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An Oscillatory Free Convective Flow Through Porous Medium in a Rotating Vertical Porous Channel

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K.D.Singh[α] & Alphonsa Mathew[σ]

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I. Introduction

Free convection flows in a rotating porous medium are of great interest in a number of industrial applications such as fiber and granular insulation, geothermal systems etc. Buoyancy is also of importance in an environment where difference of temperatures can give rise to complicated flow patterns. In recent years, the problems of free convection have attracted the attention of a large number of scholars due to its diverse applications.

The flow of fluids through highly porous medium bounded by vertical porous plates find numerous engineering and geophysical applications, viz. in the fields of agricultural engineering to study the underground water resources, in petroleum technology to study the movement of natural gas, oil and water through the oil channels/reservoirs[1,2,10]. A series of investigations have been made by different scholars where the porous medium is either bounded by horizontal, vertical surfaces or parallel porous plates. Raptis [8] analyzed the unsteady flow through a porous medium bounded by an infinite porous plate subjected to a constant suction and variable temperature. Raptis and Perdikis [9] further studied the problem of free convective flow through a porous medium bounded by a vertical porous plate with constant suction when the free stream velocity oscillates in time about a constant mean value.

Apart from the above two dimensional studies a number of three dimensional flows through porous medium have also been studied. Singh *et al.* [16] analyzed the effects of periodic permeability on the three dimensional flow through highly porous medium bounded by an infinite porous surface. Singh *et al.* [15] also investigated the effect of permeability variation on the heat transfer and three dimensional flow through a highly porous medium bounded by an infinite porous plate with constant suction. Singh and Verma [13] studied further the flow of a viscous incompressible fluid through porous medium when the free stream velocity oscillates in time about a non-zero constant mean.

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In the recent years a number of studies have appeared in the literature involving rotation to a greater or lesser extent viz. Vidyanidhu and Nigam [19], Gupta [4], Jana and Datta [5], Singh [11,17]. Injection/suction effects have also been studied extensively for horizontal porous plate in rotating frame of references by Ganapathy [3], Mazumder [7], Mazumder *et al.* [6], Soundalgekar and Pop [18], Singh [12] for different physical situation. The flows of fluids through porous medium bounded by rotating porous channels find many industrial applications particularly in the fields of centrifugation, filtration and purification processes. In view of these applications Singh and Sharma [14] studied the effect of the permeability of the porous medium on the three dimensional Couette flow and heat transfer. In the present paper an attempt has been made to study the effects of the permeability of the porous medium and injection/suction through the porous parallel vertical plates on the free convective flow through a highly porous medium. The entire system rotates about an axis perpendicular to the planes of the plates.

II. Mathematical Analysis

Consider an oscillatory free convective flow of a viscous incompressible fluid through a highly porous medium bounded between two infinite vertical porous plates distance d apart. A constant injection velocity, w_0, is applied at the stationary plate $z^*=0$ and the same constant suction velocity, w_0, is applied at the plate $z^*=d$, which is oscillating in its own plane with a velocity $U^*(t^*)$ about a non-zero constant mean velocity U_0. The origin is assumed to be at the plate $z^*=0$ and the channel is oriented vertically upward along the x^*-axis. The channel rotates as a rigid body with uniform angular velocity Ω^* about the z^*-axis. Since the plates are infinite in extent, all the physical quantities except the pressure, depend only on z^* and t^*. Denoting the velocity components u^*, v^*, w^* in the x^*, y^*, z^* directions, respectively and temperature by T^*, the flow in the rotating system is governed by the following equations:

$$w_z^* = 0, \tag{1}$$

$$u_t^* + w_0^* u_z^* = -p_x^*/\rho + \upsilon u_{zz}^* + 2\Omega^* v^* + g\beta(T^* - T_d) - \upsilon u^*/\mathrm{K}^*, \tag{2}$$

$$v_t^* + w_0^* v_z^* = -p_y^*/\rho + \upsilon v_{zz}^* - 2\Omega^* u^* - \upsilon v^*/\mathrm{K}^* \tag{3}$$

$$T_t^* + w_0 T_z^* = \frac{k}{\rho C_p} T_{zz}^*, \tag{4}$$

where υ is the kinematic viscosity, t is the time, ρ is the density and p^* is the modified pressure, T^* is the temperature, C_p is the specific heat at constant pressure, k is the thermal conductivity, g is the acceleration due to gravity, β the coefficient of volume expansion and K^* is the permeability of the medium.

The boundary conditions for the problem are

$$\left.\begin{aligned} &u^* = v^* = 0, \quad T^* = T_0 + \varepsilon(T_0 - T_d)\cos\omega^* t^* && \text{at} \quad z^* = 0, \\ &u^* = U^*(t^*) = U_0(1 + \varepsilon\cos\,\omega^* t^*), \quad v^* = 0, \quad T^* = T_d, && \text{at} \quad z^* = d \end{aligned}\right\} \tag{5}$$

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11. Singh, K.D. (2000), An oscillatory hydromagnetic Couette flow in a rotating system, J. Appl. Math and Mech., **80**, 429-432.

Notes

where ω^* is the frequency of oscillations and ε is a very small positive constant. By introducing the following non-dimensional quantities

$\eta = z^*/d$, $t = \omega^* t^*$, $u = u^*/U_0$, $v = v^*/U_0$, $\Omega = \Omega^* d^2/\upsilon$ the rotation parameter, $\omega = \omega^* d^2/\upsilon$ the frequency parameter, $\lambda = w_0 d/\upsilon$ the injection/suction parameter, $\mathrm{K} = \mathrm{K}^*/d^2$ the permeability parameter, $\theta = \dfrac{T^* - T_d}{T_0 - T_d}$, $Gr = \dfrac{\upsilon g \beta (T_0 - T_d)}{U_0 w_0^2}$ the Grashof number, $\mathrm{Pr} = \dfrac{\mu C_p}{k}$ the Prandtl number and suppressing the stars '*' the equations (2) to (4) become

$$\omega q_t + \lambda q_\eta = q_{\eta\eta} + \omega U_t + Gr\lambda^2\theta - 2i\Omega(q - U) - (q - U)/\mathrm{K}, \tag{6}$$

$$\omega\theta_t + \lambda\theta_\eta = \frac{1}{\mathrm{Pr}}\theta_{\eta\eta}, \tag{7}$$

where $q = u + iv$.

