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Study of shock velocity and shock strength of oblique shock wave in rotating medium: The theory of earthquake

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The CCW method has been used to study the propagation of strong spherical diverging oblique shock in rotating medium. Assuming the initial density distribution region Law as $\rho_0 = \rho' r^{-\omega}$, where ρ' is the density at center and ω is density parameter taken as constant, the expressions for shock velocity and shock strength have been obtained. The effect of propagation distance, adiabatic heat index, wedge angle, density parameter and angular velocity on shock velocity and shock strength have been discussed through tables and figures.

Introduction

An earthquake is a sudden vibration or trembling in the earth. Earthquake motion is caused by the quick release of strong potential energy into kinetic energy of motion. Earthquake generates oblique strong spherical shock waves. The study of strong spherical oblique shock in non-uniform rotating medium is of interest to many researchers.

The study of propagation of oblique shock waves is immense important for production of very high pressure and other flow variables. Using several approximate techniques. Many authors Chaturani [4], Kumar [10], Yadav [23] tackle the propagation of diversing shock waves through a rotating gas have been studied. The motion of converging cylindrical and spherical shock waves in perfect gas with constant specific heats has been studied by Stanyukovich [18] using similarly method. The propagation of spherical converging shock in various metals has been studied by Yadav and Singh [32] by Whitham method. Yadav et al. [25] have studied the propagation of spherical converging strong shock in uniform medium by CCW method. Afraimovich, E.L. et al. [1] studied the shock acoustic waves generated by earthquakes. It was found that in spite of the difference of earthquake characteristics, the local time, the season, and the level of geomagnetic disturbance, for the four earthquake, the time period of the ionsophere response is 180-390s and the amplitude exceeds, by a factor of two as a minimum, the standard vibration of back ground fluctuations in total electron content in this range of periods under quite and moderate geomagnetic conditions. Wu, Y.K. et al. [22] studied the propagation characteristic of blast-induced shock waves in a jointed rock mass. And he conclude that the amplitude and principal frequency of shock attenuate with increase of distance from the charge centre and the increase of incident angle between the joint strike and the wave propagation path.

Recently Singh [17] has co-related the shock wave with earthquake and obtained the variation of normal shock in the medium having asymptotically varying density region.

In the present paper the propagation of strong spherical oblique shock wave through asymptotically varying density medium has been studied by Chisnell-Chester-Whitham method. The medium becomes inhomogeneous on account of solid body rotation. Assuming an initial density distribution law as $\rho_0 = \rho' r^{-\omega}$, where ρ' is the density at center and ω is a constant. The analytical relations for shock velocity and shock strength for freely propagation and in the influence of overtaking disturbances are obtained. The variation of shock velocity and shock strength with propagation distance (r), adiabatic heat index (γ), wedge angle (β), density parameter (ω) and angular velocity (Ω_0) have been discussed through tables and figures.

Finally the results obtained here are compared with Singh [17].

Basic Equations and Boundary Conditions

Under the assumption that the gas is in viscid and non-conducting of heat the basic equations governing the spherically symmetrical flow enclosed by the shock front are

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial r}+\frac{1}{\rho}\frac{\partial p}{\partial r}-\frac{v^2}{r}=0 \quad (1)$$

$$\left(\frac{\partial}{\partial t}+u\frac{\partial}{\partial r}\right)\rho+\rho\left(\frac{\partial u}{\partial r}+\frac{2u}{r}\right)=0 \quad (2)$$

$$\left(\frac{\partial}{\partial t}+u\frac{\partial}{\partial r}\right)pp^{-\gamma}=0 \quad (3)$$

$$\left(\frac{\partial}{\partial t}+u\frac{\partial}{\partial r}\right)(vr)=0 \quad (4)$$

where u and v are the redial and azimuthal components of the particle velocity, p, r and g are respectively, the pressure, density and adiabatic index of medium. The boundary conditions for strong oblique shock are

$$p=\frac{2\rho_0 U^2\sin^2\beta}{\gamma+1} \quad (5)$$

$$\rho=\frac{\gamma+1}{\gamma-1}\rho_0 \quad (6)$$

$$u=\frac{2U\sin\beta}{\gamma+1};a=sU\sin\beta\frac{\gamma-1}{\gamma+1} \quad (7)$$

$$s=\sqrt{2\gamma/(\gamma-1)} \quad (8)$$

Where, u (r,t), p (r,t) and r (r,t) denote particle velocity, the pressure and density region respectively at a distance are from the origin at time t and γ is adiabatic heat index of the medium. And p_0, ρ_0, denotes undisturbed values of pressure and density in front of the shock, U be the shock velocity and a_0 is velocity of sound in undisturbed medium.

