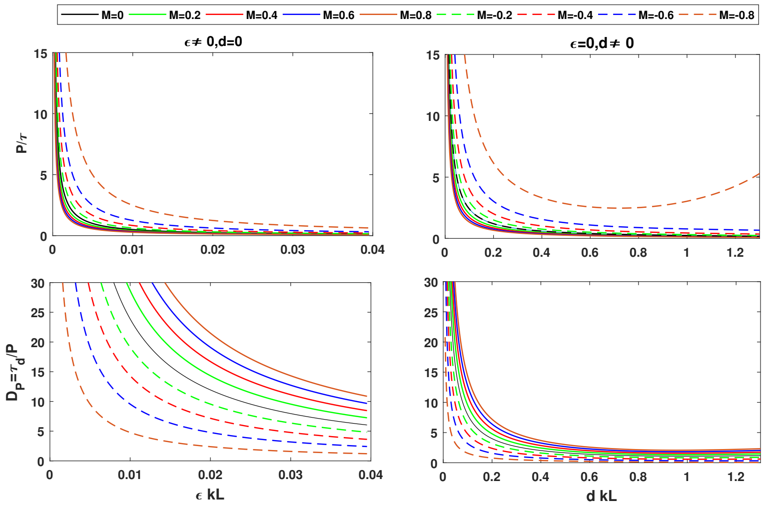

Figure 2: The dimensionless period of oscillations P/τ and the damping quality τ_d/P of the propagating waves in the presence of compressive viscosity (left panels), thermal conductivity (right panels) are plotted as function of ϵkL and d_ckL for different Mach numbers (black lines ($M = 0$), green lines ($M = \pm0.2$), red lines ($M = \pm0.4$), blue lines ($M = \pm0.6$) and brown lines ($M = \pm0.8$). Solid lines correspond to positive Mach numbers and dashed lines correspond to negative Mach numbers.

of kL for different Mach numbers (black lines ($M = 0$), green lines ($M = \pm0.2$), red lines ($M = \pm0.4$), blue lines ($M = \pm0.6$) and brown lines ($M = \pm0.8$). Solid lines correspond to positive Mach numbers and dashed lines correspond to negative Mach numbers. Solid lines are for positive Mach numbers and dashed lines are for negative Mach numbers. So, in Figure 2 the dimensionless period of oscillations and the damping quality of the propagating waves in the presence of compressive viscosity (left panels), thermal conductivity (right panels) are displayed as function of ϵkL and $d_c kL$ for different Mach numbers, respectively. It can be seen that for positive Mach numbers, by increasing the value of Mach numbers the period of the oscillations of propagating waves decrease, but the damping qualities of the waves increases. Also, for negative Mach numbers, as the values of Mach numbers increase, the period of the oscillations increases and the damping qualities decrease. The damping quality of the propagating waves in the opposite direction to the background velocity is stronger than the damping quality of the waves in the direction of the background velocity. In addition, the effect of thermal conductivity on damping quality is higher than compressive viscosity. In the next section, the effect of a steady flow on the physical quantities of standing waves within a solar corona loop in the presence of compressive viscosity and thermal conductivity is studied by the MacCormack numerical solution method.

3 Numerical solution of slow MHD equations

In the previous section, the effect of plasma background velocity in the presence of compressive viscosity and thermal conductivity on the physical quantities of propagating magneto-acoustic waves was investigated. In this section, the effect of plasma background velocity in the presence of viscosity and thermal conductivity mechanism on the physical quantities of standing magneto-acoustic waves is studied. For this purpose, MHD equations are solved numerically by the MacCormack method. And the physical quantities such as damping time, damping quality and period of oscillations are estimated.

3.1 MacCormack's method

The MacCormack method is a variation of the two-step Lax-Wendroff method. This method is widely used in discretization for numerical solution of hyperbolic partial differential equations. To better understand, consider the following first order hyperbolic equation

$$\frac{\partial f}{\partial t} + c\frac{\partial f}{\partial z} = 0 \tag{8}$$

The application of MacCormack scheme to the above equation combines in two steps; a predictor step which is followed by a corrector step. predictor step: forward differencing

$$f_i^* = f_i^n - \frac{c\Delta t}{\Delta z}(f_{i+1}^n - f_i^n). \tag{9}$$

Here, n and i are the time and space step numbers, respectively. corrector step: backward differencing

