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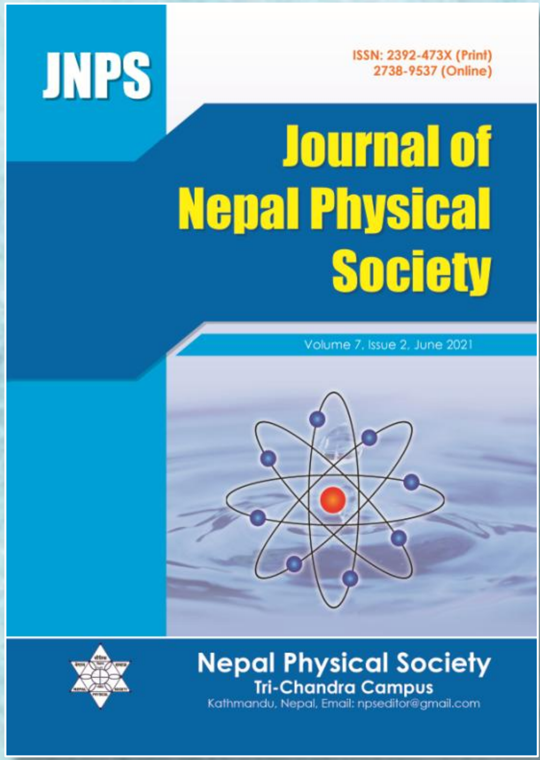

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Temporal Ion Velocity Variation with Obliqueness in Magnetized Plasma Sheath

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ABSTRACT

A narrow region having sharp gradients in physical parameters is formed whenever plasma comes into contact with a material wall. In this work, the temporal velocity variation of ions in such a sheath has been studied in the presence of an external oblique magnetic field. The Lorentz force equation has been solved for the given boundary conditions using Runge-Kutta method. In order to satisfy the Bohm criterion, ions enter the sheath region with ion acoustic velocity. It is observed that all components of the velocity waves are damped in plasma in the time scale of one second. The computed oscillatory part of ion velocity match with the equation of the damped harmonic oscillator. Thus obtained damping constants as well as the frequency of all three components are nearly equal for obliqueness less than 60^0 after which they are distinctly different. This is due to the fact that the magnetic field becomes almost parallel to the wall. In earlier studies, only the final velocity profiles are reported and hence this study is useful in understanding how the ion velocities evolve in time as they move from sheath entrance towards the wall.

Keywords: Quasineutral plasma, Plasma sheath, Bohm criterion, Frequency of oscillation, Damping constant.

1. INTRODUCTION

Plasma is an ionized state of matter and it faces a material wall in all practical applications. The quasineutral property of plasma breaks down as they come close to the wall and a narrow region having sharp gradients in physical parameters is formed, known as plasma sheath. The plasma-wall transition regions are different in absence and presence of external magnetic fields. In presence of oblique magnetized field it consists of three distinct regions: collisional presheath, magnetic presheath and non-neutral electrostatic Debye sheath [1-3]. The understanding of plasma-wall transition regions and the respective plasma parameters play crucial role in all applications such as fusion experiment, sputtering, etching, etc. [3]. The plasma sheath is one of the oldest problems in plasma and in recent years, the sheath formed between magnetized plasma and a particle absorbing wall has received a considerable amount of attention [2, 4-9].

R. Chodura was the first to consider effect of magnetic field in the sheath region, and modified the Bohm criterion, which was earlier valid only for non-magnetic cases [1, 10]. Hatami et al. investigated the effect of magnetic field on multi-component magnetized plasma sheath [11]. It has been observed that the fluctuation of velocity and density of ions depend on the external magnetic field. The lighter ion gyrates several times for the given magnetic field whereas the heavier ion cannot finish one gyration. Zou et al. studied the plasma sheath structure in an oblique magnetic field using fluid model [12]. It is found that the oblique magnetic field has significant effect on the plasma parameters. Due to the magnetic field, the ion flow velocity made helical path and the Lorentz force speeds them up. Khoramabadi et al. investigated numerically the ion temperature effects on magnetized DC plasma sheath [13]. They found that the ion temperature affects the positive space charge and the ion energy, decreases the sheath thickness, and hence also the ion flux toward the wall. By using KTS model Chalise and Khanal observed the plasma sheath region in an oblique magnetic field [14, 15]. They found that in presence of the magnetic field the plasma-wall transition has two clear regions i.e. magnetic field dependent region and electric field dependent region where the magnetic field and the electric fields, respectively, are dominant. Basnet et al. studied sheath properties in the presence of non-Maxwellian electrons in case of electronegative magnetized plasma [5]. They were able to extend the Bohm condition for the electronegative magnetized plasma. The effect of ion-neutral collisions and the obliqueness of the magnetic field was presented and found that the wall potential and hence the ion velocity increased towards the wall. Basnet et al. studied the effect of presheath electron temperature on tungsten wall sputtering in case of plasma having two species of positive ions [7]. They concluded that the angle of incidence at the wall and its sputtering rate is highly affected by electron temperature at the presheath-sheath boundary. Adhikari et al. presented the variation of velocity of ions in a magnetized plasma sheath with varying magnetic field [16]. It has been found that the mean value and frequency of oscillation changes with the magnetic field. The maximum amplitude of normal component of velocity is almost independent of the magnetic field but the maximum amplitude of other component of velocity change and shows oscillating nature as the magnetic field changes.

