

# MHD Viscoelastic Flow of a Conducting Fluid near an Oscillating Flat Plate

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**ABSTRACT:** In this paper the magnetohydrodynamic flow of a viscoelastic incompressible and electrically conducting fluid near an infinite oscillating flat plate in presence of a transverse magnetic field fixed relative to the fluid has been considered. Fourier Sine transforms and Laplace transform techniques have been used to solve the governing equations. The effects of magnetic field, elasticity of the fluid, frequency of oscillation of the plate and the time of commencement of motion on the velocity field have been studied and the results are shown in different graphs.

**KEYWORDS:** Magneto-hydrodynamic flow, Oscillating flat plate, Viscoelastic fluid, Fourier Sine transform, Laplace transform.

## I. INTRODUCTION

The study of the non-Newtonian fluids has gained considerable importance in recent times due to its applications in various branches of science, engineering and technology; particularly in material processing, chemical and nuclear industries and bio-engineering. For a variety of reasons, non-Newtonian fluids are classified on the basis of their behavior in shear. A fluid with a linear relationship between the shearing stress and the rate of strain giving rise to a constant viscosity is known as Newtonian fluid. Otherwise the fluid is called as non-Newtonian fluid. Viscoelastic fluids are non-Newtonian which are characterized by the fluid models like Maxwell model, Oldroyd model, Rivlin-Ericksen second order model, Johnson Seagalman model and have been presented by many investigators in various analytical and computational schemes. The viscoelastic fluids are encountered in number of areas like petrochemical, biomedical and environmental engineering.

Stokes (1901) and Rayleigh (1911) studied the viscous flow problem about an infinite flat plate which executes harmonic oscillations parallel to it. Arroea and Gupta (1974) considered the flow due to an oscillating infinite plate covered by a layer of an incompressible conducting viscous fluid with its upper surface being free. Choudhary (1977), Ray and Das (1977) and many authors have made similar studies on the flow near an oscillating flat plate. Biswal and Mishra (1984) studied the flow of a conducting viscoelastic fluid near an oscillating flat plate in presence of a parallel stationary plate. Three dimensional convective MHD flow of a viscous incompressible fluid confined in a long vertical channel whose both sides are made up of permeable plates was discussed by Choudhary and Sharma (2003) through a set of nonlinear ordinary differential equations whose solutions were obtained analytically to obtain the velocity and heat transfer profiles and the effects of magnetic field and injection parameters were also studied. Hydro magnetic flow of Rivlin-Ericksen fluid down an inclined plane was studied by Suvan and Venkatrama (2002). The effects of magnetic and viscoelastic parameters were investigated on velocity and flux of the fluid drag per unit width and temperature distribution. The flow of a Viscoelastic fluid on an oscillating flat plate has been investigated by Hayet et al. (2004). Wouter et al. (2005) have studied the velocity based approach to viscoelastic flow. MHD mixed convection flow of a Viscoelastic fluid past an infinite vertical porous plate with mass transfer has been investigated by Choudhary et al. (2006). Roy Mohapatra et al. (2007) have worked on momentum and heat transfer in the MHD stagnation point flow of viscoelastic fluid. Similar type of flow problems have been studied by Masood Khan (2009), Khan et al. (2009), Mishra et al. (2010) and Satyaarayana et al. (2011). Recently Devika et al. (2013) have investigated on MHD oscillatory flow of a viscoelastic fluid in a porous channel. Also Imran et al. (2014) have worked on MHD

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oscillating flows of a rotating second grade fluid in porous medium. Riaz et al. (2015) have investigated the flows of generalized second grade fluid generated by an oscillating flat plate.

The aim of this paper is to study the motion of a viscoelastic incompressible and electrically conducting fluid near an infinite oscillating flat plate in presence of a transverse magnetic field fixed relative to the fluid. Fourier Sine transforms and Laplace transform techniques have been used to solve the basic equations. The effects of magnetic field, elasticity of the fluid, frequency of oscillation of the plate and the time of commencement of motion on the velocity field have been studied.