$$f_i^{**} = f_i^n - \frac{c\Delta t}{\Delta z}(f_i^* - f_{i-1}^*). \tag{10}$$

final step: combine the two forward and backward differencing

$$f_i^{n+1} = \frac{1}{2}(f_i^* + f_i^{**}). \tag{11}$$

The MacCormack method is second-order accurate in both time and space. For the numerical solution of the perturbed and linearized equations 2-5 using the MacCormack method, the initial and boundary conditions of perturbed quantities in the corona loops are considered as follows:

$$\begin{aligned}
&v_1(z,0) = A_v sin(\pi z),\\
&\rho_1(z,0) = 0, p_1(z,0) = 0, T_1(z,0) = 0,\\
&v_1(0,t) = 0, v_1(z_{max},t) = 0,\\
&\frac{\partial}{\partial z}p_1(0,t) = 0, \frac{\partial}{\partial z}p_1(z_{max},t) = 0, \frac{\partial}{\partial z}T_1(0,t) = 0, \frac{\partial}{\partial z}T_1(z_{max},t) = 0.
\end{aligned} \tag{12}$$

Here, A_v is the dimensionless amplitude of the initial velocity profile and z_{max} is maximum numerical value of z. To run the simulation for calculating physical quantities of slow magneto-acoustic waves, $\mu = 0.6$ (mean molecular weight), $L = 0.751R_\odot \simeq 400$Mm and $n_0 = 5 \times 10^8 cm^{-3}$ were selected for the length and equilibrium density of a coronal loop, which were motivated with the SUMER and Yohkoh/SXT space telescopes observations [27, 26]. To run the simulation, the dimensionless loop length was divided into 4001 grid points. Temporal evolution of perturbed velocity of each points at temperatures 2, 4 and 6 MK for different Mach numbers was extracted and plotted as function of time over a period of 300 minutes with time intervals of 0.001 minutes (for fundamental mode). For example, in the Figure 3 the temporal evolution of the perturbed velocity in the presence of viscosity for a piece of loop located at $z = 0.4$ as function of dimensionless time for 2MK (first row panels), 4MK (second row panels) and 6MK (third row panels). The black, green, red, and blue lines indicate the values of Mach number 0, 0.2, 0.4, and 0.6, respectively. Solid lines correspond to positive Mach numbers (flow along to the direction of magnetic field) and dashed lines correspond to negative Mach numbers (flow opposite to the direction of magnetic field). Figure 3 shows that at a constant Mach number, by increasing the temperature, in other words by increasing the viscosity and thermal conductivity coefficient, the damping is stronger. Also, at a constant temperature with increasing the magnitude value of the Mach number, damping become stronger. To obtain damping time, damping quality and period of oscillations in the presence of viscosity and thermal conductivity, a cosine damping function is fitted to the numerical data as follows

$$f(t) = A_d exp(-\gamma_d t) cos(\omega t + \phi)), \tag{13}$$

Here, A_d is the amplitude of the oscillations, ϕ is the initial phase and $\gamma_d = 1/\tau_d$ is the inverse of the damping time of the oscillations. For example, in the Figure 4, the data of temporal evolution of the perturbed velocity in the presence of both compressive viscosity and thermal conductivity are fitted by a damping cosine functions at temperatures of 6 MK for different values of the Mach numbers 0, -0.2, -0.4, and -0.6, and fit parameters are written in the panels. The physical quantities of a coronal loop in the presence of viscosity and thermal conductivity, are extracted for the different Mach numbers and temperatures are listed in Tables 1 and 2, respectively. In tables 3 and 4, the magnitude values and range of the physical quantities such as damping times, damping qualities are written for the first harmonic oscillation mode for different positive and negative Mach numbers (M=0, $\pm 0.2, \pm 0.4, \pm 0.6$) and temperatures($T_0$ = 2,4 and 6 MK) in the presence of viscosity and thermal conductivity, respectively. Furthermore, in table 5, the magnitude values and range of these quantise for different positive and negative Mach numbers (M=0, $\pm 0.2, \pm 0.4, \pm 0.6$) and temperatures($T_0$ = 2,4 and 6 MK) in the presence of both viscosity and thermal conductivity. It can be seen that physical quantities change significantly with Mach numbers. At temperatures above 4 megawatts Kelvin and Mach numbers more than 2 results match the observational results of space telescopes.