In all cases, it is well established that the sheath parameters fluctuate and ultimately reach a steady state, however, in most cases only the final velocity profiles are studied and analyzed. As the evolution of ion velocities can provide better understanding of the sheath formation; as an extension of our earlier work [17]; in this work we have studied the temporal ion velocity variation in plasma sheath with obliqueness of an external magnetic field which has crucial role in all plasma applications where magnetic field is present.

2. METHODS AND MODEL

The plasma consists of positive hydrogen ions and electrons bounded by two parallel planes at x = 0 and $x = L$ as shown in Fig. 1. The left hand boundary, x = 0 is the sheath entrance, i.e., the plasma side whereas the right hand boundary $x = L$ represents the material wall, which is considered to be non-emitting. The magnetic field $\vec{B}$ acts on the y-z plane that makes an angle θ with the negative z-direction.

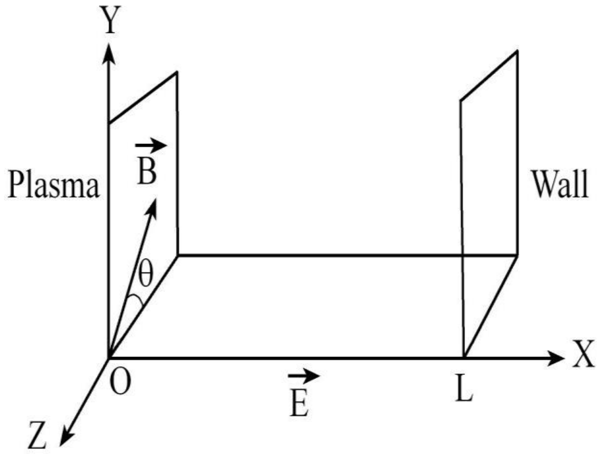

Fig. 1: Schematic geometry of plasma sheath model.

The force equation is the Lorentz force equation

$$m_i \frac{d\vec{v}_i}{dt} = q\left[-\vec{x}\frac{\partial \phi}{\partial x} + \left(\vec{v}_i \times \vec{B}\right)\right] \ldots (1)$$

where q, m_i, $\vec{v}_i$ and ϕ are the charge, mass, velocity of ions and potential, respectively.

The resultant velocity (vector sum) of the oscillating parts of the velocity is written as

$$v_0 = \left[\left(v_x - v_{xm}\right)^2 + \left(v_y - v_{ym}\right)^2 + \left(v_z - v_{zm}\right)^2\right]^{0.5} \ldots (2)$$

where v_{xm}, v_{ym} and v_{zm} are the mean value of oscillating parts of velocity.

The equation of fitted curve is

$$v = v_0 \exp\left(-\frac{t}{\tau}\right) \ldots (3)$$

where τ is the characteristics time is written as

$$\tau = t_1 + \frac{v_1 - v}{v_1 - v_2}\Delta t \ldots (4)$$

with v_1 and v_2 are the resultant velocity at time t_1 and t_2, respectively, and Δt is the time interval.

The equation of the damped harmonic oscillator is written as [18]

$$v(t) = v_m + Ae^{-kt}\sin(\omega t + \alpha) \; ... \; (5)$$

where, k, A and α are damping constant, amplitude and phase angle, respectively.

The damping constant is written as [18]

$$k = \frac{\ln\left(\frac{v_1 - v_m}{v_2 - v_m}\right)}{t_2 - t_1} \; ... \; (6)$$

The ion acoustic velocity for ion species is

$$c_s = (k_B T_e / m_i)^{0.5} \; ... \; (7)$$

in which k_B and T_e are the Boltzmann constant and electron temperature, respectively.

