ON UNSTEADY NON-NEWTONIAN FLOWS
IN A ROTATING SYSTEM-I

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(Received 22 XII. 1972)

An incompressible isotropic visco-elastic liquid is bounded by an infinite rigid horizontal disk at z = 0. Both the fluid and the disk are in a state of solid body rotation with a uniform angular velocity \( \Omega \) about the z-axis. At time \( t = 0^+ \), small amplitude non-torsional oscillations are superimposed on the disk, or the disk is impulsively moved with a constant acceleration so that an unsteady motion is set up in the liquid. An analysis is made of the unsteady flow generated in the visco-elastic liquid. The velocity field is calculated by using the Laplace transform treatment and the structure of the associated boundary layers is determined. This analysis provides the existence of Stokes-Ekman-Elastic boundary layers of thicknesses of the order \( \frac{r}{\Omega} \frac{1}{\sigma_r} \), \( r = 1, 2 \). Special emphasis is given to the limiting behaviour of the solution as \( t \to \infty \), and the significant interaction of the elastic parameter and rotation is examined. The surface traction at the disk is found and the effects of elasticity on this quantity are discussed. It is shown that in the absence of the elasticity, the results of this paper reduce to the corresponding results of the Newtonian rotating fluid.

1. Introduction

Many common liquids such as oils, certain paints, blood, polymer solutions, some organic liquids, and many new materials of industrial importance exhibit both viscous and elastic properties. Based on the macroscopic rheological behaviour of real materials, Oldroyd [1—2] formulated rheological equations of state for a class of incompressible, visco-elastic liquids and initiated the study of visco-elastic flows. Subsequently, Walters [3—4] considered a generalization of these constitutive rheological equations of state for wider class of visco-elastic fluids. Based upon both Oldroyd and Walters equations of state, the steady flow phenomena have received a considerable attention for various configurations.

To indicate our interest in visco-elastic flows, mention may be made of works of Beard and Walters [5] and Jones and Lewis [6] on steady boundary layer phenomena in non-Newtonian fluids. Recently, Puri and Kulshekheda [7] have considered visco-elastic fluid flows with artificial boundary conditions. Their analysis revealed that the structure of the boundary layers does not depend on the elastic parameter of the problem. This study seems to be incomplete and has limited applications.

In spite of the above works, hardly any work is done on unsteady viscoelastic fluid flows which has some particular geophysical applications. It is of interest to make an initial value investigation of the boundary layer flow in visco-elastic fluids to determine the main effects of elasticity on the structure of the flow field and the associated boundary layers.

The present paper is concerned with a study of unsteady motion of an incompressible visco-elastic liquid in a rotating frame of reference due to some physically realizable motion prescribed on the boundary of the liquid. A semi-infinite expanse of visco-elastic liquid is bounded by an infinite horizontal rigid disk at $z = 0$. Both the fluid and the disk are in a state of solid body rotation with a uniform angular velocity $\Omega$ about the $z$-axis normal to the disk. At time $t = 0+$, small amplitude non-torsional oscillations are superimposed on the disk in its own plane or the disk is moved impulsively with a constant acceleration so that an unsteady flow is set up in the liquid. The initial value problem is then solved by the Laplace transform treatment. The unsteady flow field and the thickness of the associated boundary layers are determined. Special attention is given to the limiting behaviour of the solution as $t \to \infty$ and the significant interaction of rotation and elasticity is examined. The surface traction at the disk is obtained and the effects of the elastic parameter on this physical quantity are discussed. It is shown that in the absence of the elastic parameter, the results of this paper reduce to the corresponding results of the Newtonian rotating flows.