The boundary conditions (5) can also be written in complex notations as

$$\left.\begin{aligned} &q = 0, \quad \theta = 1 + \frac{\varepsilon}{2}(e^{it} + e^{-it}) && at \quad \eta = 0, \\ &q = U(t) = 1 + \frac{\varepsilon}{2}\left(e^{it} + e^{-it}\right), \quad \theta = 0 && at \quad \eta = 1. \end{aligned}\right\} \tag{8}$$

In order to solve the system of equations (6) and (7) subject to the boundary conditions (8), we assume,

$$q(\eta, t) = q_o(\eta) + \frac{\varepsilon}{2}\left\{q_1(\eta)e^{it} + q_2(\eta)e^{-it}\right\}, \tag{9}$$

$$\theta(\eta, t) = \theta_o(\eta) + \frac{\varepsilon}{2}\left\{\theta_1(\eta)e^{it} + \theta_2(\eta)e^{-it}\right\}. \tag{10}$$

Substituting (9) and (10) into (6) and (7) and comparing the harmonic and non-harmonic terms, we get

$$q_0'' - \lambda q_0' - (l^2 + \frac{1}{\mathrm{K}})q_0 = -(l^2 + \frac{1}{\mathrm{K}}) - Gr\lambda^2\theta_0, \tag{11}$$

$$q_1'' - \lambda q_1' - (m^2 + \frac{1}{\mathrm{K}})q_1 = -(m^2 + \frac{1}{\mathrm{K}}) - Gr\lambda^2\theta_1, \tag{12}$$

$$q_2'' - \lambda q_2' - (n^2 + \frac{1}{\mathrm{K}})q_2 = -(n^2 + \frac{1}{\mathrm{K}}) - Gr\lambda^2\theta_2, \tag{13}$$

$$\theta_0'' - \mathrm{Pr}\,\lambda\theta_0' = 0, \tag{14}$$

$$\theta_1'' - \mathrm{Pr}\,\lambda\theta_1' - \mathrm{Pr}\,\omega i\theta_1 = 0, \tag{15}$$

$$\theta_2'' - \mathrm{Pr}\,\lambda\theta_2' + \mathrm{Pr}\,\omega i\theta_2 = 0, \tag{16}$$

where $l^2 = i2\Omega$, $m^2 = i(2\Omega + \omega)$ and $n^2 = i(2\Omega - \omega)$.

The corresponding transformed boundary conditions reduce to

$$\left.\begin{array}{l} q_0 = q_1 = q_2 = 0, \quad \theta_0 = \theta_1 = \theta_2 = 1 \quad at \quad \eta = 0, \\ q_0 = q_1 = q_2 = 1, \quad \theta_0 = \theta_1 = \theta_2 = 0 \quad at \quad \eta = 1. \end{array}\right\} \tag{17}$$

The solutions of equations (11) to (16) under the boundary conditions (17) are

$$q_0(\eta) = 1 + B_1 e^{n_1\eta} + B_2 e^{n_2\eta} + A_1 e^{\lambda \Pr \eta}, \tag{18}$$

$$q_1(\eta) = 1 + B_3 e^{n_3\eta} + B_4 e^{n_4\eta} + A_2 e^{m_2\eta} + A_3 e^{m_1\eta}, \tag{19}$$

$$q_2(\eta) = 1 + B_5 e^{n_5\eta} + B_6 e^{n_6\eta} + A_4 e^{m_4\eta} + A_5 e^{m_3\eta}, \tag{20}$$

$$\theta_0(\eta) = \frac{e^{\lambda \Pr \eta} - e^{\lambda \Pr}}{1 - e^{\lambda \Pr}}, \tag{21}$$

$$\theta_1(\eta) = \frac{e^{m_1 + m_2\eta} - e^{m_2 + m_1\eta}}{e^{m_1} - e^{m_2}}, \tag{22}$$

$$\theta_2(\eta) = \frac{e^{m_3 + m_4\eta} - e^{m_4 + m_3\eta}}{e^{m_3} - e^{m_4}}, \tag{23}$$

where

$$m_1 = \frac{\Pr\lambda + \sqrt{\Pr^2\lambda^2 + 4i\omega\Pr}}{2}, \quad m_2 = \frac{\Pr\lambda - \sqrt{\Pr^2\lambda^2 + 4i\omega\Pr}}{2},$$

$$m_3 = \frac{\Pr\lambda + \sqrt{\Pr^2\lambda^2 - 4i\omega\Pr}}{2}, \quad m_4 = \frac{\Pr\lambda - \sqrt{\Pr^2\lambda^2 - 4i\omega\Pr}}{2},$$

$$n_1 = \frac{\lambda + \sqrt{\lambda^2 + 4(l^2 + \frac{1}{K})}}{2}, \quad n_2 = \frac{\lambda - \sqrt{\lambda^2 + 4(l^2 + \frac{1}{K})}}{2},$$

$$n_3 = \frac{\lambda + \sqrt{\lambda^2 + 4(m^2 + \frac{1}{K})}}{2}, \quad n_4 = \frac{\lambda - \sqrt{\lambda^2 + 4(m^2 + \frac{1}{K})}}{2},$$

$$n_5 = \frac{\lambda + \sqrt{\lambda^2 + 4(n^2 + \frac{1}{K})}}{2}, \quad n_6 = \frac{\lambda - \sqrt{\lambda^2 + 4(n^2 + \frac{1}{K})}}{2},$$

$$A_1 = \frac{-Gr\lambda^2}{(1 - e^{\lambda\Pr})[\lambda^2\Pr(\Pr - 1) - (l^2 + \frac{1}{K})]}, \quad A_2 = \frac{-Gr\lambda^2 e^{m_1}}{(e^{m_1} - e^{m_2})[m_2(m_2 - \lambda) - (m^2 + \frac{1}{K})]}$$

$$A_3 = \frac{Gr\lambda^2 e^{m_2}}{(e^{m_1} - e^{m_2})[m_1(m_1 - \lambda) - (m^2 + \frac{1}{K})]}, \quad A_4 = \frac{-Gr\lambda^2 e^{m_3}}{(e^{m_3} - e^{m_4})[m_4(m_4 - \lambda) - (n^2 + \frac{1}{K})]},$$