The quasineutral condition for this plasma is

$$n_{i0} = n_{e0} \; ... \; (8)$$

At the sheath edge (x = 0), the potential $\phi(x=0)=0$ but to prevent the divergence of simulating result, the value of electric field is $\partial\phi(x=0)/\partial x = 0.01$. In order to satisfy Bohm criterion, the boundary values of velocity is $v_{i0} = (c_s, c_s, c_s)$. The compiled governing equations (1)-(6) are solved numerically for varying obliqueness of constant uniform magnetic field B = 3 mT, electron temperature T_e = 1 eV and electron density n_{0e} = 10^8 cm^{-3} in consistent with earlier works [16, 17].

3. RESULTS AND DISCUSSION

The temporal variation of ion velocity for the obliqueness of $\theta = 30^0$ is shown in Fig. 2. The oscillation of ion velocity decreases as time evolves because of loss of energy of ions. The mean value of x, y and z-components of the velocity are found to be 2.54 m/s, 6.62×10^3 m/s and 1.16×10^4 m/s, respectively. The vector sum of all three oscillating components of velocity at the sheath entrance is 10.46×10^3 m/s. Thus, the equation of fitted curve can be written as $v = 10.46\times10^3 e^{-t/0.14}$ m/s. The computed plot and fitted plots exactly match as shown in Fig. 3. The damping constants and frequency of oscillation for each oscillating components are the almost same as shown in Table 1.

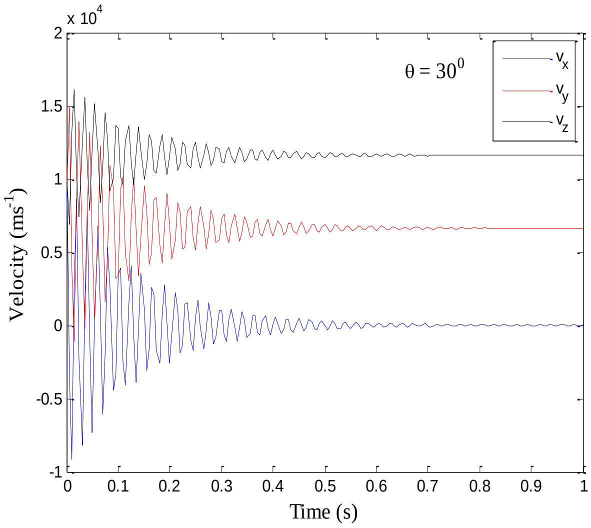

Fig. 2: Oscillation of velocity components (v_x, v_y & v_z) at constant uniform magnetic field B = 3 mT and obliqueness $\theta = 30^0$.

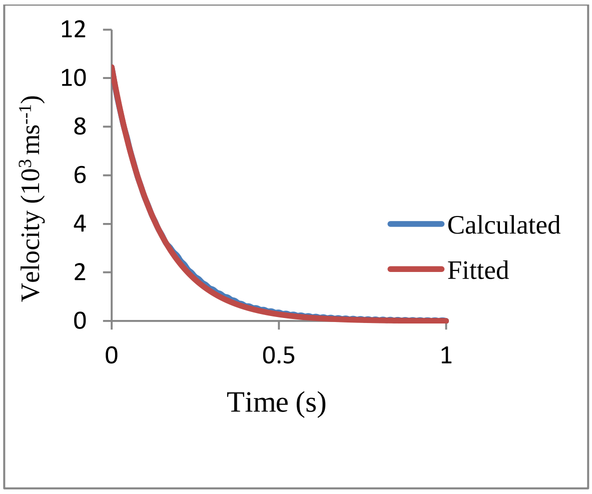

Fig. 3: Fitting of oscillating part of total velocity at constant uniform magnetic field B = 3 mT and obliqueness $\theta = 30^0$.

Table 1: The observed value of damping constants and frequency of oscillation for obliqueness 30^0.

Angle	Damping constant (k, s^{-1})			Frequency of oscillation (Hz)		
	v_x	v_y	v_z	v_x	v_y	v_z
30^0	6.78	6.90	6.82	46.51	45.45	46.51

The oscillation of velocity profile for the obliqueness $\theta = 60^0$ is shown in Fig. 4. The resultant of *x*, *y* and *z*-components of initial velocity is 10.41×10^3 m/s with their mean values are -7.35 m/s, 1.16×10^4 m/s and 6.76×10^3 m/s, respectively. For this configuration of magnetic field, the equation of fitted curve is written as $v = 10.41\times10^3\, e^{-t/0.14}$ m/s and the comparison of computed and fitted plots is shown in Fig. 5. The damping constants and frequency of oscillation for each oscillating components are shown in Table 2.