## II. FORMULATION OF THE PROBLEM

The Cartesian coordinates  $x$ ,  $y$ , and  $z$  are chosen such that  $x$ -axis is taken along the plate and  $y$ -axis is normal to it. The plate  $y=0$  is suddenly starts performing harmonic oscillation from rest about the axis  $x=0$  in presence of an externally applied transverse magnetic field of uniform strength  $H_0$  fixed relative to the fluid. As the plate is infinite in length, the physical quantities depend only on “ $y$ ” and “ $t$ ”, the time. So the velocity field consistent with continuity criterion is

$$u = u(y, t), v = 0, w = 0 \tag{1}$$

The pressure in the fluid is assumed to be constant.

Following Roy and Das (1977), the momentum equation for the flow is simplified to

$$\frac{\partial u}{\partial t} + \lambda_1 \frac{\partial^2 u}{\partial t^2} = \nu \frac{\partial^2 u}{\partial y^2} + \nu \lambda_2 \frac{\partial^3 u}{\partial t \partial y^2} - \frac{\sigma \mu_e^2 H_0^2}{\rho} u \tag{2}$$

Here  $\rho$  is the density,  $\nu$  is the kinematic viscosity,  $\sigma$  is the electrical conductivity,  $\mu_e$  is the magnetic permeability,

$\lambda_1$  is the stress relaxation time and  $\lambda_2$  is the strain retardation time. The term  $\frac{\sigma \mu_e^2 H_0^2}{\rho} u$  represents the ponder

motive force parallel to the plate.

The boundary conditions are

$$\left. \begin{aligned} t \leq 0 : u(y, t) = 0 \forall y, \frac{\partial u}{\partial t} = 0 \\ t > 0 : y = 0, u(y, t) = U_0 \cos nt \\ y \rightarrow \infty, u(y, t) = 0 \\ y \rightarrow \infty, \frac{\partial u}{\partial y} = 0 \end{aligned} \right\} \tag{3}$$

Here we use the transformations

$$\tau = \frac{t}{T}, r = \frac{y}{\sqrt{\nu T}}, \alpha_1 = \frac{\lambda_1}{T}, \alpha_2 = \frac{\lambda_2}{T} \tag{4}$$

From equation (4), we get

$$\frac{\partial u}{\partial t} = \frac{\partial u}{\partial \tau} \frac{1}{T}, \frac{\partial^2 u}{\partial t^2} = \frac{\partial^2 u}{\partial \tau^2} \frac{1}{T^2}, \frac{\partial u}{\partial y} = \frac{\partial u}{\partial r} \frac{1}{\sqrt{\nu T}}$$

$$\frac{\partial^2 u}{\partial y^2} = \frac{\partial^2 u}{\partial r^2} \frac{1}{\nu T}, \frac{\partial^3 u}{\partial t \partial y^2} = \frac{\partial^3 u}{\partial \tau \partial r^2} \frac{1}{\nu T^2}$$

Hence from equation (2), we get

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$$\frac{\partial u}{\partial \tau} \frac{1}{T} + \lambda_1 \frac{1}{T^2} \frac{\partial^2 u}{\partial \tau^2} = \nu \frac{\partial^2 u}{\partial r^2} \frac{1}{\nu T} + \nu \lambda_2 \frac{\partial^3 u}{\partial \tau \partial r^2} \frac{1}{\nu T^2} - \frac{\sigma \mu_e^2 H_0^2}{\rho} u$$

Multiplying T both sides of this equation, we get

$$\frac{\partial u}{\partial \tau} + \alpha_1 \frac{\partial^2 u}{\partial \tau^2} = \frac{\partial^2 u}{\partial r^2} + \alpha_2 \frac{\partial^3 u}{\partial \tau \partial r^2} - mu \tag{5}$$

Where  $m = \frac{\sigma \mu_e^2 H_0^2}{\rho}$

The boundary conditions are

$$\left. \begin{aligned} \tau \leq 0 : u(r, \tau) = 0 \forall r, \frac{\partial u}{\partial \tau} = 0 \\ \tau > 0 : r = 0, u(r, \tau) = U_0 \cos w \tau \\ r \rightarrow \infty, u(r, \tau) = 0 \\ r \rightarrow \infty, \frac{\partial u}{\partial r} = 0 \end{aligned} \right\} \tag{6}$$

Where  $w = nT$

### III. SOLUTION OF THE EQUATIONS

We shall solve equation (5) by using Fourier Integral Transforms.