2. The constitutive equations of state, motion and continuity

Walters [8] formulated the rheological equations of state for the viscoelastic liquid $B'$ which are

\[
p_{ik} = -p \varepsilon_{ik} + p'_{ik},
\]

\[
p'_{ik}(x,t) = 2 \int \psi(t - t') \frac{\partial x'}{\partial x'^m} \frac{\partial x'}{\partial x'^r} \delta^{mr}(x', t') \, dt',
\]

where $p_{ik}$ is the stress tensor, $p$ is an arbitrary isotropic pressure, $\varepsilon_{ik}$ is the metric tensor of a fixed coordinate system $x'$, $p'_{ik}$ is the part of the stress tensor related to change of shape of a material element (or the reduced stress tensor $x'' = x''(x,t,t')$ is the position at time $t'$ of the element which is instantaneous at the point $x'$ at time $t$), $\dot{e}_{ik}^{ij}$ is the rate of strain tensor and

\[
\psi(t - t') = \int_0^\infty \frac{N(\tau)}{\tau} \exp\left[-\frac{(t - t')}{\tau}\right] \, d\tau,
\]

$N(\tau)$ being the distribution function of relaxation time $\tau$. 

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The Oldroyd rheological equations of state (1) for the visco-elastic liquid $B$:

$$
\left( p^{\tau k} + \lambda_1 \frac{\delta}{\delta t} p^{\tau k} \right) = 2\eta_0 \left[ \epsilon^{(1)jk} + \lambda_2 \frac{\delta}{\delta t} \epsilon^{(1)jk} \right],
$$

(2.4)

as a special case of the Walters liquid $B'$, when

$$
N(\tau) = \eta_0 \frac{\lambda_2}{\lambda_1} \delta(\tau) + \eta_0 \left( \frac{\lambda_1 - \lambda_2}{\lambda_2} \right) \delta(\tau - \lambda_1),
$$

(2.5)

substituted in Eqs. (2.2) and (2.3), where $\delta(\tau)$ is the Dirac delta function of time $\tau$, $\eta_0$ is the coefficient of viscosity, $\lambda_1$, $\lambda_2$, $\lambda_1 < \lambda_2$ are the relaxation and retardation times respectively and $\delta(\tau)$ represents the convective derivative which is a total derivative following a typical fluid element taking into account the rotational as well as the translational motion of the element. The convective derivative of any contravariant tensor $a^{ik}$ is given by

$$
\frac{\delta}{\delta t} a^{ik} = \frac{\partial}{\partial t} a^{ik} + \nu \frac{\partial a^{ik}}{\partial x^m} - \frac{\partial}{\partial x^m} \left( \nu \frac{\partial a^{ik}}{\partial x^m} - \frac{\partial a^{ik}}{\partial x^m} \right),
$$

(2.6)

where $\nu'$ is the velocity vector.

The constitutive equations for the Newtonian liquid and the Maxwell quid follow from (2.4) when $\lambda_1 = \lambda_2$, and $\lambda_2 = 0$ respectively. The Newtonian quid is also given by $N(\tau) = \eta_0 \delta(\tau)$.

Walters has also shown that for liquids of short memory (that is, small viscoelasticity), the equation of state has the simplified form

$$
p^{\tau k} = 2\eta_0 \epsilon^{(1)jk} - 2\eta_0 \frac{\delta}{\delta t} \epsilon^{(1)jk},
$$

(2.7)

where $\eta_0 = \int_0^\infty N(\tau) \, d\tau$, is the limiting viscosity at small rates of shear and

$$
k_0 = \int_0^\infty \tau N(\tau) \, d\tau.
$$

Eqs. (2.1) and (2.7) constitute the equations of state for another class of liquids called the Walters liquid $B''$.

For the Oldroyd liquid $B$, $k_0 = \eta_0 (\lambda_1 - \lambda_2)$ so that Eq. (2.7) becomes

$$
p^{\tau k} = 2\eta_0 \epsilon^{(1)jk} - 2\eta_0 (\lambda_1 - \lambda_2) \frac{\delta}{\delta t} \epsilon^{(1)jk},
$$

(2.8)

in this case, the approximation is equivalent to neglecting the second order terms in $\lambda_1$ and $\lambda_2$. 

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Using the equations of state (2.1) and (2.7), the equation of motion and continuity in a rotating Cartesian frame of reference can be written as

\[ \frac{\partial v}{\partial t} + (v \cdot \nabla)v + 2\Omega \times v = -\nabla P + \nu \nabla^2 v - k_\eta \frac{\partial}{\partial t} \nabla^2 v + 2(v \cdot \nabla)v \nabla^2 v - \nabla^2 \left[ \left( v \cdot \nabla \right) v \right] \]

\[ \text{div} \, v = 0, \]

where \( \Omega \) is the rotation vector, \( P \) is the pressure including the centrifugal term, \( \nu = \eta/\rho \) is the kinematic viscosity, \( k_\eta = k_0/\rho \) is the elastic parameter and \( \rho \) is the density of the liquid.