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$$A_5 = \frac{Gr\lambda^2 e^{m_4}}{(e^{m_3} - e^{m_4})[m_3(m_3 - \lambda) - (n^2 + \frac{1}{\mathrm{K}})]}, \qquad B_1 = -\left[\frac{e^{n_2} + A_1(e^{n_2} - e^{\lambda \Pr})}{e^{n_2} - e^{n_1}}\right],$$

$$B_2 = \left[\frac{e^{n_1} + A_1(e^{n_1} - e^{\lambda \Pr})}{e^{n_2} - e^{n_1}}\right], \qquad B_3 = -\left[\frac{e^{n_4} + A_2(e^{n_4} - e^{m_2}) + A_3(e^{n_4} - e^{m_1})}{e^{n_4} - e^{n_3}}\right],$$

$$B_4 = \left[\frac{e^{n_3} - A_2(e^{m_2} - e^{n_3}) - A_3(e^{m_1} - e^{n_3})}{e^{n_4} - e^{n_3}}\right], \qquad B_5 = -\left[\frac{e^{n_6} + (e^{n_6} - e^{m_4}) + A_5(e^{n_6} - e^{m_3})}{e^{n_6} - e^{n_5}}\right],$$

$$B_6 = \left[\frac{e^{n_5} - A_4(e^{m_4} - e^{n_5}) - A_5(e^{m_3} - e^{n_5})}{e^{n_6} - e^{n_5}}\right].$$

III. Results and Discussion

Now for the resultant velocities and the shear stresses of the steady and unsteady flow, we write

$$u_0(\eta) + iv_0(\eta) = q_0(\eta) \quad \text{and} \tag{24}$$

$$u_1(\eta) + iv_1(\eta) = q_1(\eta)e^{it} + q_2(\eta)e^{-it}. \tag{25}$$

The solution (18) corresponds to the steady part which gives u_0 as the primary and v_0 as the secondary velocity components. The amplitude and the phase difference due to these primary and secondary velocities for the steady flow are given by

$$R_0 = \sqrt{u_0^2 + v_0^2} \quad , \quad \phi_0 = \tan^{-1}(v_0 / u_0) \tag{26}$$

The resultant velocity R_0 for the steady part is presented in Fig.1.a, b for small and large values of rotations respectively of the vertical porous channel. The two values of the Prandtl number $\Pr$ as 0.7 and 7.0 are chosen to represent air and water respectively. In Fig.1.a, b the curve I corresponds to the flow through an ordinary medium. It is very clear from Fig.1.a that R_0 increases with the Grashof number Gr, the rotation of the channel Ω, suction velocity λ, and the permeability parameter K. In the case of Prandtl number $\Pr$, R_0 is increasing near the oscillating plate.

Similarly for large rotations Ω shown in Fig 1.b., the amplitude R_0 increases with Gr, the free convection currents, and the permeability parameter K and R_0 also oscillates with the increase of the rotation Ω of the channel. It is interesting to note that increase of Prandtl number $\Pr$ leads to an increase of R_0 near the oscillating plate, but to a decrease near the stationary plate. However, the effects of λ, the suction/injection at the plates are reversed i.e. the amplitude R_0 increases near the stationary plate and decreases thereafter.

The phase difference ϕ_0 for the steady flow is shown graphically in Fig 2.a, b for small and large rotations respectively. Fig.2.a shows that the phase angle ϕ_0 is decreasing near the oscillating plate with the increase of Gr or $\Pr$ or λ and Ω, but increases with the permeability parameter K. Similarly for large rotations Ω shown in Fig 2.b., the phase difference decreases with rotation Ω and Prandtl number $\Pr$. But the increase of permeability parameter K, Grashof number Gr and the suction/injection at the plates λ leads to an increase of ϕ_0. The amplitude and the phase difference of shear stresses at the stationary plate $(\eta = 0)$ for the steady flow can be obtained as,

$$\tau_{0r} = \sqrt{\tau_{0x}^2 + \tau_{0y}^2}, \text{ and } \quad \phi_{or} = \tan^{-1}(\tau_{oy} / \tau_{ox}), \tag{27}$$

$$\text{where,} \quad \tau_{ox} + i\tau_{oy} = (\partial q / \partial \eta)_{\eta=0} = n_1 B_1 + n_2 B_2 + \lambda \Pr A_1. \tag{28}$$

Here τ_{ox} and τ_{oy} are, respectively, the shear stresses at the stationary plate due to the primary and secondary velocity components. The numerical values of the amplitude τ_{0r} of the steady shear stress and the phase difference of the shear stresses at the stationary plate ($\eta = 0$) for the

$\Pr$	Gr	Ω	λ	K	τ_{0r}	ϕ_{0r}
0.7	5	5	2	∞	3.717	1.351
0.7	5	5	2	1	3.44	1.765
7.0	5	5	2	1	2.498	0.967
0.7	10	5	2	1	5.461	-1.042
0.7	5	10	2	1	4.372	1.314
0.7	5	5	3	1	3.304	-1.269
0.7	5	5	2	2	3.575	-1.363
0.7	5	25	2	∞	6.607	1.029
0.7	5	25	2	1	6.581	1.02
7.0	5	25	2	1	6.389	0.873
0.7	10	25	2	1	6.902	1.154
0.7	5	50	2	1	9.392	0.922
0.7	5	25	3	1	6.313	1.07
7.0	5	25	2	2	6.594	1.024

Table 1: Values of τ_{0r} and ϕ_{0r} for various $\Pr$, Gr, Ω, λ, and K.

steady flow are presented in Table -1. The permeability parameter K, the Grashof number Gr, and the rotation parameter Ω lead to an increase of τ_{0r} for both the cases

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of small or large rotations. It is also observed that τ_{0r} decreases with Pr and λ for small and large rotations. Similarly the values for ϕ_{0r}, the steady phase difference, increases with the suction parameter λ and the permeability parameter K for both the cases of small or large rotations. But the effect is reverse in the case of Prandtl number Pr. The increase of Ω leads to an increase in ϕ_{0r} for small rotations. But the effect will be reverse in the case of large rotations.

