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FLUCTUATING FLOW OF A VISCOELASTIC FLUID PAST A POROUS PLATE IN A ROTATING MEDIUM WITH AN APPLIED MAGNETIC FIELD*

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The problem of fluctuating flow of Rivlin-Ericksen viscoelastic incompressible conducting fluid past a porous flat plate with constant suction in a rotating medium in the presence of a transverse magnetic field in the case when free-stream velocity oscillates in magnitude but not in direction has been studied. It has been observed that the mean velocity fields f_1 and g_1 both increase with increasing Ω_1 (angular velocity of the medium) whereas f_1 decreases in the neighbourhood of the plate. Magnetic field (M) increases f_1 and decreases g_1. f_1 and g_1 are not found to be affected by the elasticity (S) of the fluid. In case of f_1 and g_1 strong fluctuations are felt in the neighbourhood of the plate. The transient velocity fields f_2 and g_2 show much fluctuations at larger distance from the plate. When $\lambda > \Omega_1$, strong fluctuations are felt in comparison to when $\lambda < \Omega_1$. When $\lambda = \Omega_1$ (resonant frequency), the fluctuations become quicker. Effects of M and S are greatly felt throughout the flow and their presence increases the fluctuations in the stream-velocity. With the increase in λ and Ω_1 the drag on the plate decreases. Both magnetic field and elasticity increases the drag on the plate. Lateral stress decreases with increasing elasticity and magnetic field (when Ω_1 fixed). Also lateral stress shows fluctuations with the increasing Ω_1 (when λ fixed).

1. INTRODUCTION

Due to the development of practical boundary layer control system, interest in problems concerning suction has been renewed. Lighthill (1954) has given an interesting account for boundary layers which have a regular fluctuation flow superimposed on the mean boundary layer flow. After that a large number of papers dealing with this subject have been brought out by many authors like Stuart (1955), Watson (1958) and Messiha (1966). Suryaprakashrao (1963) extended this idea to MHD flow. Later on, Kaloni (1967), Soundalgekar and Puri (1969) and Puri (1973) extended their ideas to non-Newtonian viscoelastic flows.

The flows in rotating medium and the flows with rotating boundaries constitute the important class of great theoretical and technical interest. Due to this important

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class of flows many authors like Greenspan (1968), Thornley (1968), Debnath and Mukerjee (1973) have paid their attention towards it. Puri (1975) has studied the fluctuating flow of a viscous fluid on a porous plate in rotating medium with constant suction. Recently, Ashok Kumar (1978) has discussed the fluctuating flow of a viscous incompressible conducting fluid on a porous plate with constant suction in rotating medium in the presence of a transverse magnetic field when the free-stream velocity is some periodic function of time.

In the present paper we have attempted to extend Ashok Kumar's (1978) problem to viscoelastic fluid (Rivlin-Ericksen model).

2. Basic Equations of Motion

The constitution equation characterizing Rivlin-Ericksen second order fluid is

$$T_{ij} = -p\delta_{ij} + 2\phi_1 E_{ij} + \phi_2 D_{ij} + 4\phi_3 E_i^m E_{mj} \qquad \ldots(2.1)$$

where $E_{ij} = \frac{1}{2}(u_{i,j} + u_{j,i})$ = strain rate tensor;

$D_{ij} = a_{i,j} + a_{j,i} + 2u_{m,i}\, u^m{}_j$ = deformation rate tensor;

$a_i = \frac{\partial u_i}{\partial t} + u_{i,j}\, u^j$ acceleration vector;

where (∂) denotes covariant derivative. The ϕ (i = 1,2,3) are in general functions of temperature and material properties. For many liquids such as aqueous solution of poly-acrylamid and poly-isobutylene ϕ_i may be taken as constants