**3. Formulation of the problem**

We consider an incompressible visco-elastic liquid bounded by an infinite rigid horizontal disk at \( z = 0 \). Both the fluid and the disk are in a state of solid body rotation with a uniform angular velocity \( \Omega \) about the \( z \)-axis normal to the disk. In addition to rotation, the disk performs non-torsional ellipt harmonic oscillation in its own plane or the disk is moved impulsively with constant acceleration so that an unsteady flow is set up in the liquid.

We consider an unsteady motion with the velocity components depending on \( z \) and \( t \) alone. The boundary conditions to be satisfied are

\[ u + iv = U(t), \quad w = 0, \quad \text{on} \quad z = 0, \]

\[ u, v \to 0 \quad \text{as} \quad z \to \infty, \]

where \( U \) is a constant with dimension of velocity, and \( f(t) \) is an arbitrary but physically realizable function of time \( t \).

We further prescribe an assumption of periodicity or the initial condition as

\[ (u, v) = (0, 0) \quad \text{at} \quad t = 0 \quad \text{for all} \quad z > 0. \]

From (2.10), (3.1) and (3.2), it follows that \( w = 0 \), and the non-linear terms involved in the equations of motion disappear automatically. Consequently, in the absence of pressure gradient, the velocity field is governed by the linear equation

\[ \frac{\partial v}{\partial t} + 2\Omega k \times v = \left( v - k_\eta \frac{\partial}{\partial t} \nabla^2 v \right) \nabla^2 v, \]

where \( k \) is the unit vector parallel to the \( z \)-axis.

Remark: Eq (3.4) reduces to that for viscous rotating flows when \( k_\eta = 0 \), which have been investigated by DERNATH and HALL [9] and THORNLEY [10].

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This equation has to be solved subject to the boundary conditions (3.1), (3.2) and an assumption of periodicity or the initial condition (3.3).

4. The solution of the initial value problem

It is convenient to introduce non-dimensional variables $z'$, $t'$, $u'$ and $v'$ by

$$z' = \frac{z}{D}, \quad t' = \frac{t}{\Omega}, \quad (u', v') = \frac{1}{U} (u, v), \quad D = \left[ \frac{\nu}{\Omega} \right]^{\frac{1}{2}}. \quad (4.1)$$

In terms of the non-dimensional variables, Eq. (3.4) reduces to, dropping the primes,

$$\frac{\partial^2}{\partial t \partial z^2} v + k \frac{\partial^3 v}{\partial t \partial z^3} + 2k \times v = 0, \quad (4.2)$$

where

$$k = \frac{k_0}{D^2}. \quad (4.3)$$

Introducing the notation $p = u + iv$, Eq. (4.2), the boundary conditions (3.1) — (3.2) and the initial condition can be written in the form

$$\left( \frac{\partial}{\partial t} - \frac{\partial^3}{\partial z^3} \right) p + k \frac{\partial^3 p}{\partial z^3} + 2ip = 0, \quad (4.4)$$

$$p = f(t) \text{ on } z = 0, \quad t > 0, \quad (4.5)$$

$$p \rightarrow 0 \text{ as } z \rightarrow \infty, \quad t > 0, \quad (4.6)$$

$$p = 0 \text{ at } t = 0, \text{ for all } z > 0. \quad (4.7)$$

The initial value problem posed above can usually be solved by the Laplace transform method. The Laplace transform and its inverse are defined by (Sneddon, [11])

$$\tilde{p}(z, s) = \int_0^\infty e^{-st} p(z, t) \, dt, \quad (4.8)$$

$$p(z, t) = \frac{1}{2\pi i} \int_{c-i\infty}^{c+i\infty} e^{st} \tilde{p}(z, s) \, ds, \quad c > 0. \quad (4.9)$$

To determine the principal features of the unsteady flow, we consider the following cases of interest: (a) $f(t) = a e^{i\omega t} + b e^{-i\omega t}$ and (b) $f(t) = t$, where
$a, b$ are complex constants and $\omega$ is the non-dimensional frequency of oscillations of the disk.