If we define the Fourier Sine Transform

$$u^*(\varphi, \tau) = \sqrt{\frac{2}{\pi}} \int_0^\infty u(r, \tau) \sin \varphi r dr \tag{7}$$

Then it is known [Sneddon (1951)] that

$$u(r, \tau) = \sqrt{\frac{2}{\pi}} \int_0^\infty u^*(r, \tau) \sin \varphi r d\varphi \tag{8}$$

Multiplying both sides of equation (5) by  $\sin \varphi r$ , we get

$$\sqrt{\frac{2}{\pi}} \frac{\partial u}{\partial \tau} \sin \varphi r + \sqrt{\frac{2}{\pi}} \alpha_1 \frac{\partial^2 u}{\partial \tau^2} \sin \varphi r = \sqrt{\frac{2}{\pi}} \frac{\partial^2 u}{\partial r^2} \sin \varphi r + \sqrt{\frac{2}{\pi}} \alpha_2 \frac{\partial^3 u}{\partial \tau \partial r^2} \sin \varphi r - \sqrt{\frac{2}{\pi}} mu \sin \varphi r$$

Then integrating this equation both sides with respect to r within the limits 0 to  $\infty$ , we get

$$\int_0^\infty \sqrt{\frac{2}{\pi}} \frac{\partial u}{\partial \tau} \sin \varphi r dr + \int_0^\infty \sqrt{\frac{2}{\pi}} \alpha_1 \frac{\partial^2 u}{\partial \tau^2} \sin \varphi r dr = \int_0^\infty \sqrt{\frac{2}{\pi}} \frac{\partial^2 u}{\partial r^2} \sin \varphi r dr + \int_0^\infty \sqrt{\frac{2}{\pi}} \alpha_2 \frac{\partial^3 u}{\partial \tau \partial r^2} \sin \varphi r dr - \int_0^\infty \sqrt{\frac{2}{\pi}} mu \sin \varphi r dr$$

Simplifying this equation, we get

$$\frac{\partial u^*}{\partial \tau} + \alpha_1 \frac{\partial^2 u^*}{\partial \tau^2} + mu^* = \int_0^\infty \sqrt{\frac{2}{\pi}} \frac{\partial^2 u}{\partial r^2} \sin \varphi r dr + \int_0^\infty \sqrt{\frac{2}{\pi}} \alpha_2 \frac{\partial^3 u}{\partial \tau \partial r^2} \sin \varphi r dr \tag{9}$$

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$$\begin{aligned}
 \text{Now } & \int_0^\infty \sqrt{\frac{2}{\pi}} \frac{\partial^2 u}{\partial r^2} \sin \varphi r dr \\
 &= \sqrt{\frac{2}{\pi}} \left\{ \left[ \sin \varphi r \cdot \frac{\partial u}{\partial r} \right]_0^\infty - \int_0^\infty \frac{\partial u}{\partial r} \cos \varphi r \varphi dr \right\} \\
 &= -\sqrt{\frac{2}{\pi}} \varphi \int_0^\infty \frac{\partial u}{\partial r} \cos \varphi r dr \\
 &= -\sqrt{\frac{2}{\pi}} \varphi [0 - U_0 \cos w \tau] - \varphi^2 u^* \\
 &= \sqrt{\frac{2}{\pi}} \varphi U_0 \cos w \tau - \varphi^2 u^* \tag{10}
 \end{aligned}$$