3. Formulation of the Problem and its Solution

Let x- and y- axes be taken in the two dimensional infinite porous plate and z- axes normal to it. Let u, V and W be the velocity components parallel to x -, y- and z- axes, respectively. A uniform mangnetic field of strength B_0 in the z-direction has been applied about which the medium is rotating with a constant velocity Ω. As in Suryaprakashrao (1962, 1963) it has been assumed that the Reynolds number is small, so that the induced magnetic field is negligible in comparison to the imposed magnetic field. Further, since no external electric field is applied, and the effect of polarization of ionized fluid is negligible, it can be assumed that the electric field is zero. The equations of motion and continuity for an incompressible viscoelastic Rivlin-Ericksen conducting fluid in a medium rotating with a constant velocity Ω about z-axis are given by

$$\left(\frac{\partial u}{\partial t} + W\frac{\partial u}{\partial z} - 2\Omega V\right) = -\frac{\partial}{\partial x}\left(\frac{p}{\rho} - \frac{r^2\Omega^2}{2}\right) + \alpha\frac{\partial^2 u}{\partial z^2} + \beta\frac{\partial^3 u}{\partial z^2 \partial t} - \frac{\sigma}{\rho}B_0^2 u \qquad \ldots(3.1)$$

$$\left(\frac{\partial V}{\partial t} + W\frac{\partial V}{\partial z} + 2\Omega u\right) = -\frac{\partial}{\partial y}\left(\frac{p}{\rho} - \frac{r^2\Omega^2}{2}\right) + \left(\alpha + \beta\frac{\partial}{\partial t}\right)\frac{\partial^2 V}{\partial z^2} + 2\gamma\left(\frac{\partial V}{\partial z}\frac{\partial^2 W}{\partial z^2} + \frac{\partial W}{\partial z}\frac{\partial^2 V}{\partial z^2}\right) - \frac{\sigma}{\rho}B_0^2 V, \qquad \ldots(3.2)$$

$$\left(\frac{\partial W}{\partial t}+W\frac{\partial W}{\partial z}\right)= -\frac{\partial}{\partial z}\left(\frac{p}{\rho}-\frac{r^2\Omega^2}{2}\right)+2\alpha\frac{\partial^2 W}{\partial z^2}+2\beta\left[\frac{\partial^3 W}{\partial z^2\partial t}\right.$$
$$\left.+\frac{\partial^2}{\partial z^2}\left(W\frac{\partial W}{\partial z}\right)+\frac{\partial}{\partial z}\left\{\left(\frac{\partial u}{\partial z}\right)^2+\left(\frac{\partial V}{\partial z}\right)^2+\left(\frac{\partial W}{\partial z}\right)^2\right\}\right]$$
$$+\gamma\frac{\partial}{\partial z}\left\{4\left(\frac{\partial W}{\partial z}\right)^2+\left(\frac{\partial u}{\partial z}\right)^2+\left(\frac{\partial V}{\partial z}\right)^2\right\}, \qquad \ldots(3.3)$$

$$\frac{\partial W}{\partial z}=0, \qquad \ldots(3.4)$$

where σ is the electric conductivity, ρ the density, α the kinematic coefficient of viscosity β the kinematic coefficient viscoelasticity γ the kinematic coefficient of cross-viscosity. Equation (3.4) shows that W is atmost a function of time. Hence the suction velocity W normal to the plate is assumed here to be $W=-W_0$, W_0 is a positve real number, $B_0=\mu_m H_0$, μ_m is magnetic permeability. Since the free-stream velocity $U(t)$ oscillates in magnitude but not in direction, we take

$$U(t)=U_0(1+\epsilon e^{i\omega t}), \qquad \ldots(3.5)$$

where ω is the frequency and U_0 is the mean of U.

In view of (3.4) (or $W=-W_0$) eqns. (3.1) to (3.3) are reduced to

$$\frac{\partial u}{\partial t}-W_0\frac{\partial u}{\partial z}-2\Omega V=-\frac{\partial}{\partial x}\left(\frac{p}{\rho}-\frac{r^2\Omega^2}{2}\right)+\alpha\frac{\partial^2 u}{\partial z^2}$$
$$+\beta\frac{\partial^3 u}{\partial z^2\partial t}-\frac{\sigma}{\rho}B_0^2 u, \qquad \ldots(3.6)$$

$$\frac{\partial V}{\partial t}-W_0\frac{\partial V}{\partial z}+2\Omega u=-\frac{\partial}{\partial y}\left(\frac{p}{\rho}-\frac{r^2\Omega^2}{2}\right)+\alpha\frac{\partial^2 V}{\partial z^2}$$
$$+\beta\frac{\partial^3 V}{\partial z^2\partial t}-\frac{\sigma}{\rho}B_0^2 V, \qquad \ldots(3.7)$$

$$0=-\frac{\partial}{\partial z}\left(\frac{p}{\rho}-\frac{r^2\Omega^2}{2}\right)+(2\beta+\gamma)\frac{\partial}{\partial z}\left\{\left(\frac{\partial u}{\partial z}\right)^2+\left(\frac{\partial V}{\partial z}\right)^2\right\}. \qquad \ldots(3.8)$$