4 Summary and conclusion

In this paper, the effect of background velocity on the physical quantities of propagating and standing slow waves has been carefully studied. To study the effect of background velocity on the slow waves in the corona loops, ccoronal loops are modeled as a straight magnetic flux tube of length L along the z axis with a constant cross section, temperature, constant magnetic field along the loop length and a steady flow of plasma along the loop axis in the presence of thermal conductivity and compressive viscosity. The MHD equations are perturbed and linearized in the presence of viscosity, thermal conductivity, and background velocity of plasma. The linearized MHD equations were solved by applying the appropriate initial values and boundary conditions analytically and numerically using McCormack's method. The physical quantities such as damping time, damping quality and period of oscillations for different values of positive (flow along to the direction of magnetic field) and negative (flow opposite to the direction of magnetic field) of Mach numbers at different temperatures are calculated. The results of this study show that:

- Flow leads to the period of oscillation and the damping quality of propagating slow waves decreases and increases, respectively, with increasing magnitude values of positive Mach numbers

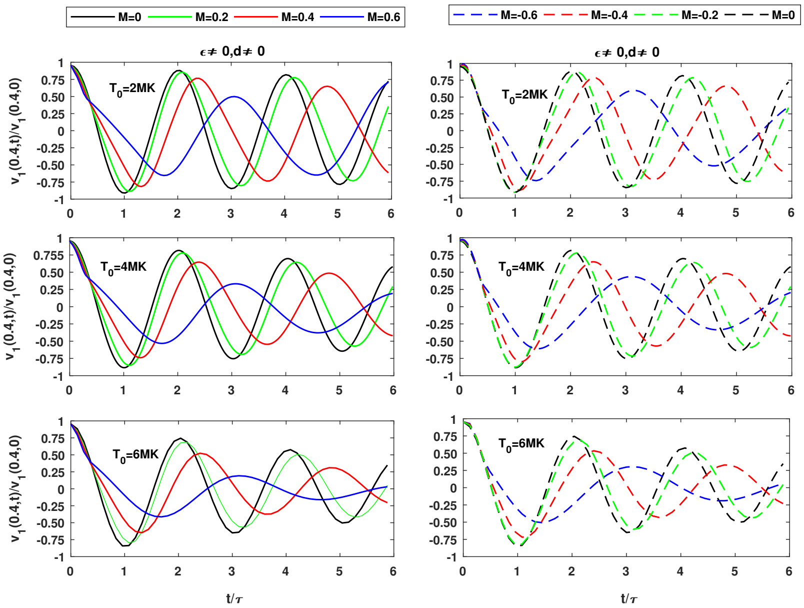

Figure 3: Temporal evolution of the perturbed velocity in the presence of viscosity for a segment of loop located at z=0.4 as function of dimensionless time are plotted for different temperatures, 2MK (first row panels), 4MK (second row panels), 6MK (third row panels). The black, green, red, and blue lines indicate the values of Mach numbers 0, 0.2, 0.4, and 0.6, respectively. Solid and dashed lines correspond to positive and negative Mach numbers respectively.

Table 1: The magnitude of the physical quantities such as estimated damping times, period of oscillation, damping qualities in the presence of compressive viscosity, are written for the first harmonic oscillation mode for different values of Mach number and temperatures(T_0 = 2,3,4 and 6 MK).

T_0(MK)	ϵ	M	P(min)		τ_d(min)		$D_p = \tau_d/P$	
			$M \geq 0$	$M \leq 0$	$M \geq 0$	$M \leq 0$	$M \geq 0$	$M \leq 0$
2	0.001	0	62.09	62.09	1250.20	1250.20	19.87	19.87
		± 0.2	64.03	65.87	1000.03	714.00	15.90	10.98
		± 0.4	74.01	75.18	454.87	384.00	6.09	5.10
		± 0.6	101.05	99.00	277.23	217.00	2.77	2.22
4	0.003	0	44.20	44.20	833.04	833.04	18.93	18.93
		± 0.2	46.12	46.97	625.02	368.00	13.50	7.83
		±0.4	52.03	52.91	313.06	163.00	5.90	4.77
		±0.6	69.14	68.22	166.40	156.00	2.39	2.19
6	0.007	0	36.18	36.18	172.30	172.30	4.77	4.77
		± 0.2	38.20	37.73	156.70	138.00	4.10	4.32
		± 0.4	43.76	42.91	116.81	100.00	2.69	2.38
		± 0.6	57.02	53.18	89.20	56.00	1.56	1.09