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The solutions (19) and (20) together give the unsteady part of the flow. The unsteady primary and secondary velocity components $u_1(\eta)$ and $v_1(\eta)$, respectively, for the fluctuating flow can be obtained as

$$u_1(\eta,t) = \{\mathrm{Real}\, q_1(\eta) + \mathrm{Real}\, q_2(\eta)\}\cos t - \{\mathrm{Im}\, q_1(\eta) - \mathrm{Im}\, q_2(\eta)\}\sin t \quad , \tag{29}$$

$$v_1(\eta,t) = \{\mathrm{Real}\, q_1(\eta) - \mathrm{Real}\, q_2(\eta)\}\sin t + \{\mathrm{Im}\, q_1(\eta) + \mathrm{Im}\, q_2(\eta)\}\cos t \quad , \tag{30}$$

The resultant velocity or amplitude and the phase difference of the unsteady flow are given by

$$R_1 = \sqrt{u_1^2 + v_1^2} \quad , \quad \phi_1 = \tan^{-1}(v_1 / u_1) \tag{31}$$

For the unsteady part, the resultant velocity or the amplitude R_1 are presented in Fig.3.a, b. for the two cases of rotation Ω small and large. In Fig.3.a, b the curve I corresponds to the flow through an ordinary medium. It is observed from figure 3.a, for small rotations Ω that R_1 increases with Prandtl number Pr, free convection current Gr, the suction/injection parameter λ and permeability parameter K, but decreases with the rotation parameter Ω and the frequency of oscillations ω. Fig. 3.b, for large rotations Ω clearly shows that the amplitude R_1 increases with all the parameter Gr, Pr, λ, K, ω except that with the rotation parameter Ω, R_1 decreases near the oscillating plates.

The phase difference ϕ_1 for the unsteady part is shown in Figure 4. a, b. In Fig.4.a, b the curve I corresponds to the flow through an ordinary medium. Figure 4.*a* for small rotations Ω shows that the phase difference ϕ_1 increases with the Prandtl number Pr and the frequency of oscillations ω, but decreases with the Grashof number Gr, the suction parameter λ, the permeability parameter K. And, with the faster rotation of the channel Ω, ϕ_1 increases near the stationary plate. It is also evident from Figure 4.*b* that increase of Pr, or Gr, or λ or K leads to a decrease in ϕ_1 but the increase of the rotation parameter Ω, frequency of oscillations ω both lead to an increase in ϕ_1.

For the unsteady part of the flow, the amplitude and the phase difference of shear stresses at the stationary plate (η=0) can be obtained as

$$\tau_{1x} + i\tau_{1y} = (\partial u_1 / \partial \eta)_{\eta=0} + i(\partial v_1 / \partial \eta)_{\eta=0} \tag{32}$$

which gives

$$\tau_{1r} = \sqrt{\tau_{1x}^2 + \tau_{1y}^2} \quad , \quad \phi_{1r} = \tan^{-1}(\tau_{1y} / \tau_{1x}) \tag{29}$$

The amplitude τ_{1r} of the unsteady shear stress are shown graphically in Figure 5.a, b respectively for small and large rotations. Fig.5.a, b the curve I corresponds to the flow through an ordinary medium. It is interesting to note that the shear stress increases sharply for small oscillations of the frequency and thereafter decreases abruptly for larger frequency of oscillations. This figure shows clearly that the shear stress τ_{1r} increases with increasing Gr, or λ, or Ω. However, the effects of Prandtl number Pr and the permeability parameter K are reversed. For larger rotation Ω the variations of shear stress τ_{1r} are presented in Figure 5. b. This figure shows that the amplitude τ_{1r} increases with the free convection current Gr, the Prandtl number Pr the suction parameter λ, the rotation parameter Ω and permeability parameter K.

The phase difference ϕ_{1r} of the unsteady shear stress is shown graphically in Figure 6.a, b respectively for small and large rotations. It is interesting to note from these figures that ϕ_{1r} goes on increasing with increasing frequency of oscillations for both small and large rotations. The phase difference ϕ_{1r} decreases for both small and large rotations with the increase of Grashof number Gr and suction parameter λ. However for small rotations Ω, ϕ_{1r} increases for all values of frequency of oscillations and for large rotations ϕ_{1r} decreases very near the oscillating plate. The effects of Prandtl number Pr and the permeability parameter K, lead to an increase in ϕ_{1r} every where for large or small rotations.

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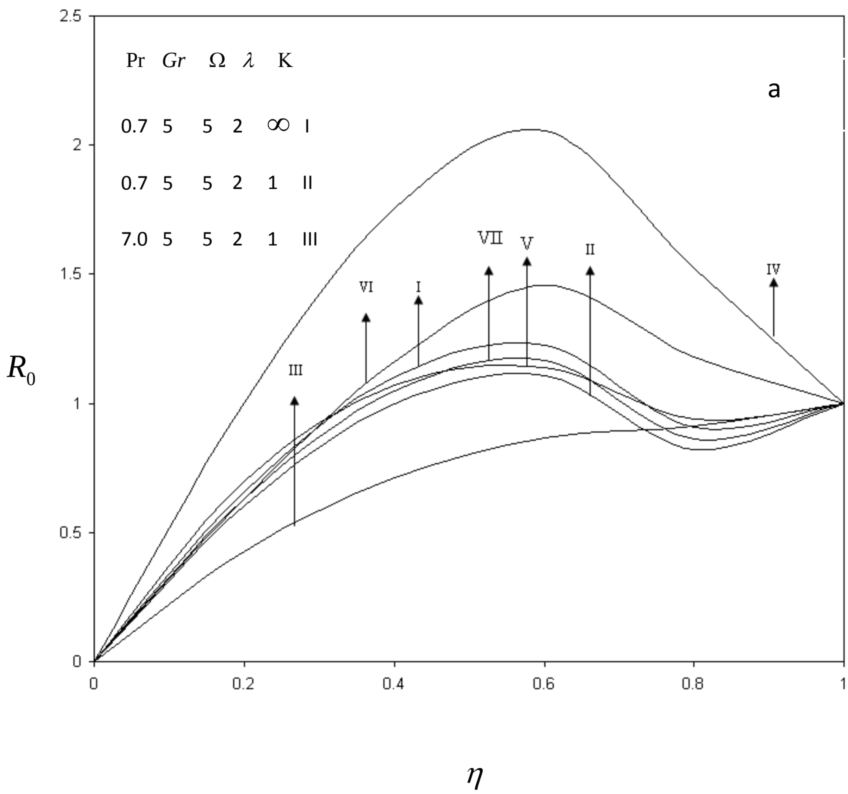