Equation (3.8) integrates to

$$-\left(\frac{p}{\rho}-\frac{r^2\Omega^2}{2}\right)+(2\beta+\gamma)\left\{\left(\frac{\partial u}{\partial z}\right)^2+\left(\frac{\partial V}{\partial z}\right)^2\right\}=\text{Const. (independent of } z).$$

Here the coordinate axes are assumed to be fixed in the rotating medium and $r^2=x^2+y^2$.

The boundary conditions of the problem are:

$$U=0,\ V=0 \text{ at } z=0,$$

$$U\to U(t),\ \frac{\partial u}{\partial z}\to 0,\ V\to 0 \text{ as } z\to\infty. \qquad \ldots(3.9)$$

Applying the second of the boundary conditions (3.9), equations (3.6) and (3.7) yields:

$$\frac{du}{dt}=-\frac{\partial}{\partial x}\left(\frac{p}{\rho}-\frac{r^2\Omega^2}{2}\right)-\frac{\sigma}{\rho}B_0^2 U \qquad \ldots(3.10)$$

$$2\Omega U = -\frac{\partial}{\partial y}\left(\frac{p}{\rho} - \frac{r^2\Omega^2}{2}\right). \quad \text{...(3.11)}$$

Eliminating $-\frac{\partial}{\partial x}\left(\frac{p}{\rho} - \frac{r^2\Omega^2}{2}\right)$ and $-\frac{\partial}{\partial y}\left(\frac{p}{\rho} - \frac{r^2\Omega^2}{2}\right)$ between (3.6), (3.7), (3.10) and (3.11), we get

$$\frac{\partial u}{\partial t} - W_0\frac{\partial u}{\partial z} - 2\Omega V = \frac{dU}{dt} + \alpha\frac{\partial^2 u}{\partial z^2} + \beta\frac{\partial^3 u}{\partial z^2 \partial t} + \frac{\sigma}{\rho}B_0^2\left(U-u\right), \quad \text{...(3.12)}$$

$$\frac{\partial V}{\partial t} - W_0\frac{\partial V}{\partial z} + 2\Omega V = 2\Omega U + \left(\alpha + \beta\frac{\partial}{\partial t}\right)\frac{\partial^2 V}{\partial z^2} - \frac{\sigma}{\rho}B_0^2 V. \quad \text{...(3.13)}$$

We assume the solutions for u and V in the neighbourhood of the plate of the form (Lighthill 1954 and Messiha 1966)

$$\left.\begin{aligned} U(z,t) &= U_0\left[f_1(z) + \epsilon f_2(z)e^{i\omega t}\right] \\ V(z,t) &= U_0\left[g_1(z) + \epsilon g_2(z)e^{i\omega t}\right] \end{aligned}\right\} \quad \text{...(3.14)}$$

where ϵ is taken positive by the suitable choice of the origin of time. Substituting for u, and V and U in eqns. (3.12) and (3.13) and equating the harmonic and non-harmonic terms, we get

$$\alpha f_1'' + W_0 f_1' - \frac{\sigma}{\rho}B_0^2 f_1 = \frac{\sigma}{\rho}B_0^2 - 2\Omega g_1, \quad \text{...(3.15)}$$

$$\left(\alpha + \beta i\omega\right) f_2'' + W_0 f_2' - \left(i\omega + \frac{\sigma}{\rho}B_0^2\right) f_2 = -\left(i\omega + \frac{\sigma}{\rho}B_0^2 + 2\Omega g_2\right), \quad \text{...(3.16)}$$

$$g_1'' + W_0 g_1' - \frac{\sigma}{\rho}B_0^2 g_1 = 2\Omega\left(f_1 - 1\right), \quad \text{...(3.17)}$$

$$\left(\alpha + \beta i\omega\right) g_2'' + W_0 g_2' - \left(i\omega + \frac{\sigma}{\rho}B_0^2\right) g_2 = 2\Omega\left(f_2 - 1\right). \quad \text{...(3.18)}$$