(Using the boundary condition as in equation (6))

$$\begin{aligned}
 \text{Again } & \int_0^\infty \sqrt{\frac{2}{\pi}} \alpha_2 \frac{\partial^3 u}{\partial \tau \partial r^2} \sin \varphi r dr \\
 &= \sqrt{\frac{2}{\pi}} \alpha_2 \left\{ \left[ \sin \varphi r \cdot \frac{\partial^2 u}{\partial \tau \partial r} \right]_0^\infty - \int_0^\infty \frac{\partial^2 u}{\partial \tau \partial r} \cos \varphi r \varphi dr \right\} \\
 &= \sqrt{\frac{2}{\pi}} \alpha_2 \varphi U_0 w \sin w \tau - \alpha_2 \varphi^2 \frac{\partial u^*}{\partial \tau} \tag{11}
 \end{aligned}$$

Now from equation (9), (10) and (11), we get

$$\begin{aligned}
 \frac{\partial u^*}{\partial \tau} + \alpha_1 \frac{\partial^2 u^*}{\partial \tau^2} + m u^* &= \left( -\varphi^2 u^* + \sqrt{\frac{2}{\pi}} \alpha U_0 \cos w \tau \right) \\
 &+ \left( -\alpha_2 \varphi^2 \frac{\partial u^*}{\partial \tau} + \sqrt{\frac{2}{\pi}} \alpha_2 \varphi U_0 w \cos w \tau \right) \\
 \text{Or } \frac{\partial u^*}{\partial \tau} + \alpha_1 \frac{\partial^2 u^*}{\partial \tau^2} + m u^* + \varphi^2 u^* + \alpha_2 \varphi^2 \frac{\partial u^*}{\partial \tau} &= \sqrt{\frac{2}{\pi}} \varphi U_0 \cos w \tau - \sqrt{\frac{2}{\pi}} \alpha_2 \varphi U_0 w \sin w \tau \\
 \text{Or } \alpha_1 \frac{\partial^2 u^*}{\partial \tau^2} + (1 + \alpha_2 \varphi^2) \frac{\partial u^*}{\partial \tau} + (\varphi^2 + m) u^* &= \sqrt{\frac{2}{\pi}} U_0 \varphi (\cos w \tau - \alpha_2 w \sin w \tau) \tag{12}
 \end{aligned}$$

The boundary conditions (6) give

$$u(\varphi, 0) = 0, \frac{\partial u^*}{\partial \tau}(\varphi, 0) = 0 \tag{13}$$

Now equation (12) can be written as

$$\alpha_1 u^{*''} + (1 + \alpha_2 \varphi^2) u^{*' } + (\varphi^2 + m) u^* = \sqrt{\frac{2}{\pi}} U_0 \varphi (\cos w \tau - \alpha_2 w \sin w \tau)$$

Taking Laplace Transform both sides of this equation, we get

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$$\alpha_1 \left( u^{*''} \right) + (1 + \alpha_2 \varphi^2) L \left( u^{*' \right) + (\varphi^2 + m) L \left( u^* \right) = \sqrt{\frac{2}{\pi}} U_0 \varphi L (\cos w \tau - \alpha_2 w \sin w \tau)$$

Then simplifying this equation and using boundary conditions (13), we get

$$\alpha_1 (p^2 \bar{u}^*) + (1 + \alpha_2 \varphi^2) p \bar{u}^* + (\varphi^2 + m) \bar{u}^* = \sqrt{\frac{2}{\pi}} U_0 \varphi \left( \frac{p - \alpha_2 w^2}{p^2 + w^2} \right)$$

$$\text{Or } \alpha_1 [\alpha_1 p^2 + (1 + \alpha_2 \varphi^2) p + (\varphi^2 + m)] \bar{u}^* = \sqrt{\frac{2}{\pi}} U_0 \varphi \left( \frac{p - \alpha_2 w^2}{p^2 + w^2} \right)$$

$$\text{Or } \bar{u}^* (\varphi, p) = \sqrt{\frac{2}{\pi}} U_0 \varphi \frac{p - \alpha_2 w^2}{\alpha_1 (p^2 + w^2) (p - a) (p - b)} \tag{14}$$

Where  $\alpha_1 (p - a) (p - b) = \alpha_1 p^2 + (1 + \alpha_2 \varphi^2) p + (\varphi^2 + m)$

$$a, b = \frac{1}{\alpha_1} \left[ - (1 + \alpha_2 \varphi^2) \pm \sqrt{(1 + \alpha_2 \varphi^2)^2 - 4 \alpha_1 (\varphi^2 + m)} \right]$$