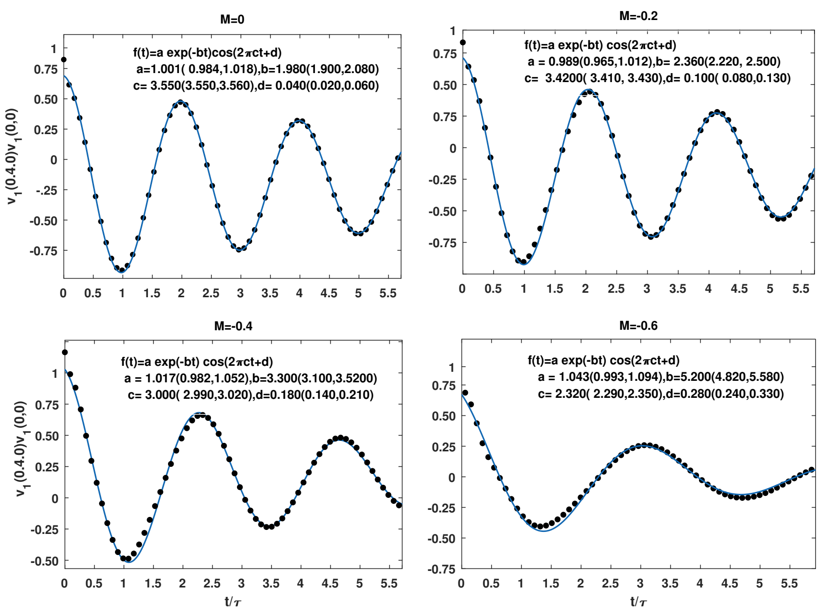

Figure 4: The data of temporal evolution of the perturbed velocity in the presence of both viscosity and thermal conductivity, are fitted by a damping cosine functions at temperatures of 6 MK for different values of the Mach numbers 0, -0.2, -0.4, and -0.6, and fit parameters are written in the panels.

Table 2: The magnitude of the physical quantities such as estimated damping times, period of oscillation, damping qualities in the presence of compressive viscosity, are written for the first harmonic oscillation mode for different values of Mach number (M=0, ± 0.2, ±0.4, ±0.6) and temperatures(T_0 = 2,3,4 and 6 MK).

T_0(MK)	d_c	M	P(min)		τ_d(min)		$D_p = \tau_d/P$	
			$M \geq 0$	$M \leq 0$	$M \geq 0$	$M \leq 0$	$M \geq 0$	$M \leq 0$
2	0.040	0	62.89	62.89	416.00	416.00	6.61	6.61
		± 0.2	65.35	65.35	357.00	312.00	5.72	4.77
		± 0.4	75.18	75.18	277.00	227.00	3.68	3.01
		± 0.6	99.00	98.85	200.00	125.00	2.02	1.26
3	0.086	0	51.54	51.54	151.00	151.00	2.92	2.92
		± 0.2	53.76	53.76	142.00	125.00	2.64	2.32
		±0.4	61.72	61.72	111.00	89.00	1.79	1.44
		±0.6	82.64	81.96	73.00	56.00	0.88	0.68
4	0.153	0	44.75	44.75	98.00	98.00	2.18	2.18
		± 0.2	46.62	46.97	86	80.00	1.86	1.74
		± 0.4	54.02	53.85	60.00	54.00	1.11	0.98
		± 0.6	76.00	73.60	33.00	31.00	0.44	0.42
6	0.344	0	-	-	-	-	-	-
		± 0.2	-	-	-	-	-	-
		± 0.4	-	-	-	-	-	-
		± 0.6	-	-	-	-	-	-

Table 3: The magnitude values and range of the physical quantities such as damping times, period of oscillations, damping qualities are written for fundamental mode for different positive and negative Mach numbers (M=0, 0.2, 0.3, 0.4, 0.6) and temperatures(T_0 = 2,3,4 and 6 MK) in the presence of compressive viscosity.

T_0(MK)	ϵ	M	P(min)	τ_d(min)	$D_p = \tau_d/P$
2	0.001	0-0.6	62-101	1250-277	19.87-2.77
		0-(-0.6)	62-99	1250-217	19.87-2.22
3	0.002	0-0.6	50-74	1010-220	29.34-3.97
		0-(-0.6)	49-74	1011-210	29.34-3.20
4	0.003	0-0.6	44-69	833-166	18.93-2.39
		0-(-0.6)	44-68	833-156	18.93-2.19
6	0.007	0-0.6	35-57	172-75	4.79-1.31
		0-(-0.6)	35-53	172-56	4.79-1.05

Table 4: The magnitude values and range of the physical quantities such as period of oscillations, damping times, damping qualities are written for fundamental mode of slow waves for different positive and negative Mach numbers (M=0, ± 0.2, ± 0.3, ± 0.4, ± 0.6) and temperatures(T_0 = 2,3,4 and 6 MK) in the presence of thermal conductivity and viscosity, respectively.