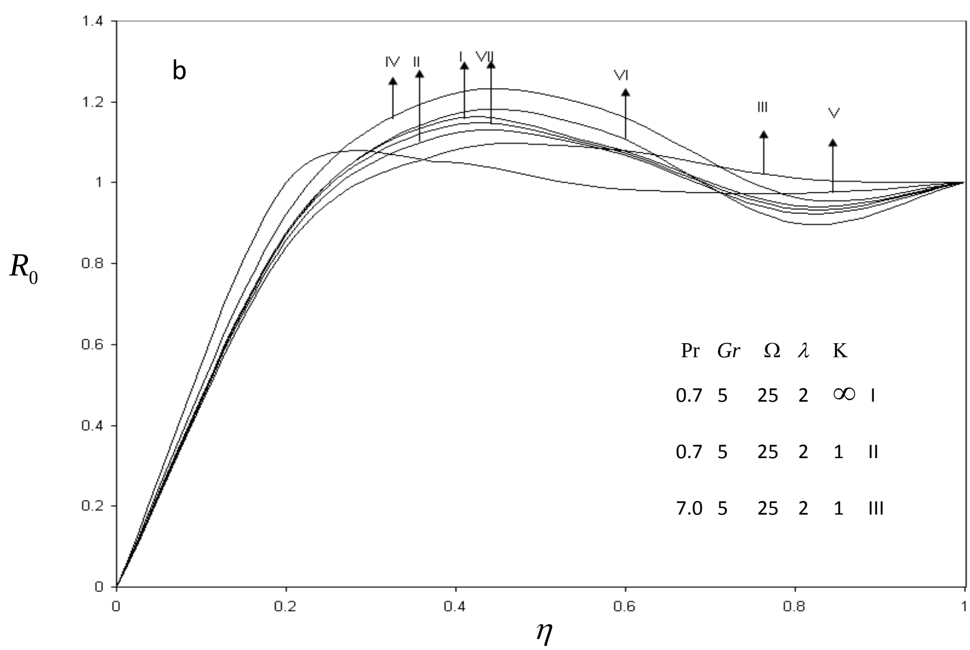
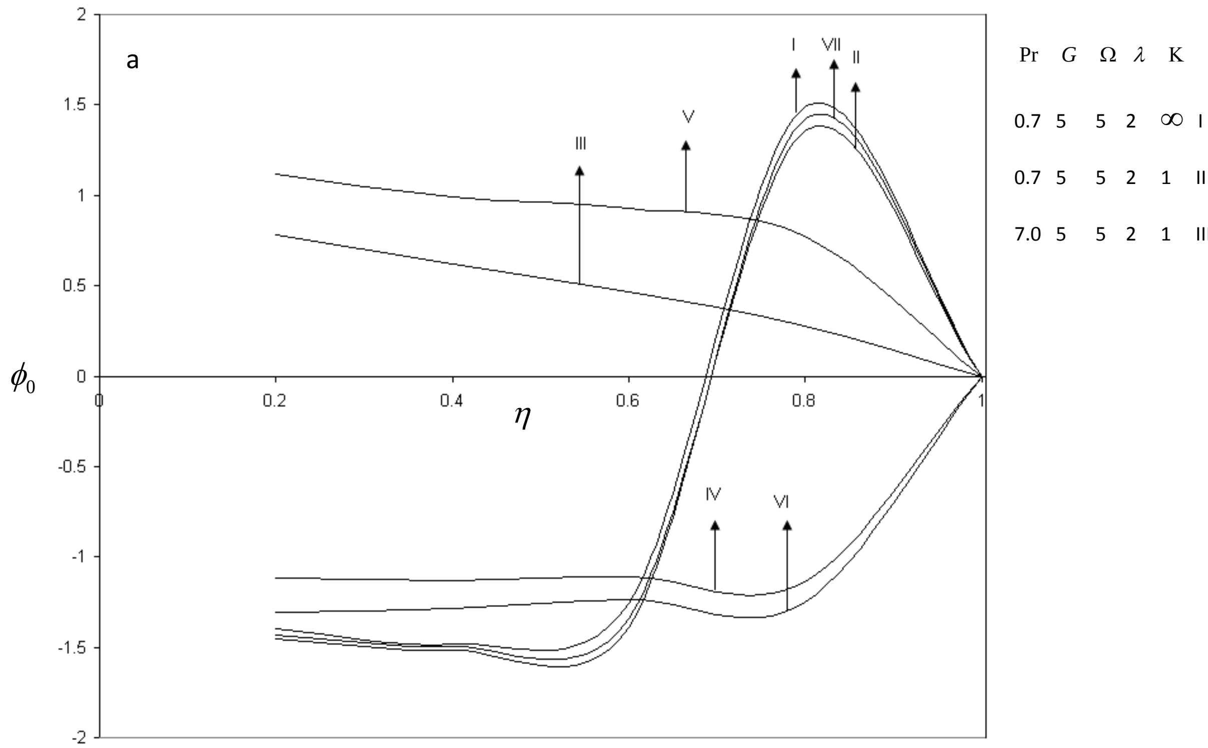


Fig.1 a, b : Resultant velocity R_0 for small and large rotations due to u_0 and v_0