Making use of the following non-dimensional quantities :

$$\lambda = \frac{\omega\alpha}{W_0^2}, \ \Omega_1 = \frac{\alpha\Omega}{W_0^2}, \ M = \frac{B_0}{W_0}\sqrt{\frac{\alpha\sigma}{\rho}}, \ S = -\frac{\omega\beta}{\alpha}, \ \eta = \frac{zW_0}{\alpha}. \quad \text{...(3.19)}$$

where M is the magnetic field parameter, S the viscoelastic parameter, λ the frequency of oscillations of the stream velocity, Ω_1 the angular velocity of the medium.

On using (3.19) eqns. (3.15) to (3.18) become ;

$$f_1'' + f_1' - M^2 f_1 + 2\Omega_1 g_1 = -M^2, \quad \text{...(3.20)}$$

$$g_1'' + g_1' - M^2 g_1 - 2\Omega_1 f_1 = -2\Omega_1, \quad \text{...(3.21)}$$

$$\left(1 - iS\right) f_2'' + f_2' - \left(i\lambda + M^2\right) f_2 + 2\Omega_1 g_2 = -\left(i\lambda + M\right) \quad \text{...(3.22)}$$

$$\left(1 - iS\right) g_2'' + g_2' - \left(i\lambda + M^2\right) g_2 - 2\Omega_1 f_2 = -2\Omega_1, \quad \ldots(3.23)$$

where dashes denote differentiation w. r. t. η.

In view of (3.14), boundary conditions (3.9) reduce to

$$\left.\begin{aligned} &f_1 = 0 = f_2\,,\ g_1 = 0 = g_2 \text{ at } \eta = 0 \\ &f_1\,, f_2 \to 1 \text{ and } g_1,\ g_2 \to 0 \text{ as } \eta \to \infty \end{aligned}\right\}. \quad \ldots(3.24)$$

Solutions for f_1, f_2, g_1 and g_2 under the boundary conditions (3.24) are given by

$$\left.\begin{aligned} f_1 &= 1 - e^{-\alpha_1\eta} \cos(\beta_1 \eta) \\ g_1 &= e^{-\alpha_1\eta} \sin(\beta_1 \eta) \end{aligned}\right\} \quad \ldots(3.25)$$

$$\left.\begin{aligned} f_2 &= 1 - e^{-\alpha_3\eta} \cos(\beta_3 \eta) \\ g_2 &= e^{-\alpha_3\eta} \sin(\beta_3 \eta) \end{aligned}\right\} \quad \ldots(3.26)$$

where

$$\left.\begin{aligned} \alpha_1 &= \frac{1}{2} + \frac{1}{4} \frac{[\sqrt{64\Omega_1^2 + (1 + 4M^2)^2} + (1 + 4M^2)]^{1/2}}{[(1 + 4M^2)^2 + 64\Omega_1^2]^{1/4}}, \\ \beta_1 &= \frac{1}{4} \frac{[\sqrt{64\Omega_1^2 + (1 + 4M^2)^2} - (1 + 4M^2)]^{1/2}}{[(1 + 4M^2)^2 + 64\Omega_1^2]^{1/4}}, \\ \alpha_3 &= \frac{\alpha_2 + S\beta_2}{(1 + S^2)}\,,\quad \beta_3 = \frac{\beta_2 + S\alpha_2}{(1 + S^2)}\,, \\ \alpha_2 &= \frac{1}{4} \frac{[\sqrt{l^2 + 16m^2} + l]^{1/2}}{(l^2 + 16m^2)^{1/4}}, \\ \beta_2 &= \frac{1}{4} \frac{[\sqrt{l^2 + 16m^2} - l]^{1/2}}{(l^2 + 16m^2)^{1/4}}, \\ l &= (1 + 4M^2 + 4S\lambda + 8S\Omega_1), \\ m &= (\lambda + 2\Omega_1 - SM^2). \end{aligned}\right\} \quad \ldots(3.27)$$