T_0(MK)	d_c	M	P(min)	τ_d(min)	$D_p = \tau_d/P$
2		0-0.6	62-99	416-200	6.61-2.02
	0.040	0-(-0.6)	62-99	416-125	6.61-1.26
3	0.086	0-0.6	51-83	151-73	2.91-0.88
		0-(-0.6)	51-82	151-56	2.91-0.68
4		0-0.6	44-76	98-33	2.18-0.44
	0.153	0-(-0.6)	44-74	98-31	2.18-0.42
6	0.344	0-0.6	-	-	-
		0-(-0.6)	-	-	-

Table 5: The magnitude values and range of the physical quantities such as damping times, damping qualities are written for the fundamental mode for different positive and negative Mach numbers (M=0, ± 0.2,± 0.3, ± 0.4, ± 0.6) and temperatures(T_0 = 2,3,4 and 6 MK) in the presence of thermal conductivity and compressive viscosity, respectively.

T_0(MK)	ϵ	d_c	M	P(min)	τ_d(min)	$D_p = \tau_d/P$
2	0.001	0.040	0-0.6	62-98	370-188	6.08-1.91
			0-(-0.6)	62-97	370-121	6.08-1.24
3	0.002	0.086	0-0.6	51-81	138-71	2.70-0.87
			0-(-0.6)	51-83	138-54	2.70-0.65
4	0.003	0.153	0-0.6	45-77	89-29	1.97-0.38
			0-(-0.6)	44-73	89-28	1.97-0.37
6	0.007	0.344	0-0.6	-	-	-
			0-(-0.6)	-	-	-

- The period of oscillation and the damping quality of propagating slow waves increases and decreases, respectively, with increasing magnitude values of negative Mach numbers. In other words, the propagation of the waves in the opposite direction of the background velocity of plasma makes the damping quality of the oscillations stronger. The values of the Mach numbers (positive and negative) have no effect on the damping time of the oscillations. The values of Mach numbers only change the period of the oscillations of the propagating slow waves.

- The physical quantities of standing slow magneto-acoustic waves in the solar coronal loops are varied due to the combined effects of steady flow and viscosity with positive and negative Mach numbers. By increasing magnitude values of positive (negative) Mach numbers of flow from 0 to 0.6 and temperature from 2 to 6 MK, the period of oscillations increases from 60% to 63%(52 % to 60%), damping time decreases from 22% to 43%(17 % to 32 %) and damping quality decrease from 14% to 27%(11% to 22%),respectively(see table 3).

- The physical quantities of standing slow waves in coronal plasma loop in the presence of thermal conductivity and a steady flow, by increasing Mach numbers from 0 to 0.6 and temperature from 2 to 6 MK, respectively, the period of oscillations increases from 57% to 69%(46% to 63%), damping time decreases from 32% to 48%(30% to 31 %) and damping quality decreases from 20% to 30%(19% to 19.5 %), respectivly (see table 4).

- For slow magneto-acoustic waves in a flowing coronal plasma loop in the presence of compressive viscosity and thermal conductivity, by increasing magnitude values of Mach numbers from 0 to 0.6 and temperature from 2 to 6 MK, the period of oscillations increases from 57% to 71%,(55% to 63%) damping time decreases from 32% to 50% (31% to 33%)and damping quality decreases from 19% to 31%(18.5% to 23%), respectively (see table 5).

- As the Mach numbers increase, the dampness of the slow standing waves changes from a weak damping state ($\mathrm{D_p} > 2$) to a strong damping ($\mathrm{D_p} < 2$) and the values of the physical quantities calculated correspond to the observational results (see, *e.g.*, [30, 26, 18]). The results of this study in the absence of thermal conductivity correspond to the numerical results of Kumar *et al.* (2016)[35], who investigated the propagation of slow waves in a flowing viscous coronal plasma.

- In general, the results of this study show that the background velocity of viscous plasma in the presence of thermal conductivity, significantly changes the physical quantities of slow magneto-acoustic waves. As a result, the background velocity is an effective factor in the damping of slow waves and should be considered along with other factors such as compressive viscosity, thermal conductivity, gravitational stratification and radiation in theoretical models.