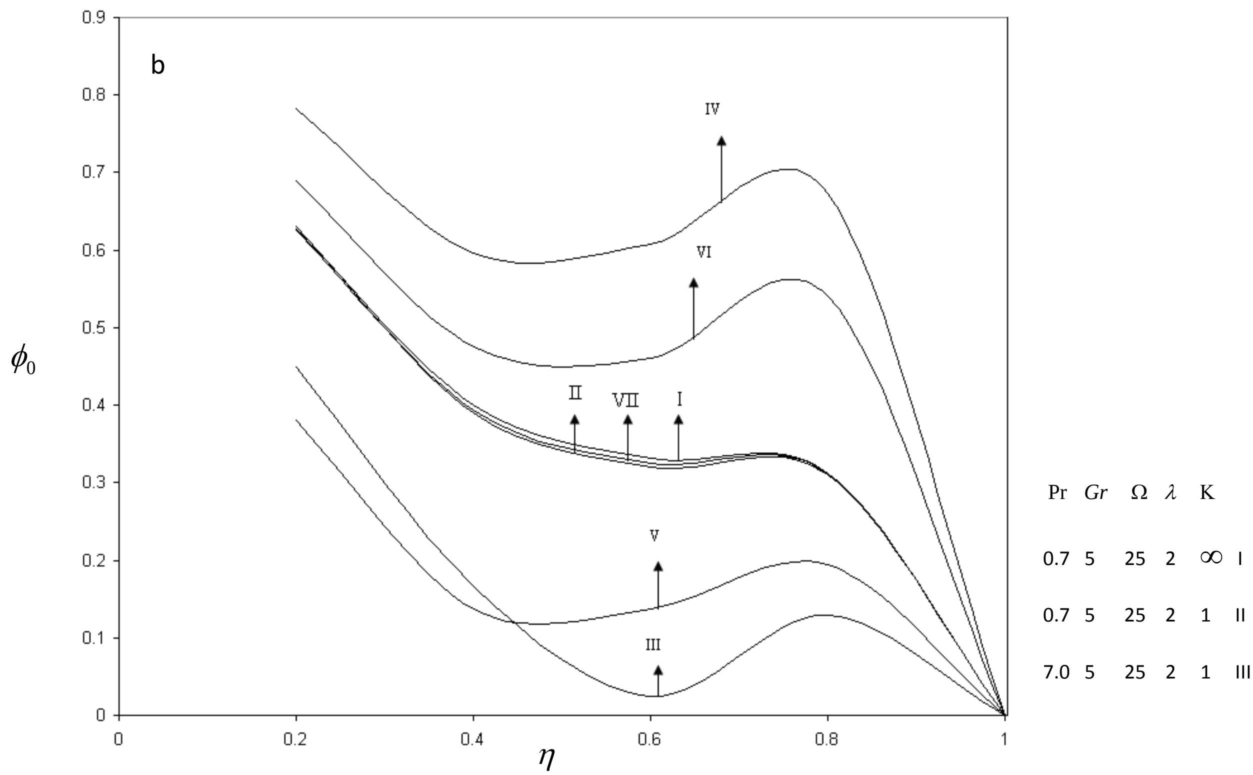


Fig.2 a, b : Phase angle ϕ_0 for small and large rotations due to u_0 and v_0

Notes