Therefore,

$$u = U_0\,[(1 - e^{-\alpha_1\eta}.\cos\beta_1\eta) + \epsilon\, e^{i\omega t}.(1 - e^{-\alpha_3\eta}\cos\beta_3\eta)] \quad \ldots(3.28)$$

and

$$V = U_0\,[e^{-\alpha_1\eta}\sin\beta_1\eta + \epsilon\, e^{i\omega t}\, e^{-\alpha_3\eta}\sin\beta_3\eta]. \quad \ldots(3.29)$$

Drag on the plate ($\eta = 0$) is given by

$$\frac{\omega T_x}{W_0\,\rho\,U_0} = \frac{1}{U_0}\left(\frac{\partial u}{\partial\eta}\right)_{\eta=0} - \frac{S}{\omega U_0}\left(\frac{\partial^2 u}{\partial\eta\,\partial t}\right)_{\eta=0}$$

$$= \alpha_1 + \epsilon\,\alpha_3\,(1 - S)\,e^{i\omega t} \quad \ldots(3.30)$$

and the lateral stress on the plate ($\eta = 0$) is given by

$$\frac{\omega T_y}{W_0\,\rho\,U_0} = \frac{1}{U_0}\left(\frac{\partial V}{\partial\eta}\right)_{\eta=0} - \frac{S}{\omega U_0}\left(\frac{\partial^2 V}{\partial\eta\,\partial t}\right)_{\eta=0}$$

$$= \beta_1 + \epsilon\,\beta_3\,(1 - S)\,e^{i\omega t} \quad \ldots(3.31)$$

$$\therefore\ T_x = \left| \frac{\omega\, T_x}{\rho\, W_0\, U_*} \right| = \left\{ \alpha_1^2 + \epsilon^2\, \alpha_3^2\, (1 - S)^2 + 2\alpha_1\, \alpha_3\, \epsilon\, (1 - S) \cos \omega t \right\}^{1/2} \quad \ldots(3.32)$$

$$\text{and } T_y = \left| \frac{\omega\, T_y}{\rho\, W_0\, U_0} \right| = \left\{ \beta_1^2 + \epsilon^2\, \beta_3^2\, (1 - S)^2 + 2\beta_1\, \beta_3\, \epsilon\, (1 - S) \cos \omega t \right\}^{1/2}. \quad \ldots(3.33)$$

The displacement thickness δ is defined as

$$\delta = \int_0^\infty \left(1 - \frac{u}{U_0} \right) dz \text{ or } \frac{\delta\, W_0}{\alpha} = \int_0^\infty \left(1 - \left(\frac{u}{U_0} \right) \right) d\eta$$

$$\therefore\ \delta = \frac{\alpha\alpha_1}{(\alpha_1^2 + \beta_1^2) W_0} + \frac{\alpha\, \epsilon\, \alpha_3 \cos \omega t}{(\alpha_3^2 + \beta_3^2) W_0}. \quad \ldots(3.34)$$

The unperturbed displacement thickness δ_0 is given by

$$\delta_0 = \frac{\alpha\alpha_1}{W_0\, (\alpha_1^2 + \beta_1^2)}, \quad \ldots(3.35)$$

$$\therefore\ \Delta = \frac{W_0}{\alpha}\, (\delta - \delta_0) = \frac{\epsilon\, \alpha_3 \cos \omega t}{(\alpha_3^2 + \beta_3^2)}, \quad \ldots(3.36)$$

For $\quad \omega t = 1, \epsilon = 0.2, \Delta = \dfrac{0.2\ \alpha_3 \cos 1}{(\alpha_3^2 + \beta_3^2)}$. $\quad \ldots(3.37)$

4. Conclusion

Graphs for f_1, g_1, f_2, and g_2 versus η have been plotted for different values of Ω_1 (= 1, 2, 4); M (= 2, 4, 6); λ (= 2, 4, 6) and S (= 2, 4, 6) in Figs. 1-8.