References

[1] Ofman, L., Romoli, M., Poletto, G., Noci, G., & Kohl, J. L. 1997, ApJ, 491, L111.

[2] De Forest C. E., & Gurman, J. B. 1998, ApJ, 501, L217.

[3] Williams, D. R., Phillips, K. J. H., Rudawy, P., et al. 2001, MNRAS, 326, 428.

[4] Wang, T. J., Solanki, S. K.,Curdt, W., Innes, D. E., & Dammasch, I. E. 2002, ApJ, 574, L101.

[5] Wang, T. J.,Solanki, S. K., Innes, D. E., Curdt, W., & Marsch, E. 2003, A&A, 402, L17.

[6] Kim, S., Nakariakov, V. M., & Shibasaki, K. 2012, ApJ, 756, L36.

[7] Jess, D. B., De Moortel, I., Mathioudakis, M., & et al. 2012, ApJ, 757, 160.

[8] Marsh, M. S., Walsh, R. W., & Plunkett, S. 2009, ApJ, 697, 1674.

[9] Van Doorsselaere, T., & et al. 2011, ApJ, 727, L32.

[10] Kiddie, G., De Moortel, I., Del Zanna,G., McIntosh, S. W., & Whittaker, I, 2012, Sol. Phys., 279, 247.

[11] Krishna Prasad, S., Banerjee, D., & Van Doorsselaere, T. 2014, ApJ, 789, 118.

[12] Ofman, L., Nakariakov, V. M., & DeForest, C. E. 1999, ApJ, 514, 441.

[13] Berghmans, D., & Clette, F. 1999, Sol. Phys., 186, 207.

[14] Srivastava, A. K., & Dwivedi, B. N. 2010, New Astron., 15, 8S.

[15] Liu, W., Nitta, N. V., Schrijver, C. J., Title, A. M., & Tarbell, T. D. 2010, ApJ, 723, L53.

[16] Liu, W., Title, A. M., Zhao, J., Ofman, L., Schrijver, C. J., & et al. 2011, ApJ, 736, L13.

[17] Wang, T. J. 2011, Space Sci. Rev., 158, 397.

[18] Abedini, A. 2016, Ap&SS , 361, 133, DOI: 10.1007/s10509-016-2717-0.

[19] Sudip Mandal, S., Krishna Prasad, & Banerjee, D. 2018, ApJ, 853, 134.

[20] De Moortel, I., & Hood, A. W. 2003, A&A, 408, 755.

[21] Abedini, A., & Safari, H. 2011, New Astron., 317, 16A.

[22] Abedini, A., Safari, H., & Nasiri, S. 2012, Sol. Phys., 280, 137.

[23] Abedini, A. 2021, J. Astrophys Astron., 42, 16, DOI: 10.1007/s12036-021-09733-3.

[24] Kumar, N., Kumar, P., & Singh, S. 2006, A&A, 453, 1067.

[25] Konkol, P., Murawski, K., Lee, D. & Weide, K. 2010, A&A, 523, A34.

[26] Gupta, R. 2014, A&A, 568, A96.

[27] Ofman, L., & Wang, T. J. 2002, ApJ, 580, L85.

[28] De Moortel, I., Ireland, J., Hood, A. W., & Walsh, R. W. 2002, A&A, 387, 705.

[29] Carbonell, M., Oliver, R., & Ballester, J. L. 2004, A&A,, 415, 739.

[30] Roberts, B. 2006, RAS, 447, A364.

[31] Krijger, J. M., Roudier, T., & Rieutord, M. 2002, A&A, 387, 672.

[32] Gabriel, A. H., Bely-Dubau, F., & Lemaire, P. 2003, ApJ, 589, 623.

[33] Gruszecki, M., Murawski, K., & Ofman, L. 2008, A&A, 488, 757.

[34] Carbonell, M., Oliver, R., & Ballester, J. L. 2009, New Astron., 14, 277.

[35] Kumar, N., Kumar, A., & Murawski, K. 2016, Ap&SS , 361, 143.

[36] Pandey, V. S., & Dwivedi, B. N. 2006, Sol. Phys., 236, 127.

[37] Sigalotti, L. Di. G., Mendoza-Briceño, C. A., & Luna-Cardozo, M. 2007, Sol. Phys., 246, 187.