Here 0 is used for the state immediately ahead of the oblique shock.

3. Theory

Using basic equations we get characteristic equation for C_+ disturbances given as

$$dp+\rho a du+\frac{2\rho a^2 u}{(u+a)}\frac{dr}{r}-\frac{\rho a v^2}{(u+a)r}\frac{dr}{r}=0 \quad (9)$$

And the characteristic equation for C_- disturbances is given by

$$dp-\rho a du+\frac{2\rho a^2 u}{(u-a)}\frac{dr}{r}+\frac{\rho a v^2}{(u-a)r}\frac{dr}{r}=0 \quad (10)$$

Using boundary in equation (9) and simplifying, we get

$$dU^2+\frac{2U^2}{2+s}\left[\frac{4\gamma}{\{2+s(\gamma-1)\}}\frac{dr}{r}+\frac{d\rho_0}{\rho_0}\right]=\frac{s(\gamma+1)^2 r^2\Omega_0^2}{(2+s)\{2+s(\gamma-1)\}\sin^2\beta}\frac{dr}{r} \quad (11)$$

In this case it is assumed that the density of medium varies asymptotically in which strong spherical oblique shock propagates. We have asymptotic density distribution.

$$\rho_0 = \rho' r^{-\omega} \tag{12}$$

$$d\rho_0 = -\omega\rho' r^{-\omega-1} \text{ than } \frac{d\rho_0}{\rho_0} = -\frac{\omega}{r}dr \tag{13}$$

3 (a) Freely Propagation of Spherical Shock in Rotating Medium

For freely propagation considering C_+ disturbances and using equation (13 and 11), we get

$$dU^2 + \frac{2}{2+s}\left[\frac{4\gamma}{\{2+s(\gamma-1)\}} - w\right]U^2\frac{dr}{r} = \frac{S(\gamma+1)^2 r\Omega_0^2}{(2+s)\{2+s(\gamma-1)\}\sin^2\beta}dr \tag{14}$$

$$\frac{dU^2}{dr} + \frac{A}{r}U^2 = \frac{Br\Omega_0^2}{\sin^2\beta} \tag{15}$$

where $A = \frac{2}{2+s}\left[\frac{4\gamma}{2+s(\gamma-1)} - \omega\right]$, $B = \frac{s(\gamma+1)^2}{(2+s)\{2+s(\gamma-1)\}}$

And

On solving equation (15), we get the expression for shock velocity for strong spherical oblique shock propagating freely in the medium having density distribution $\rho_0 = \rho' r^{-\omega}$

$$U = \left[K' r^{-A} + \frac{\Omega_0^2 r^2 B}{\sin^2\beta(A+2)}\right]^{1/2} \tag{16}$$

Where K' is constant of integration

The equilibrium state of the medium is assumed to be specified by the condition $\partial/\partial t = 0 = u$ and $v_0 = r\Omega_0$ where Ω_0 is the initial angular velocity of rotating medium. Consequently, the equilibrium condition prevailing in front of the shock can be written as

$$\partial p_0 = \rho' r^{1-\omega}\Omega_0^2 dr \tag{17}$$

Integrating

$$p_0 = \rho'\Omega_0^2 \frac{r^{2-\omega}}{2-\omega} \tag{18}$$

Where constant of integration taken to be zero

$$a_0 = \Omega_0 r\sqrt{\frac{\gamma}{2-\omega}} \tag{19}$$

And

from equation (16) and (19) following expressions are obtained for freely propagating strong spherical oblique shock in asymptotically varying density region.