The solution of equation (4.4) in the transformed space subject to the transformed boundary conditions is obtained in the form

$$\bar{p}(z, s) = \bar{f}(s) \exp \left\{ - m(1 + sk)^{\frac{1}{2}} z \right\}, \quad (4.10)$$

where $m = (s + 2i)^{1/2}$.

The inverse Laplace transformation yields

$$p(z, t) = \frac{1}{2\pi i} \int_{c-i\infty}^{c+i\infty} e^{st} \bar{p}(z, s) ds. \quad (4.11)$$

The evaluation of this integral with (4.10) is almost a formidable task. It is then necessary to resort to approximate methods.

To determine the effects of elasticity on the flows, it is of interest to find the solution for large time $t$ which can be achieved by evaluating (4.11) for small $s$. For small values of $s$,

$$\bar{p}(z, s) \sim \bar{f}(s) \exp \left\{ - z(s + 2i + 2i\sqrt{s}) \right\}. \quad (4.12)$$

The integral (4.11) can readily be evaluated with (4.12). Making reference to the table of Campbell and Foster [12], the solution for the flow field $p(z, t)$ given by

$$p(z, t) = \frac{a}{2} e^{i\omega t} \left[ \exp \left( -z \sqrt{i(2 + \omega) - 2k\omega} \right) \text{erfc} \left( \frac{z}{2} \sqrt{\frac{1 + 2ik}{t}} + \sqrt{\frac{i(2 + \omega) - 2k\omega}{1 + 2ik}} \right) \right]$$

$$+ \frac{b}{2} e^{-i\omega t} \left[ \exp \left( -z \sqrt{i(2 - \omega) + 2k\omega} \right) \text{erfc} \left( \frac{z}{2} \sqrt{\frac{1 + 2ik}{t}} - \sqrt{\frac{i(2 - \omega) + 2k\omega}{1 + 2ik}} \right) \right], \quad (4.13)$$

where $\text{erfc}(x)$ is the complementary error function defined by

$$\text{erfc}(x) = 1 - \text{erf}(x) = \frac{2}{\sqrt{\pi}} \int_{x}^{\infty} e^{-s^2} ds. \quad (4.13)$$

This solution describes general features of the unsteady boundary layer flow in a visco-elastic liquid. It is important to note that the effects of elastict

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4.13 is exactly identical with those of Thornley, and Debnath and Hall or viscous rotating flows. In the limit \( t \to \infty \), (4.13) is asymptotically equal to

\[
\gamma(z, t) \sim \alpha e^{\omega t} \exp \left[ -z \left( (2 + \omega) i - 2k\omega \right)^{\frac{1}{2}} \right] + b e^{-\omega t} \exp \left[ -z \left( (2 - \omega) + 2k\omega \right)^{\frac{1}{2}} \right]
\]

\[
= a \exp \left\{ i\omega t - (x_1 + i\beta_1) z \right\} + b \exp \left\{ -i\omega t - z(x_2 + i\beta_2) \right\}, \quad (4.15)
\]

where

\[
(2 + \omega) i - 2k\omega)^{\frac{1}{2}} = x_1 + i\beta_1, \quad (2 - \omega) + 2k\omega)^{\frac{1}{2}} = x_2 + i\beta_2, \quad (4.16a,b)
\]

with

\[
\begin{align*}
x_1 &= \left[ k^2\omega^2 + \left( 1 + \frac{\omega}{2} \right)^{\frac{1}{2}} - k\omega \right]^{\frac{1}{2}}, \\
\beta_1 &= \left[ k^2\omega^2 + \left( 1 + \frac{\omega}{2} \right)^{\frac{1}{2}} + k\omega \right]^{\frac{1}{2}}, \\
x_2 &= \left[ k^2\omega^2 + \left( 1 - \frac{\omega}{2} \right)^{\frac{1}{2}} + k\omega \right]^{\frac{1}{2}}, \\
\beta_2 &= \left[ k^2\omega^2 + \left( 1 - \frac{\omega}{2} \right)^{\frac{1}{2}} - k\omega \right]^{\frac{1}{2}}.
\end{align*}
\]

The steady state solution (4.15) clearly suggests the existence of the Stokes-Ekman-Elastic boundary layers of thicknesses of the order \( \frac{\nu}{\Omega} \frac{1}{x_1} \), \( = 1, 2 \). These boundary layers remain bounded for both resonant and non-resonant cases. In the absence of elastic parameter, the solution (4.14) with he associated boundary layers agrees with the corresponding results for the Newtonian fluids.