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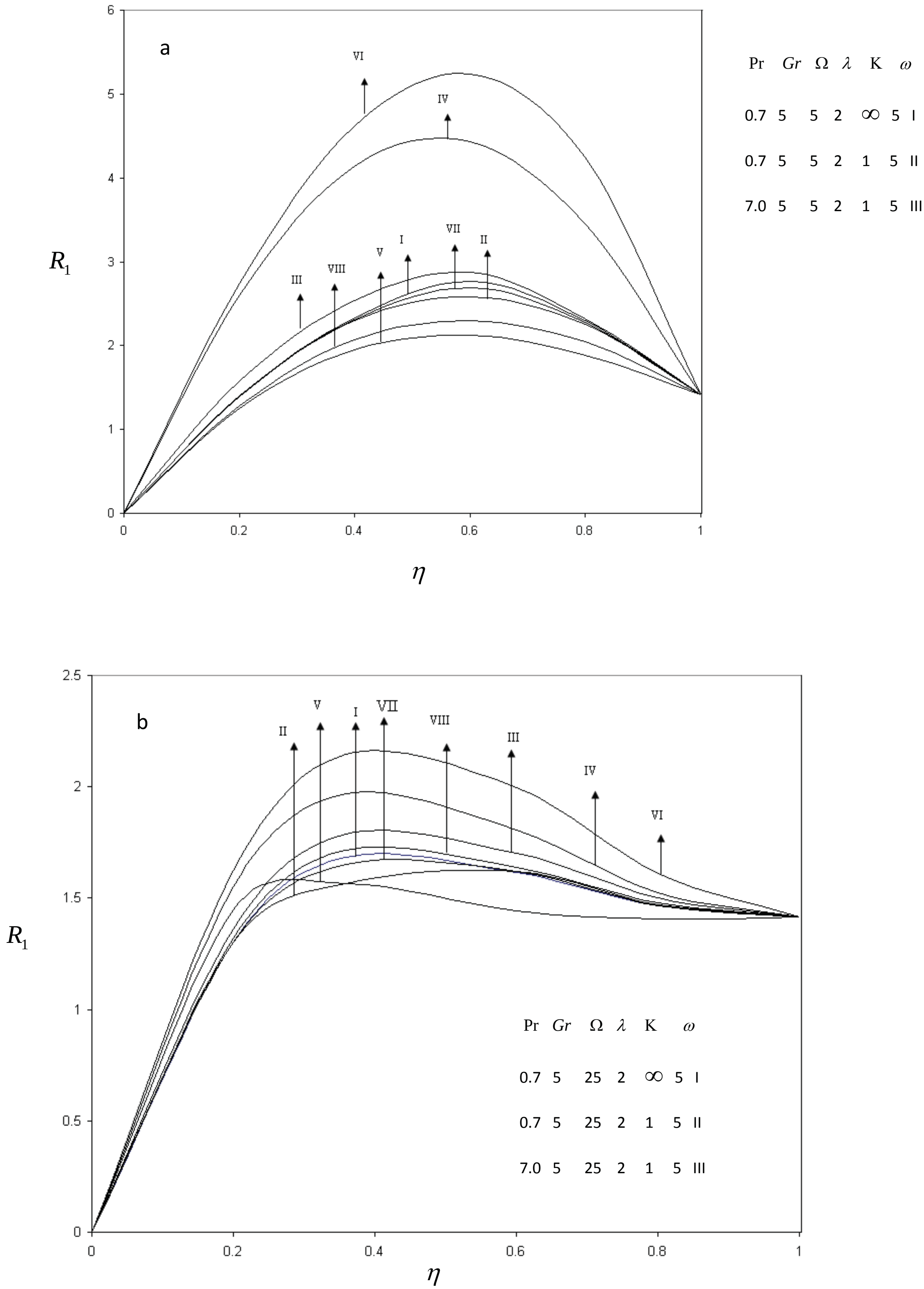
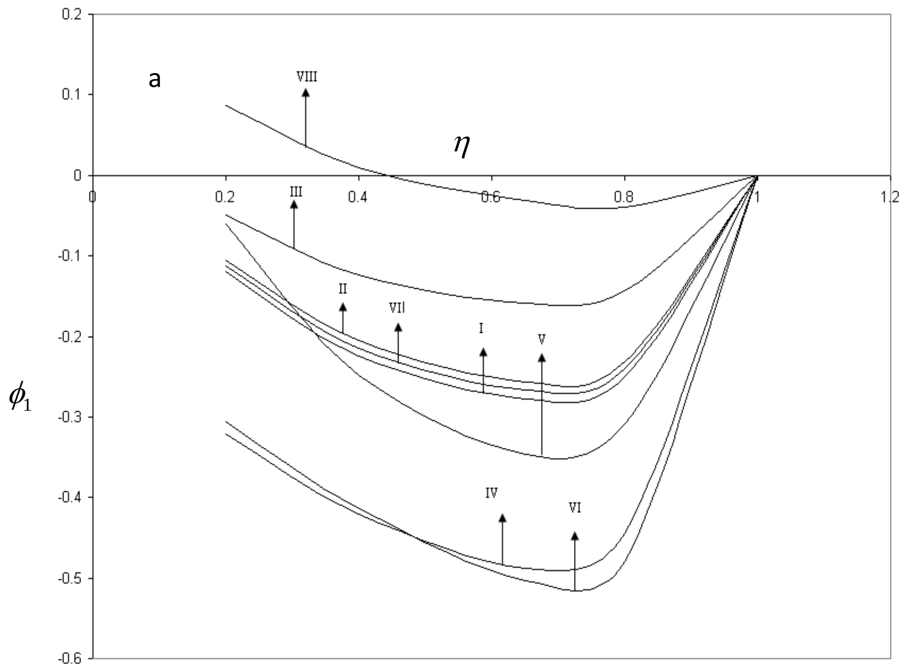
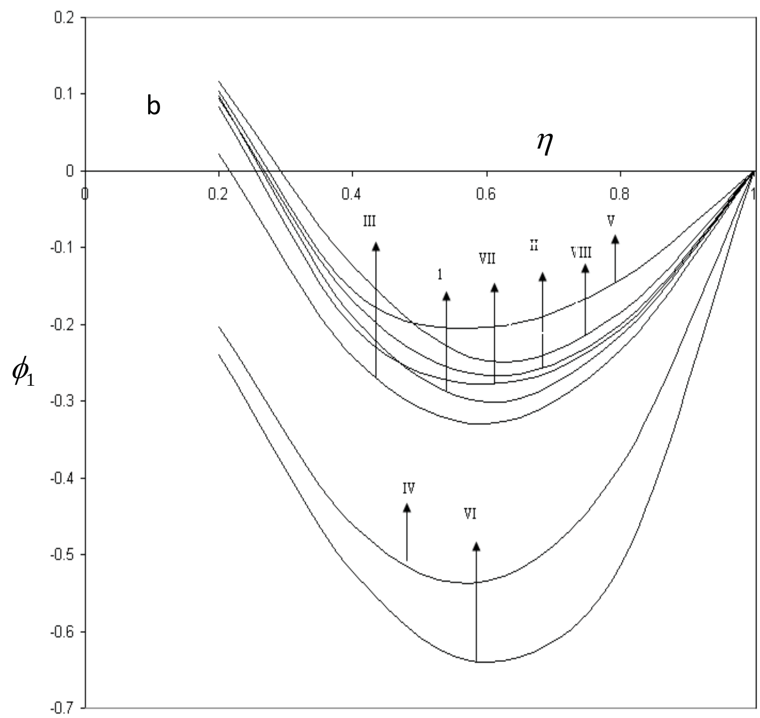