Now taking the inverse Laplace Transform of (14), we get

$$u^* (\varphi, \tau) = \sqrt{\frac{2}{\pi}} U_0 \varphi (A \cos w \tau + B w \sin w \tau + C e^{a\tau} + D e^{b\tau}) \tag{15}$$

$$\text{Where } A = \frac{\varphi^2 (1 + \alpha_2 \varphi^2) - w^2 (\alpha_1 - \alpha_2)}{(\varphi^2 - \alpha_1 \varphi^2) + w^2 (1 + \alpha_2 \varphi^2)^2}, B = \frac{(1 + \alpha_1 \alpha_2 w^2)}{(\varphi^2 - \alpha_1 \varphi^2)^2 + w^2 (1 + \alpha_2 \varphi^2)^2}$$

$$C = \frac{A (1 + \alpha_2 \varphi^2 + \alpha_1 a) + B w \alpha_1}{\left[ (1 + \alpha_2 \varphi^2)^2 - 4 \alpha_1 (\varphi^2 + m) \right]^{1/2}}, D = \frac{A (1 + \alpha_2 \varphi^2 + \alpha_1 b) + B w \alpha_1}{\left[ (1 + \alpha_2 \varphi^2)^2 - 4 \alpha_1 (\varphi^2 + m) \right]^{1/2}}$$

From equation (15) and (9), we get

$$u(r, \tau) = \frac{2}{\pi} U_0 \int_0^\infty \varphi \sin \varphi r (A \cos w \tau + B w \sin w \tau + C e^{a\tau} + D e^{b\tau}) d\varphi \tag{16}$$

### IV. PARTICULAR CASES

1. The Solution of the Newtonian viscous liquid can be recovered as a particular case by putting  $m=0$  and  $\alpha_1 = \alpha_2 = \alpha$  and then by considering  $\alpha \rightarrow 0$ , we get

$$\frac{u(r, \tau)}{U_0} = e^{-kr} \cos(w \tau - kr) - \frac{1}{\pi} \int_0^\infty e^{-x\tau} \sin(r\sqrt{x}) \frac{x}{x^2 + w^2} dx \tag{17}$$

Where  $2k^2 = w$

When  $\tau \rightarrow 0$ , we get the quasi steady state solution

$$\frac{u(r, \tau)}{U_0} = e^{-kr} \cos(w \tau - kr) \tag{18}$$

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2. The case of impulsively started plane wall can also be recovered as a particular case when  $w = 0$

### V. CONCLUSION

The problem of the flow of a conducting non-Newtonian liquid near a plane wall which starts performing harmonic oscillation from rest in the presence of a transverse magnetic field of uniform strength has been solved by using integral transform method. Solutions have been obtained for velocity field and the following conclusions have been drawn.

1. From Figure-1 it is observed that the velocity in a thin liquid layer near the plate increases with the time  $\tau$ . Beyond this liquid layer near the plate, the velocity decreases as  $\tau$  increases. Finally, the velocity increases with the time.
2. Also figure-1 shows the effect of magnetic number  $M$  on the velocity field for  $w\tau = \frac{\pi}{6}$  and  $\alpha_1 - \alpha_2 = 0.05$ . It is observed that magnetic number  $M$  decreases the velocity at any point. When the plate just starts oscillating, i.e. for small values of time, the effect of the magnetic number  $M$  is much appreciable.
3. Figure-2 depicts the effect of  $w\tau$  which may be taken as the frequency of oscillation of the plate on the velocity at any point for  $\tau = 0.1, \alpha_1 - \alpha_2 = 0.05, M = 1.0$ . We observe the following

In a thin liquid layer near the plate as  $w\tau$  increases, the velocity decreases. But an opposite effect is observed in a liquid layer beyond this. At the final stage, the velocity decreases as  $w\tau$  increases. It is interesting to note that the curve for velocity intersect at two points.