Then shock strength

$$\frac{U}{a_0} = \left[\frac{2-\omega}{\gamma}\left\{Kr^{-(A+2)}\Omega_0^{-2} + \frac{B}{(A+2)\sin^2\beta}\right\}\right]^{1/2} \tag{20}$$

non-dimensional particle velocity

$$\frac{u}{a_0} = \left[\frac{4(2-\omega)}{\gamma(\gamma+1)^2}\left\{Kr^{-(A+2)}\Omega_0^{-2}\sin^2\beta + \frac{B}{(A+2)}\right\}\right]^{1/2} \quad (21)$$

non-dimensional pressure is

$$\frac{p}{\rho_0} = \frac{2\gamma\sin^2\beta}{\gamma+1}\left[\frac{2-\omega}{\gamma}\left\{Kr^{-(A+2)}\Omega_0^{-2} + \frac{B}{(A+2)\sin^2\beta}\right\}\right] \quad (22)$$

And non-dimensional density

$$\frac{\rho}{\rho'} = \left(\frac{\gamma+1}{\gamma-1}\right)r^{-\omega}$$

For the C_+ disturbance generated by the shock, the fluid velocity increment, is obtained by using equation

$$du_+ = \frac{2U\sin B}{\gamma+1}\left[\frac{Br^2\Omega_0^2}{2U^2\sin^2\beta} - \frac{A}{2}\right]\frac{dr}{r} \quad (23)$$

3(b) Propagation of strong spherical oblique shock under the influence of overtaking disturbances

The characteristic equation for C_ disturbances is given by

$$dp - \rho a du + \frac{2\rho a^2 u}{(u-a)}\frac{dr}{r} + \frac{\rho a v^2}{(u-a)}\frac{dr}{r} = 0 \quad (24)$$

In order estimate strength of overtaking disturbances using boundary conditions and simplifying, we get

$$dU^2 + \frac{2U^2}{(2-s)}\left[\frac{4\gamma}{\{2-s(\gamma-1)\}}\frac{dr}{r} + \frac{d\rho_0}{\rho_0}\right] = -\frac{s(\gamma+1)^2 r^2\Omega_0^2}{(2-s)\{2-s(\gamma-1)\}\sin^2\beta}\frac{dr}{r} \quad (25)$$

Using equation (13) and simplifying, we get

$$dU^2 + \frac{2U^2}{(2-s)}\left[\frac{4\gamma}{\{2-s(\gamma-1)\}} - \omega\right]U^2\frac{dr}{r} = -\frac{s(\gamma+1)^2 r^2\Omega_0^2}{(2-s)\{2-s(\gamma-1)\sin^2\beta\}}\frac{dr}{r} \quad (26)$$

This equation can we written is

$$\frac{dU^2}{dr} + \frac{A'}{r}U^2 = \frac{B' r\Omega_0^2}{\sin^2\beta} \quad (27)$$

Where

$$A' = \frac{2}{2-s}\left[\frac{4\gamma}{\{2-s(\gamma-1)\}} - \omega\right], \quad B' = -\frac{s(\gamma+1)^2}{(2-s)\{2-s(\gamma-1)\}} \quad (28)$$

Then for C_- disturbance generated by shock the fluid velocity increment is given by

$$du\_ = \frac{2U\sin\beta}{\gamma+1}\left[\frac{B' r^2\Omega_0^2}{2U^2\sin^2\beta} - \frac{A'}{2}\right]\frac{dr}{r} \quad (29)$$

In presence of C_+ and C_- that is the effect of overtaking disturbances the resultant fluid velocity increment is given by

$du_+ + du_- = du^*$

$$du_+ + du_- = \frac{2\sin\beta}{\gamma+1}dU^* \quad (30)$$

Using values from equations (23) and (29), we get

$$\frac{2U^{*}\sin\beta}{\gamma+1}\left[\frac{Br^{2}\Omega_0^2}{2U^{*2}\sin^2\beta}-\frac{A}{2}\right]\frac{dr}{r}+\frac{2U^{*}\sin\beta}{\gamma+1}\left[\frac{B'r^{2}\Omega_0^2}{2U^{*2}\sin^2\beta}-\frac{A'}{2}\right]\frac{dr}{r}=\frac{2\sin\beta}{(\gamma+1)}dU^{*} \quad (31)$$

on simplying, we get

$$\frac{dU^{*2}}{dr}+\frac{D}{r}U^{*2}=\frac{Cr\Omega_0^2}{\sin^2\beta} \quad (32)$$

Where $C = B + B^{'}$ and $D = A + A^{'}$

Thus, we get

$$U^{*}=\left\{K^{'}r^{-D}+\frac{\Omega_0^2 r^2 C}{(D+2)\sin^2\beta}\right\}^{1/2} \quad (33)$$