5. The solution for small values of the elastic parameter

Following the argument of Puri and Kulshrestha [7], the solution \( \phi(z, s) \) can be approximated for small \( k \) and is given by

\[
\tilde{p}(z, s) = \tilde{f}(s) \left( 1 - \frac{sk\omega}{2} \right) e^{-msz}. \quad (5.1)
\]

Making reference to Campbell and Foster [12], the solution for the velocity distribution for case (a) can be found explicitly as

\[
p(z, t) = \alpha e^{\omega t} \left[ \left( 1 - \frac{1}{2} \lambda_2 \omega z \right) \exp \left( -\lambda_2 s \right) \text{erfc} \left( \frac{z}{2\sqrt{t}} - \lambda_1 \sqrt{t} \right) \\
+ \left( 1 + \frac{1}{2} \lambda_1 \omega z \right) \exp \left( \lambda_1 s \right) \text{erfc} \left( \frac{z}{2\sqrt{t}} + \lambda_1 \sqrt{t} \right) \right]
\]
where

\[ + \frac{b}{2} e^{-\omega t} \left[ \left( 1 + \frac{x}{2} \omega \lambda \right) \exp \left( -\lambda z \right) \text{erfc} \left( \frac{x}{2 \sqrt{t}} - \lambda \right) \right] \]

\[ + \left( 1 - \frac{x}{2} \omega \lambda z \right) \exp \left( i \omega z \right) \alpha \text{erfc} \left( \frac{x}{2 \sqrt{t}} - \lambda \right) \]

\[ + \frac{(a + b)}{k} \frac{kz}{2 \sqrt{t}} \left( 1 - \frac{z^2}{2t} \right) \exp \left( -2it - \frac{z^2}{4t} \right) \]

\[ + \frac{skuz}{2\sqrt{\pi t}} \left( b - a \right) \exp \left( -2it - \frac{z^2}{4t} \right), \quad (5.2) \]

Solution (5.2) is exactly identical with that of Puri and Kulshrestha when \( \omega = 0 \) and \( a + b = 1 \). This result indicates the existence of the combined Stokes-Ekman layers of thicknesses of the order \((\Omega^2 - \omega)^{1/2}\) provided \( \omega \neq \Omega \). Apparently, the structure of the boundary layers remains unaffected by the elastic parameter \( k \). However, in the absence of \( k \), solution (5.2) agrees with that of Thornley.

In the limit \( t \to \infty \), with \( \omega \neq \Omega \), result (5.2) approaches to the ultimate steady-state solution which is identical with that for Newtonian fluid flow in a rotating system.

At the resonant frequency, \( \omega = \Omega \), one of the two boundary layer states above becomes infinite. Like Newtonian rotating flows, it follows that

\[ \lim_{t \to \infty} \lim_{\omega \to \Omega} p(z,t) = \lim_{\omega \to \Omega} \lim_{t \to \infty} p(z,t), \quad (5.4) \]

for even non-zero values of \( k \).

To obtain a meaningful solution at the resonant frequency, \( \omega \to \Omega \), we take the double limit \( t \to \infty, \omega \to \Omega \) in this particular order and the resultant solution is found to consist of the Stokes layer, and the Rayleigh layer of thickness of the order \( \Omega^2 \).