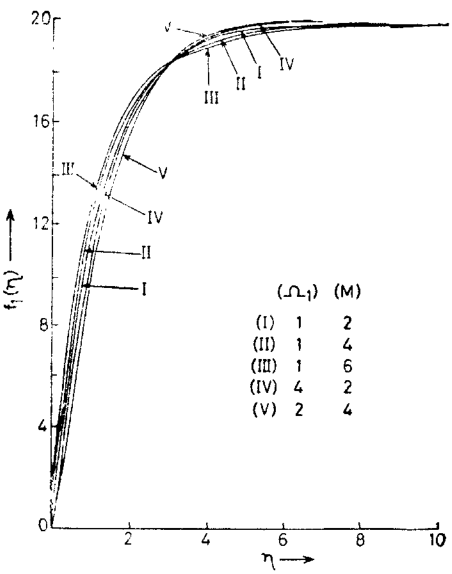

FIG. 1. Graphs for $f_1(\eta)$ versus η.

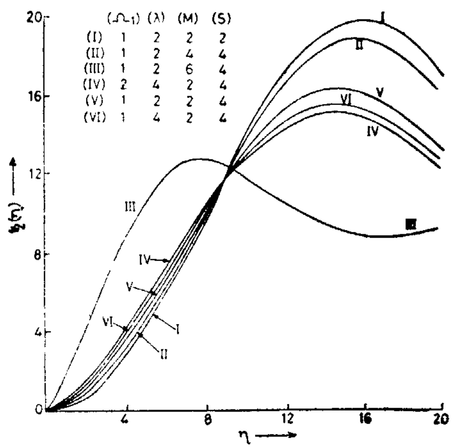

FIG. 2. Graphs for $f_2(\eta)$ versus η when $\lambda < \Omega_1$.

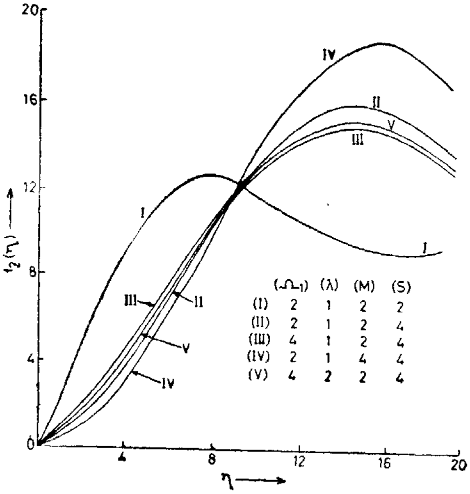

FIG. 3. Graphs for f_2 (η) versus η when $\lambda < \Omega_1$.

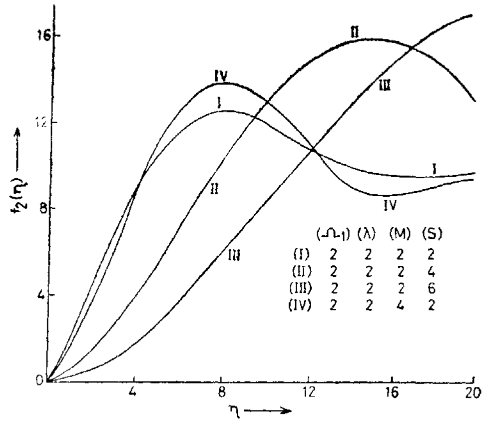

FIG. 4. Graphs for f_2 (η) versus η when $\lambda = \Omega_1$.

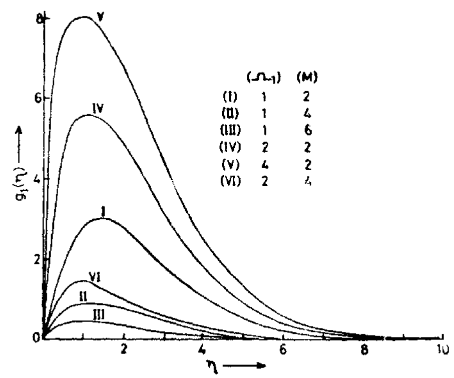

FIG. 5. Graphs for g_1 (η) versus η.