4. Figure-3 shows the effect of  $M$  on the velocity field for  $w\tau = \frac{\pi}{6}, \tau = 0.1$  and  $\alpha_1 - \alpha_2 = 0.05$ . It is seen that the velocity field is affected considerably by  $M$ .

Figure-1 shows that the velocity in a thin liquid layer near the plate increases with the time  $\tau$ . Beyond this liquid layer near the plate, the velocity decreases as  $\tau$  increases. Finally, the velocity increases with the time. Also figure-1 shows the effect of magnetic number  $M$  on the velocity field for  $w\tau = \frac{\pi}{6}$  and  $\alpha_1 - \alpha_2 = 0.05$ . It is observed that magnetic number  $M$  decreases the velocity at any point. When the plate just starts oscillating, i.e. for small values of time, the effect of the magnetic number  $M$  is much appreciable.

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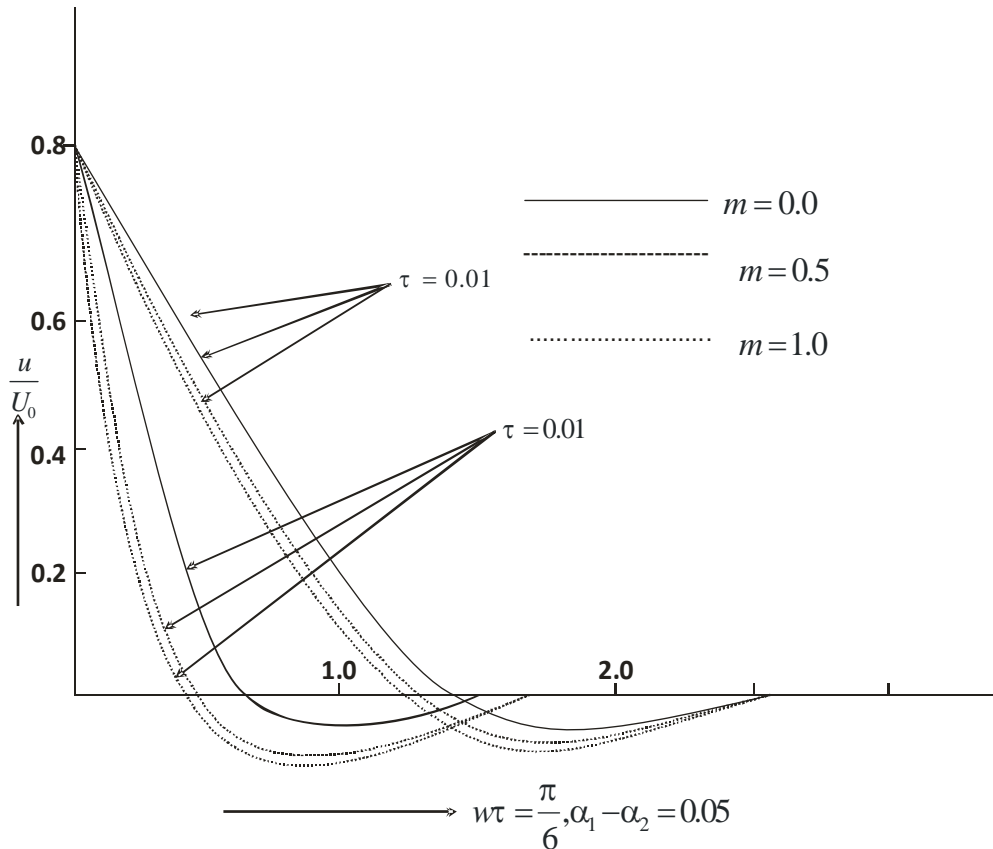


Figure-1: Velocity distribution for different values of  $\tau$

Figure-2 depicts the effect of  $w\tau$  which may be taken as the frequency of oscillation of the plate on the velocity at any point for  $\tau = 0.1, \alpha_1 - \alpha_2 = 0.05, M = 1.0$ . We observe the following: In a thin liquid layer near the plate as  $w\tau$  increases, the velocity decreases. But an opposite effect is observed in a liquid layer beyond this. At the final stage, the velocity decreases as  $w\tau$  increases. It is interesting to note that the curve for velocity intersect at two points.