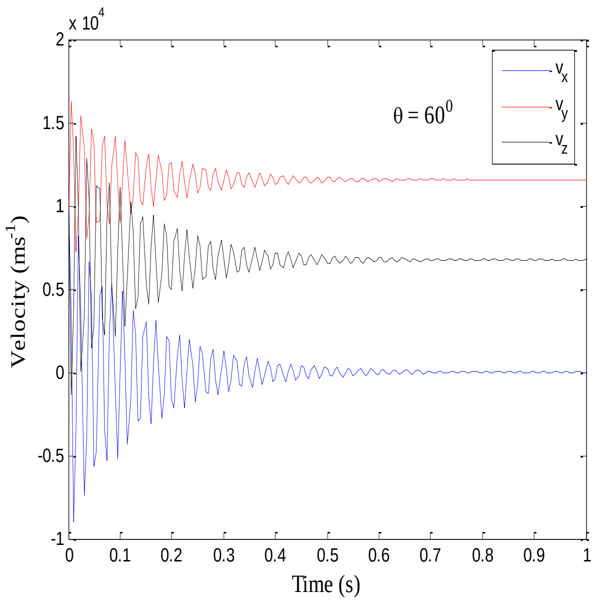

Fig. 4: Oscillation of velocity components (v_x, v_y & v_z) at constant uniform magnetic field B = 3 mT and obliqueness $\theta = 60^0$.

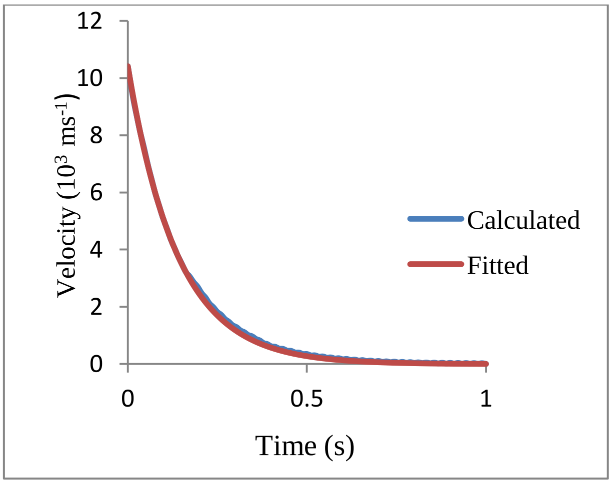

Fig. 5: Fitting of oscillating part of total velocity at constant uniform magnetic field B = 3 mT and obliqueness $\theta = 60^0$.

Table 2: The observed value of damping constants and frequency of oscillation for obliqueness 60^0.

Angle	Damping constant (k, s^{-1})			Frequency of oscillation (Hz)		
	v_x	v_y	v_z	v_x	v_y	v_z
60^0	6.92	6.74	6.67	46.51	46.51	46.51

In case of magnetic field parallel to the wall, i.e., when the obliqueness is $\theta = 90^0$ the temporal velocity variation is shown in Fig. 6. The mean values of *x*, *y* and *z*- components are -2.18 m/s, 9.79 $\times10^3$ m/s and 71.95 m/s, respectively. It is found that the resultant of three components of initial velocity is 13.80×10^3 m/s and the equation of fitted curve is $v = 13.80\times10^3\, e^{-t/0.14}$ m/s. In this magnetic configuration, the computed and fitted plot is shown in Fig. 7. The observed value of damping constants and frequency of oscillation are shown in Table 3.

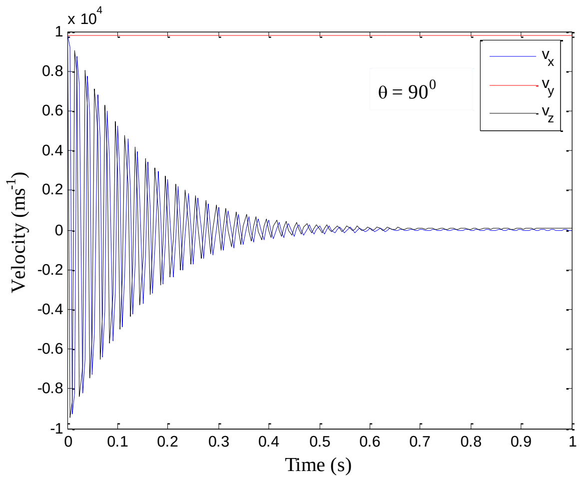

Fig. 6: Oscillation of velocity components (v_x, v_y & v_z) at constant uniform magnetic field B = 3 mT and obliqueness $\theta = 90^0$.