This equation represents the shock velocity modified by overtaking disturbances, i.e. resultant shock velocity in presence of overtaking disturbances.
Using equation (19) and (33), we get the expression for-
The shock strength modified by overtaking disturbances is

$$\frac{U^{*}}{a_0}=\left[\frac{2-\omega}{\gamma}\left\{Kr^{-(D+2)}\Omega_0^{-2}+\frac{C}{(D+2)\sin\beta}\right\}\right]^{1/2} \quad (34)$$

Non-dimensional particle velocity modified by overtaking disturbances is

$$\frac{u^{*}}{a_0}=\left[\frac{4(2-\omega)}{\gamma(\gamma+1)^2}\left\{K^{'}r^{-(D+2)}\Omega_0^{-2}\sin^2\beta+\frac{C}{(D+2)}\right\}\right]^{1/2} \quad (35)$$

Non-dimensional pressure modified by overtaking disturbances is

$$\frac{p^{*}}{p_0}=\frac{2\gamma}{\gamma+1}\left[\frac{2-\omega}{\gamma}\left\{K'r^{-(D+2)}\Omega_0^{2}+\frac{C}{(D+2)\sin^2\beta}\right\}\sin^2\beta\right] \quad (36)$$

Result and Discussion:

Shock velocity and shock strength

Table 1 : Variation of shock velocity and shock strength with propagation distance when strong spherical oblique shock propagates in asymptotically varying density region (initially taken U/a_0=8 at r=2 and $\beta=20^0$ and ω=0.5, Ω_0=4 for γ=1.01)

Propagation distance	Shock velocity		Shock strength	
	Freely Propagation	With overtaking disturbances	Freely Propagation	With overtaking disturbances
r	U	U*	U/a_0	U^*/a_0
0.8	52.9589	52.6184	20.1685	20.0388
1.0	52.3421	54.1982	15.9469	16.5124
1.2	52.0066	55.8607	13.2039	14.1824
1.4	51.8889	57.6242	11.2920	12.5401
1.6	51.9506	59.4948	9.89226	11.3288
1.8	52.1659	61.4724	8.82956	10.4048
2.0	52.5164	63.5533	8.00000	9.68128
2.2	52.9879	65.7321	7.33803	9.10290
2.4	53.5690	68.0027	6.80029	8.63256
2.6	54.2500	70.3585	6.35699	8.24457

Table (1) shows the variation of shock velocity and shock strength with propagation distance. It is found that shock velocity initially decreases and becomes minimum for a particular value of propagation distance than further increases with propagation distance for freely propagation whereas with in inclusion of overtaking disturbances shock velocity increases with propagation distance. The value of shock velocity decreases from 52.9589 to 51.8889 for freely propagation when propagation distance increase increases upto 1.4 and become minimum, if further propagation distance increases then shock velocity increases upto maximum value 54.2500, however shock velocity increases from 52.6184 to 17.3585 with the effect of overtaking disturbances as shock moves from distance 0.8 to 2.6. Theses variations are shown in figure 1.

The shock strength decreases from 12.1685 to 6.35699 for freely propagation and decreases from 20.0388 to 8.24457 with the effect of overtaking disturbances. And it is also observed that for each particular value of propagation distance the shock strength for overtaking disturbances is greater than shock strength for freely propagation. These variations are also confirmed from figure (2).

Table-2 : Variation of shock velocity and shock strength with adiabatic heat index when strong spherical oblique shock propagates in asymptotically varying density region (initially taken U/a_0 =8 at r = 2 and β =20^0 and ω= 0.5, Ω_0=4 for γ=1.01).

Adiabatic heat index	Shock velocity		Shock strength	
	Freely Propagation	With overtaking disturbances	Freely Propagation	With overtaking disturbances
γ	U	U*	U/a_0	U^*/a_0
1.01	52.5164	63.5533	8.0000	9.68128
1.02	51.3610	66.3071	7.78555	10.0511
1.03	50.5984	69.3896	7.63262	10.4672
1.04	50.0234	72.8638	7.50952	10.9383
1.05	49.5604	76.8143	7.40450	11.4763
1.06	49.1724	81.3592	7.31179	12.0979
1.07	48.8381	86.6736	7.22807	12.8277
1.08	48.5442	93.0381	7.15124	13.7058
1.09	48.2820	100.9530	7.07991	14.8034
1.10	48.0452	111.4550	7.01308	16.2689

Table (2) represents the variation of shock velocity and shock strength with adiabatic heat index. It is found that the shock velocity decreases for freely propagation whereas with the inclusion of overtaking disturbances it increases as adiabatic heat index increases from 1.01 to 1.10. The shock velocity decreases from 52.5164 to 48.0452 for freely propagation and increases from 63.5533 to 111.4550 with the effect of overtaking disturbances. The decreases in shock velocity for freely propagation is very small in comparison to increase in shock velocity for overtaking disturbance. These variation are represented in figure (3).