Fig.3 a, b : Resultant velocity R_1 for small and large rotations due to u_1 and v_1



Pr	*Gr*	Ω	λ	K	ω	
0.7	5	5	2	∞	5	I
0.7	5	5	2	1	5	II
7.0	5	5	2	1	5	III

Notes



Pr	*Gr*	Ω	λ	K	ω	
0.7	5	25	2	∞	5	I
0.7	5	25	2	1	5	II
7.0	5	25	2	1	5	III
0.7	10	25	2	1	5	IV
0.7	5	50	2	1	5	V

Fig.4 a, b : Phase angle ϕ_1 for small and large rotations due to u_1 and v_1

Notes

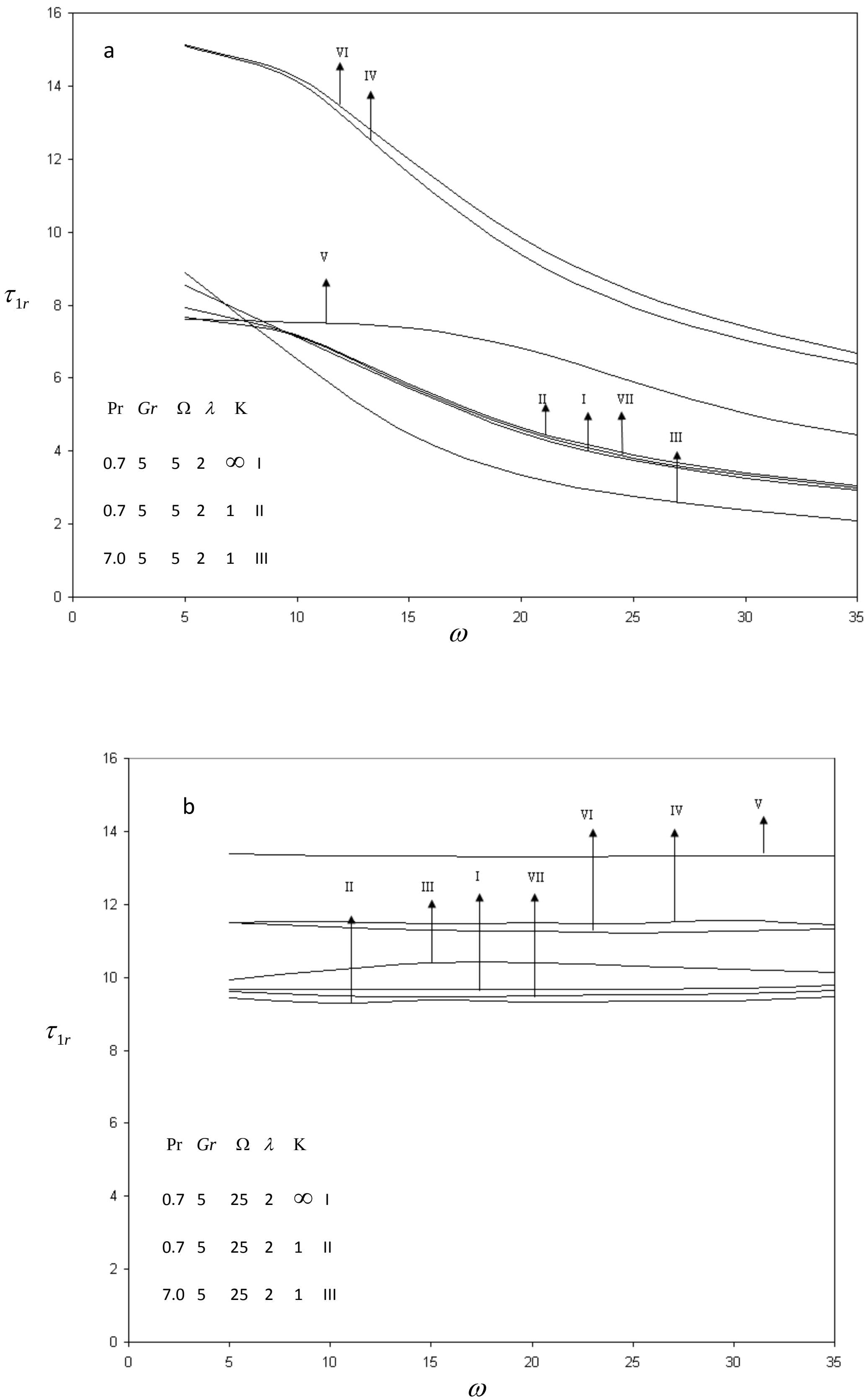
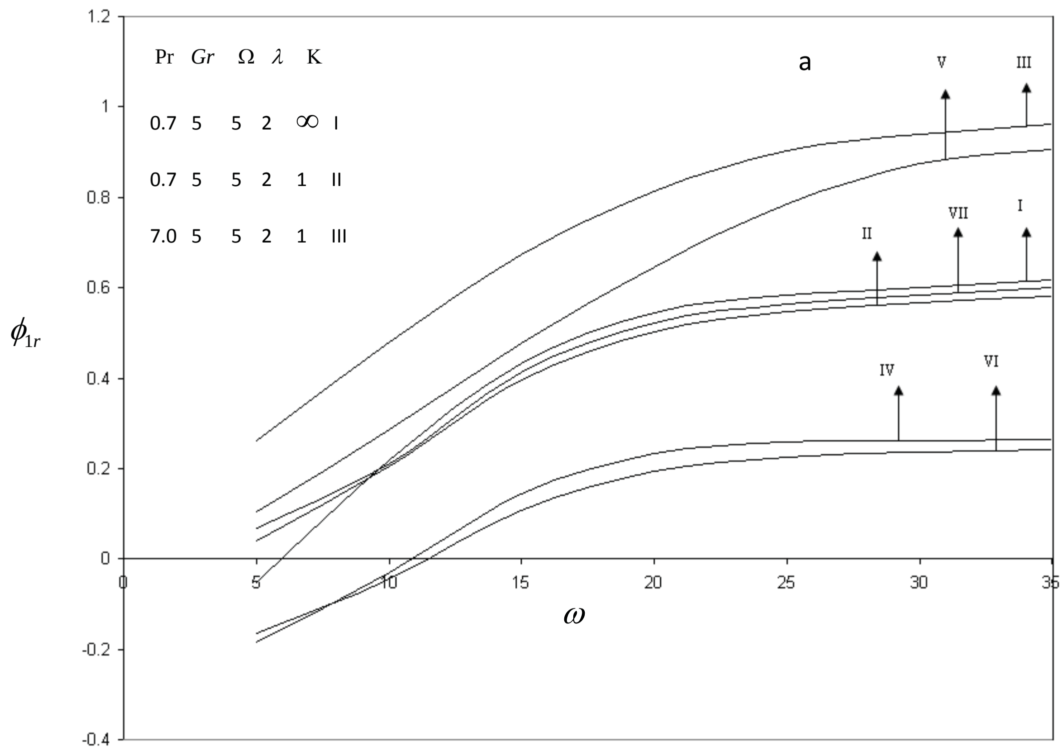


Fig. 5 a,b : The amplitude τ_{1r} of unsteady shear stresses for small and large rotations at $t = \frac{\pi}{4}$.



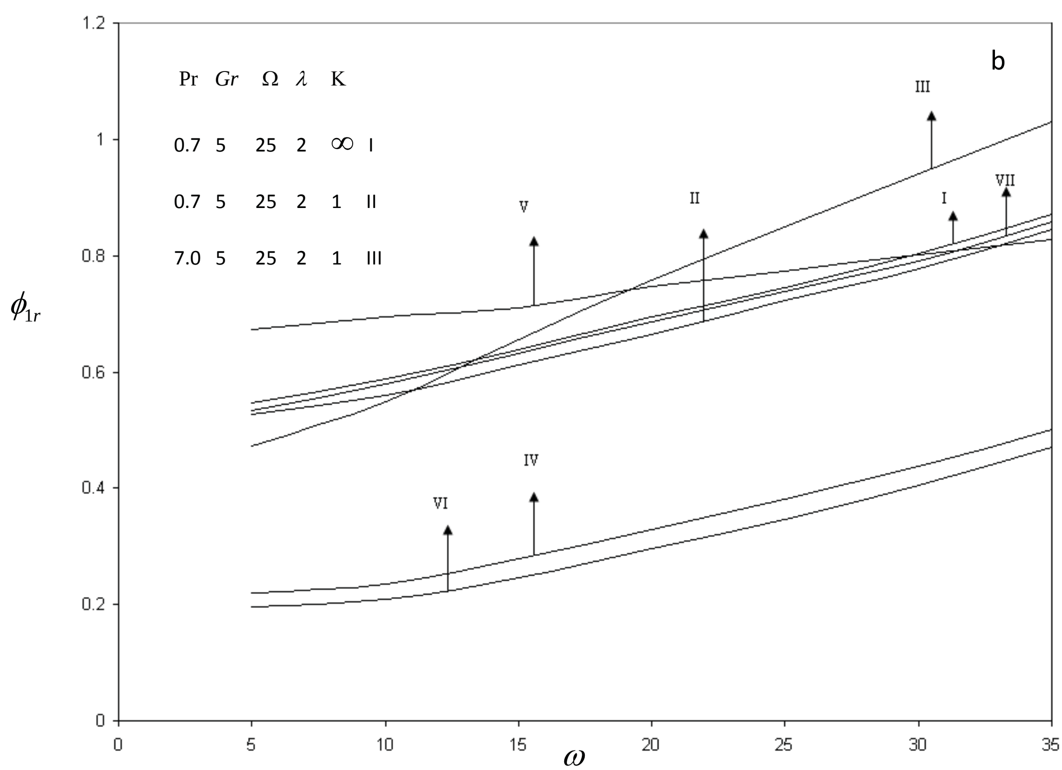


Fig. 6 a, b : The phase difference ϕ_{1r} of unsteady shear stresses for small and large rotations at $t = \frac{\pi}{4}$.

Notes