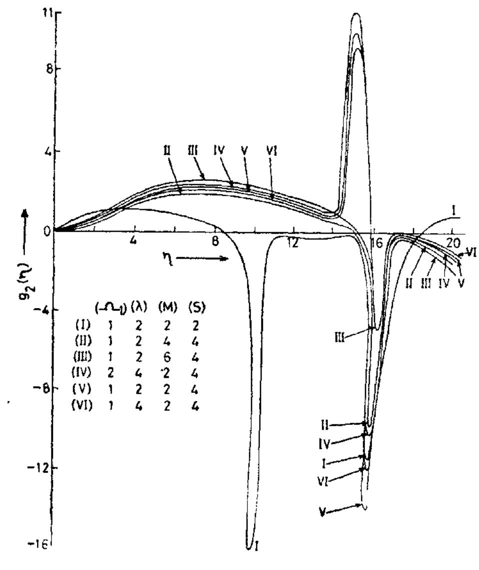

FIG. 6. Graphs for g_2 (η) versus η when $\Omega_1 < \lambda$.

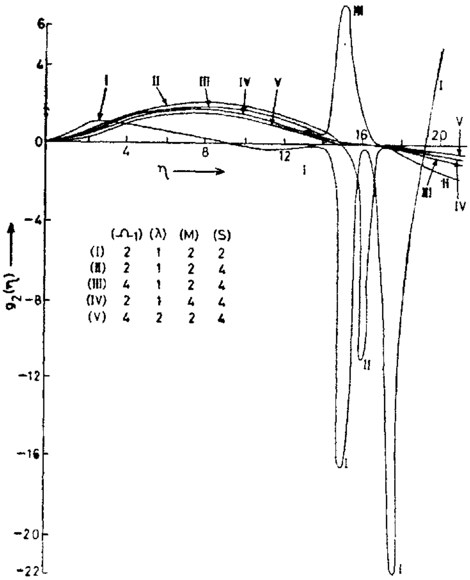

FIG. 7. Graphs for g_2 (η) versus η when $\Omega_1 > \lambda$.

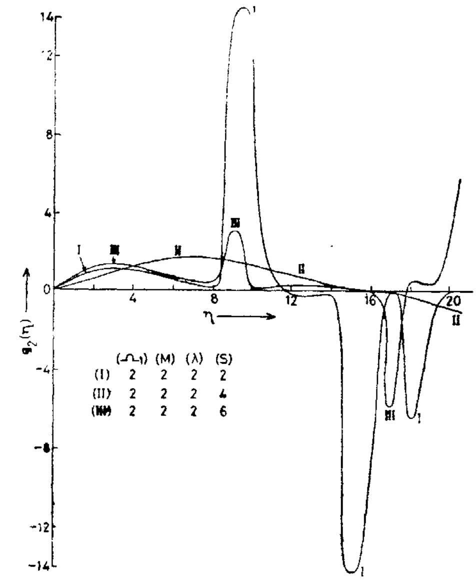

FIG. 8. Graphs for g_2 (η) versus η when $\lambda = \Omega_1$.

Effects of Ω_1, M, λ and S on f_1, f_2, g_1 and g_2 have shown for $\lambda < \Omega_1$, $\lambda > \Omega_1$ and $\lambda = \Omega_1$. It is evident from graphs that f_1 (η) decreases with increasing Ω_1 in the neighbourhood of the plate (small values of η) but for larger values of η, f_1 (η) increases with Ω_1. Also, effect of M is to increase f_1 (η) for smaller values of η but for larger values of η a reverse effect is noted. $g_1(\eta)$ increases with increasing Ω_1, whereas magnetic field M decreases g_1 (η). Strong fluctuations are felt in the neighbourhood of the plate. Evidently f_1 and g_1 are not affected by the elasticity of the fluid. Velocity fields f_2 and g_2 show much fluctuations at larger distance from the plate. When $\lambda > \Omega_1$, strong fluctuations are felt in comparison to when $\lambda < \Omega_1$. In case of $\lambda = \Omega_1$ (resonant frequency) fluctuations become quicker. Effects of M and S are greatly felt throughout the flow. In general the presence of M and S increases the fluctuations in the stream-velocity field.