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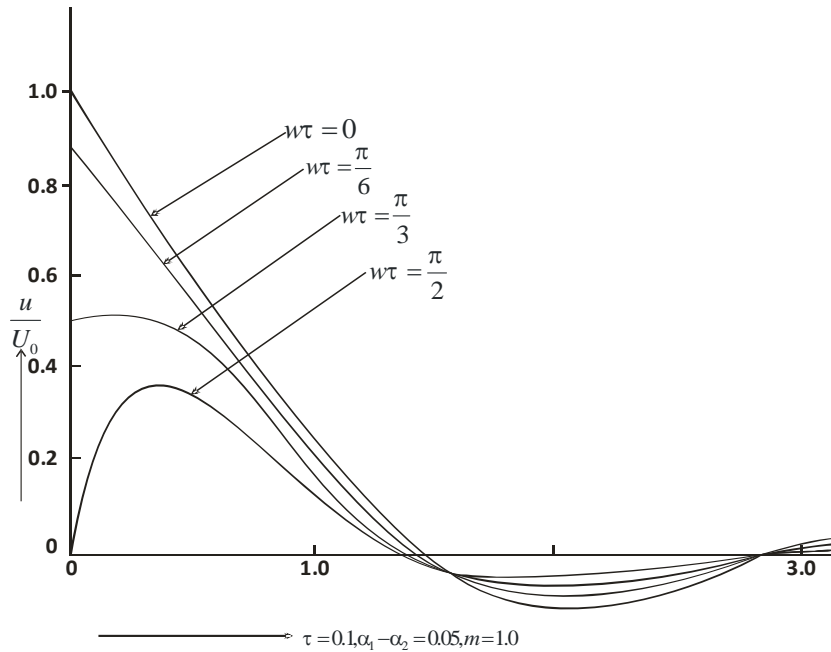


Figure-2: Velocity distribution for different values of  $w\tau$

Figure-3 shows the effect of  $M$  on the velocity field for  $w\tau = \frac{\pi}{6}$ ,  $\tau = 0.1$  and  $\alpha_1 - \alpha_2 = 0.05$ . It is seen that the velocity field is affected considerably by  $M$ .

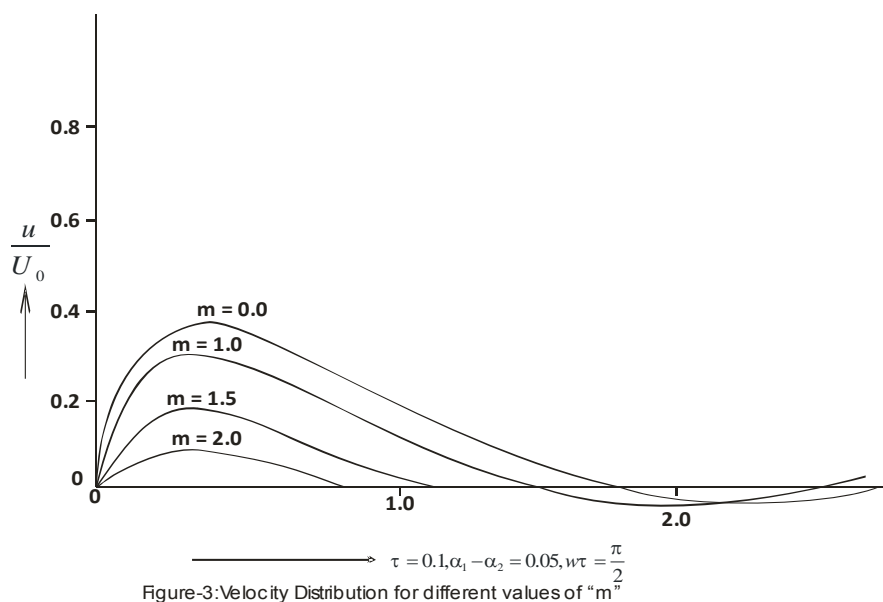


Figure-3: Velocity Distribution for different values of "m"



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