The shock strength decreases for freely propagation where as it increases with overtaking disturbances as adiabatic heat index increases from 1.01 to 1.10. Shock strength decreases from 8.0000 to 7.01300 for freely propagation and increases from 9.68128 to 16.2689, with inclusion of overtaking disturbances. These variations are represented in figure (4).

Table-3 : Variation of shock velocity and shock strength with wedge angle when strong spherical oblique shock propagates in asymptotically varying density region (initially taken U/a_0 =8 at r = 2 and β =20^0 and ω= 0.5, Ω_0=4 for γ=1.01).

Wedge angle	Shock velocity		Shock strength	
	Freely Propagation	With overtaking disturbances	Freely Propagation	With overtaking disturbances
β^0	U	U*	U/a_0	U^*/a_0
10	62.9201	86.7043	9.58483	13.2080
20	52.5164	63.5533	8.0000	9.68128
30	50.3592	58.2769	7.67138	8.87751
40	49.5880	56.3289	7.55390	8.58076
50	49.2344	55.4231	7.50003	8.44279
60	49.0503	54.9483	7.47199	8.37046
70	48.9502	54.6893	7.45675	8.33100
80	48.8996	54.5579	7.44904	8.31099
90	48.8840	54.5173	7.44666	8.30481

Table (3) shows the variation of shock velocity and shock strength with wedge angle. It is found that shock velocity and shock strength decreases (for both freely propagation as well as with the inclusion of overtaking disturbances) as the wedge increase from 10^0 to 90^0. The shock velocity decreases from 62.9201 to 48.8840 for freely propagation and it decreases from 86.7043 to 54.5173 with overtaking disturbances. These variations are represented in figure (5).

The shock strength decreases from 9.58483 to 7.44666 for freely propagation and it decreases from 13.2080 to 8.30481 with overtaking disturbances. Theses variations are represented in figure (6).

Table-4 : Variation of shock velocity and shock strength with density parameter when strong spherical oblique shock propagates in asymptotically varying density region (initially taken U/a_0 =8 at r = 2 and β =20^0 and ω= 0.5, Ω_0=4 for γ=1.01).

Density parameter	Shock velocity		Shock strength	
	Freely Propagation	With overtaking disturbances	Freely Propagation	With overtaking disturbances
ω	U	U*	U/a_0	U^*/a_0
0.5	52.5164	63.5533	8.0000	9.68128
0.6	52.7301	63.4707	7.76018	9.34086
0.7	52.9447	63.3884	7.50834	8.98940
0.8	53.1604	63.3061	7.24317	8.62553
0.9	53.3772	63.2240	6.96308	8.24760
1.0	53.5950	63.1421	6.66613	7.85359
1.1	53.8138	63.0603	6.34986	7.44092
1.2	54.0337	62.9787	6.01117	7.00629
1.3	54.2547	62.8972	5.64593	6.54530
1.4	54.4767	62.8159	5.24851	6.05194

Table (4) represents the variation of shock velocity and shock strength with density parameter for freely propagating shock as well as for overtaking disturbances when shock propagation in asymptotically varying density region. It is found that freely propagation shock velocity increases for freely propagation where as it decreases with effect of overtaking disturbances as density parameter increases from 0.5 to 1.4. The shock velocity increases slowly from 52.5164 to 54.7467 for freely propagation and decreases very slowly from 63.5533 to 62.8159 with overtaking disturbances. These results are also confirmed figure (7). The shock strength decreases with density parameter for freely propagation shock as well as with the inclusion of overtaking disturbances. The shock strength decreases from 8.0000 to 5.24851 for freely propagation and decreases from 9.68128 to 6.05194 with the inclusion of overtaking disturbances for same values of density parameter as in shock velocity. These results are also confirmed figure (8).