Drag on the plate has been plotted versus λ and Ω_1 in Figs. 9 and 10. It is found that with the increase in λ and Ω_1 drag decreases. Both M and S increase the drag on the plate.

Lateral stress decreases with increasing elasticity (S) and magnetic field (M) when Ω_1 is fixed. Also, the lateral stress shows larger fluctuations with the increasing Ω_1 (λ fixed).

If β (or S) = 0, we have $l = 1 + 4M^2$,

$$m = \lambda + 2\Omega_1, \ \alpha_2 = \alpha_3 = \frac{1}{4} \ \frac{[\sqrt{l^2 + 16m^2} - l]^{1/2}}{(l^2 + 16m^2)^{1/4}} \ ,$$

$\beta_2 = \beta_3 = \frac{1}{4} \frac{[\sqrt{l^2 + 16m^2} - l]^{1/2}}{(l^2 + 16m^2)^{1/4}}$ etc. and all the above results are reduced to those obtained by Ashok Kumar (1978) execept for notations for Newtonian viscous fluid.

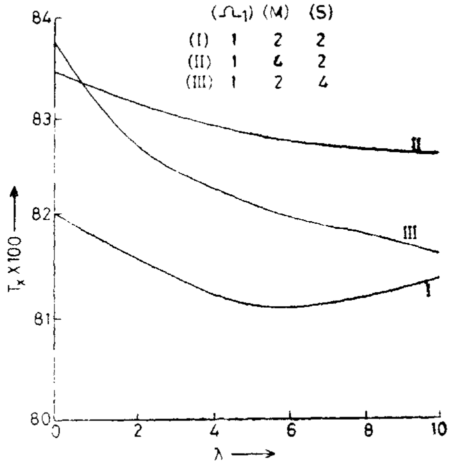

FIG. 9. Drag on the plate versus λ.

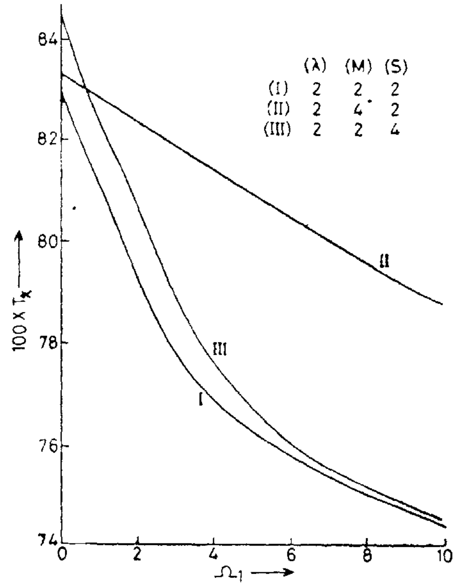

FIG. 10. Drag on the plate versus Ω_1.

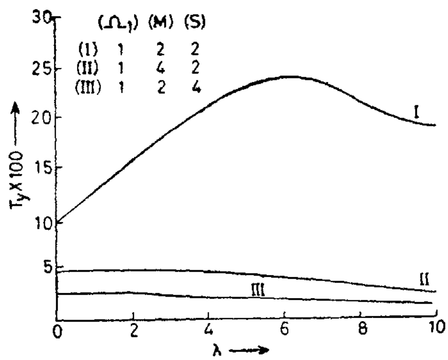

FIG. 11. Lateral stress on the plate versus λ.

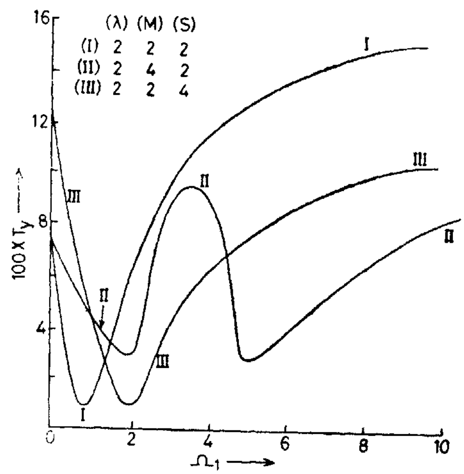

FIG. 12. Lateral stress on the plate versus Ω_1.

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