Table 3: The observed value of damping constants and frequency of oscillation for obliqueness 90^0.

Angle	Damping constant	Frequency of oscillation

	(k, s^{-1})			(Hz)		
90^0	v_x	v_y	v_z	v_x	v_y	v_z
	7.18	0.00	6.89	50.00	40.00	50.00

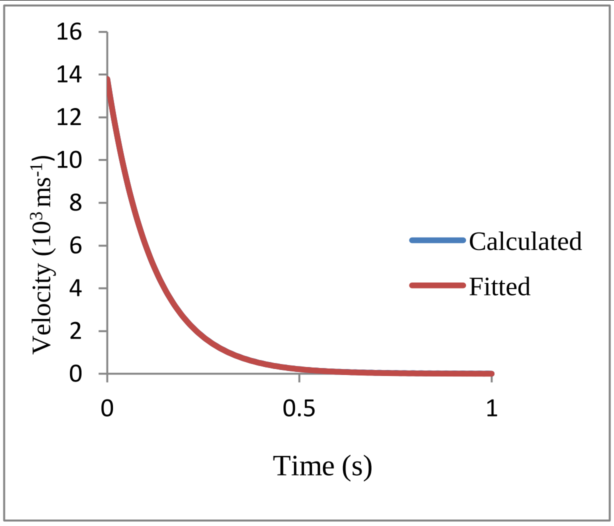

Fig. 7: Fitting of oscillating part of total velocity at constant uniform magnetic field B = 3 mT and obliqueness $\theta = 90^0$.

For comparison, the overall temporal variation of the oscillating part of ion velocity at constant uniform magnetic field B = 3 mT with the three different obliqueness is shown in Fig. 8.

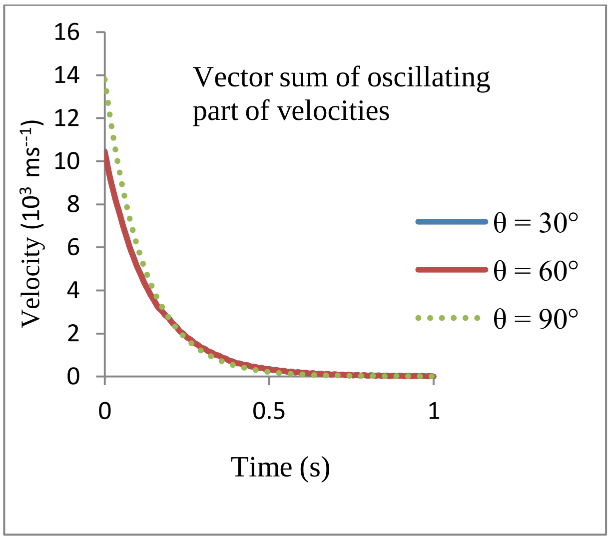

Fig. 8: Overall variation of vector sum of oscillating part of resultant velocity at constant uniform magnetic field B = 3 mT with different obliqueness.

4. CONCLUSION

The temporal ion velocity variation in magnetized plasma sheath for uniform magnetic field and three different obliqueness were studied numerically using fluid model. It is found that the velocity variations of ions as well as damping constants are affected by obliqueness of the magnetic field. The characteristics time for resultant oscillating velocity is found to be 0.14 second. The frequencies of oscillations are almost constant for the obliqueness of 30^0 and 60^0 whereas its value increases for the obliqueness of 90^0 (i.e. when the magnetic field is parallel to the wall). The computed and fitted curves are matching for the all cases of magnetic configuration. The vector sum of oscillating part of velocities at the sheath entrance for the magnetic field parallel (i.e. obliqueness is 90^0) to the wall is greater than in the other cases (i.e. 30^0 and 60^0). As there are only a few studies focusing in analyzing the time evolution of ion velocities in presence of an external magnetic this work is of importance for all plasma applications where magnetic field plays a role, like helicon plasmas, magnetic fusion devices (tokamaks, stellerators, etc.), astrophysical plasmas.

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