Table-5 : Variation of shock velocity and shock strength with angular velocity when strong spherical oblique shock propagates in asymptotically varying density region (initially taken U/a_0 =8 at r = 2 and β =20^0 and ω= 0.5, Ω_0=4 for γ=1.01).

Angular velocity	Shock velocity		Shock strength	
	Freely Propagation	With overtaking disturbances	Freely Propagation	With overtaking disturbances
Ω_0	U	U*	U/a_0	U^*/a_0
1	48.6515	53.9116	29.6450	32.8502
2	49.4487	55.9730	15.0654	17.0531
3	50.7494	59.2494	10.3078	12.0342
4	52.5164	63.5533	8.0000	9.68128
5	54.7045	68.6917	6.66665	8.37123
6	57.2653	74.4922	5.81561	7.56510
7	60.1514	80.8124	5.23603	7.03453
8	63.3182	87.5397	4.82274	6.66761
9	66.7258	94.5873	4.51759	6.40391
10	70.3392	101.8890	4.28600	6.20843

Table (5) shows the variation of shock velocity and shock strength with angular velocity for freely propagation as well as with the inclusion of overtaking disturbances when strong spherical oblique shock propagates in asymptotically varying density region. It is found that the shock velocity increases with angular velocity for both the freely propagation as well as with the inclusion of overtaking disturbances. As angular velocity increases from 1 to 10 the shock velocity increases from 48.6515 to 70.339 and from 53.9116 to 101.8890 for freely propagation as well as with the inclusion of overtaking disturbances respectively. Thus from above discussion it is clear that effect of overtaking disturbances produces considerable effect. These results are also confirmed figure (9).

The shock strength decreases with angular velocity for freely propagation as well as with the inclusion of overtaking disturbances. The shock strength decreases from 29.6450 to 4.2860 and from 32.8502 to 6.20843 for freely propagation as well as with the inclusion of overtaking disturbances respectively. These variations are also represented in figure (10)

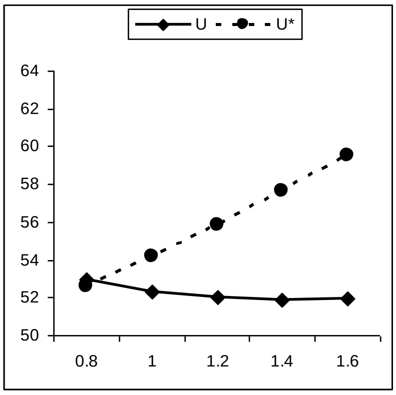

Fig.1: Shock velocity U and U^* v/s propagation distance (r).

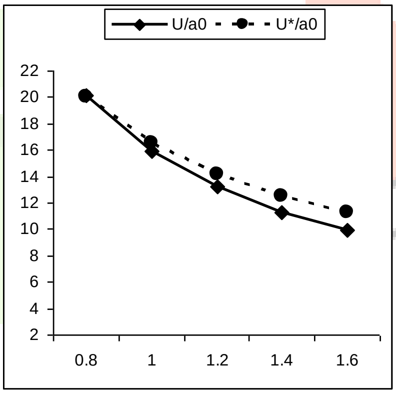

Fig.2: Shock velocity U/a_0 and U^*/a_0 v/s propagation distance (r).

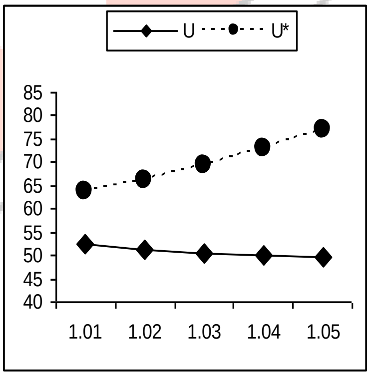

Fig.3: Shock velocity U and U^* v/s adiabatic heat (γ).

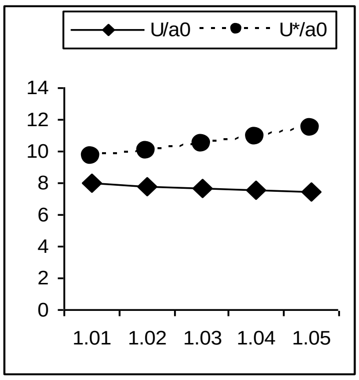

Fig.4: Shock strength U/a_0 and U^*/a_0 v/s adiabatic heat (γ).