The above analysis reveals that the structure of the boundary layer for visco-elastic rotating flows with small elastic parameter remains unaffected. The surface traction at the disk at \( z = 0 \) is given by

\[ (\tau_{zz} + i \tau_{z})_{z=0} = \left[ \frac{3}{2} \left[ 1 - \frac{k \lambda}{2t} \right] p \right]_{x=0} \]

\[ = \frac{a}{2} e^{\omega t} \left[ 2 \lambda_1 \sqrt{\pi} (C_1 - iS_1) - \frac{2}{\sqrt{\pi t}} e^{-\omega t} \right] \]

\[ + \frac{b}{2} e^{-\omega t} \left[ 2 \lambda_2 \sqrt{\pi} (C_2 - iS_2) - \frac{2}{\sqrt{\pi t}} e^{-\omega t} \right] \]

\[ \left( \tau_{zz} + i \tau_{z} \right)_{z=0} = \left[ \frac{3}{2} \left( 1 - k \frac{\lambda}{2t} \right) p \right]_{x=0} = \frac{a}{2} e^{\omega t} \left[ 2 \lambda_1 \sqrt{\pi} (C_1 - iS_1) - \frac{2}{\sqrt{\pi t}} e^{-\omega t} \right] \]

\[ + \frac{b}{2} e^{-\omega t} \left[ 2 \lambda_2 \sqrt{\pi} (C_2 - iS_2) - \frac{2}{\sqrt{\pi t}} e^{-\omega t} \right] \]
\[ \begin{align*}
&+ \frac{ka}{2} e^{\omega t} \left[ -i\omega \lambda \sqrt{i} \left( C_1 - iS_1 \right) + \frac{2i\omega}{\sqrt{\pi t}} e^{-\frac{t^2}{4t^3}} - e^{-\frac{t^2}{4t^3}} \right] , \\
&- \frac{kb}{2} e^{-i\omega t} \left[ -\lambda \sqrt{i} \left( C_2 - iS_2 \right) + \frac{2i\omega}{\sqrt{\pi t}} e^{-\frac{t^2}{4t^3}} - e^{-\frac{t^2}{4t^3}} \right] , \\
&+ \left[ \frac{k(a + b)}{4\sqrt{\pi t^3}} + \frac{ik(b - a)\omega}{\sqrt{\pi t}} \right] \exp \left( -2i\omega \right) .
\end{align*} \tag{5.5} \]

where \( C_1 \) and \( S_1 \) are the usual Fresnel integrals [11] of argument \( \lambda \sqrt{i} \) (\( i = 1, 2 \)).

The result (5.5) suggests that the surface traction at the disk is considerably modified by small values of the parameter \( k \). Further, the surface traction is unbounded for small time \( t \). This implies that the visco-elastic fluid offers a greater resistance to the flow than the Newtonian fluid. However, when \( t \) is very large, the surface traction remains bounded. In the absence of the elastic parameter, the corresponding results for the viscous rotating flows can easily be recovered.

The unsteady flow field for case (b) is obtained as

\[ p(z, t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \left[ \frac{1}{z^2} - \frac{kzm}{2s} \right] \exp \left( st - mz \right) ds . \tag{5.6} \]

An evaluation of this inversion integral gives

\[ p(z, t) = \frac{z}{2\sqrt{\pi}} \int_{0}^{t} \left( t - \tau \right) \exp \left( -2i\tau - \frac{\tau^2}{4t} \right) d\tau \\
- \frac{kz}{2} \left[ \frac{1}{\sqrt{\pi t}} \exp \left( -2i\tau - \frac{\tau^2}{4t} \right) + \sqrt{\frac{t}{2}} \left\{ \exp \left( -\frac{z}{2t} \right) \right\} \right] \exp \left( z/2t \right) \erfc \left( \frac{z}{2\sqrt{t}} \right) . \tag{5.7} \]

The surface traction at the disk can readily be calculated by using the same procedure as mentioned above.

When \( k = 0 \), the above result reduces to that for Newtonian rotating flows.

**Acknowledgement**

The first author expresses her sincere thanks to the Centre of Advanced Study in Applied Mathematics, University of Calcutta for a U G C Junior fellowship and the second wishes to express his gratitude to the Centre for a Visiting Professorship. It is a pleasure to record our grateful thanks to Prof Dr M Dutta of the Centre for providing encouragement and a good opportunity for research. This work was partially supported by the Research Council of East Carolina University, Greenville, North Carolina.
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