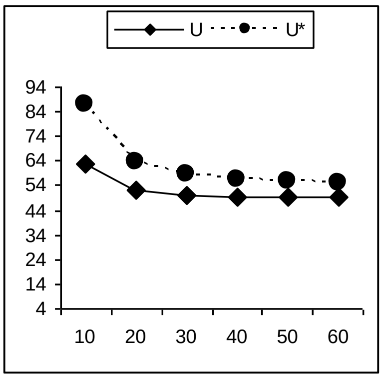

Fig.5: Shock velocity U and U^* v/s wedge angle (β^0).

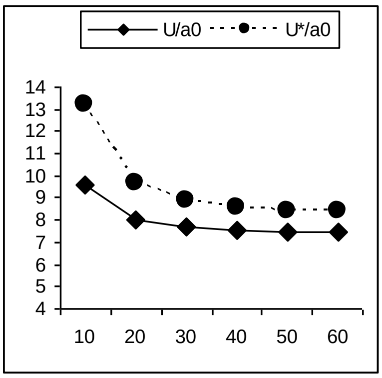

Fig.6: Shock velocity U/a_0 and U^*/a_0 v/s wedge angle (β^0).

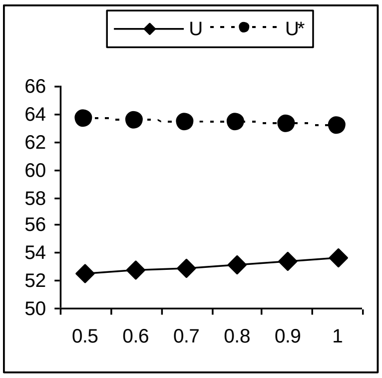

Fig.7: Shock velocity U and U^* v/s density parameter (ω).

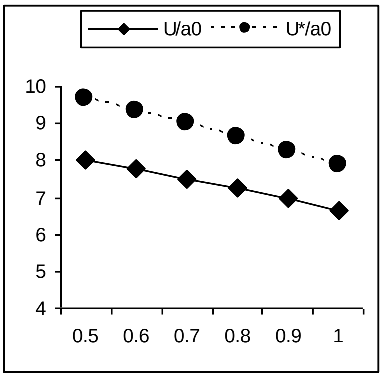

Fig.8: Shock strength U/a_0 and U^*/a_0 v/s density parameter (ω).

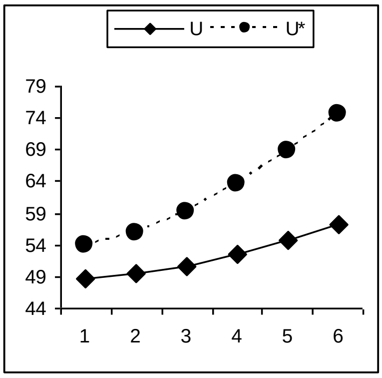

Fig.9: Shock velocity U and U^* v/s angular velocity (Ω_0).

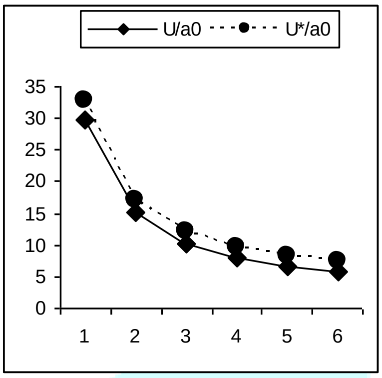

Fig.10: Shock strength U/a_0 and U^*/a_0v/s angular velocity (Ω_0).

Conclusion

Thus in rotating medium, in case of uniform medium the effect of wedge angle does not seems directly on the shock velocity and shock strength but it contribute significantly on flow variable. If wedge angle becomes 90^0 the results obtained in uniform medium for freely propagation as well as with the inclusion of overtaking disturbances are same as that for normal shock hence in this situation results are resembles with those obtained by Singh[17]. However in the present paper shock velocity and shock strength (strength of earthquake) are strongly affected with the variation of wedge angle for freely propagation as well as with the inclusion of overtaking disturbances, when strong spherical diverging oblique shock propagation in asymptotically varying density region.

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